

Soil organic carbon and biological indicators in an Acrisol under tillage systems and organic management in north-eastern Brazil

Luiz F. C. Leite^{A,C}, Francisco C. Oliveira^A, Ademir S. F. Araújo^B, Sandra R. S. Galvão^A, Janyelle O. Lemos^A, and Elzane F. L. Silva^B

^AEmbrapa Mid-North, Av. Duque de Caxias, 5650, Teresina, PI 64006-220, Brazil.

^BUniversidade Federal do Piauí, Centro de Ciências Agrárias, Campus da Socopo, Teresina, PI, Brazil.

^CCorresponding author. Email: luizf@cpamn.embrapa.br

Abstract. No-tillage and organic farming are important strategies to improve soil quality. This study aimed to quantify the effects of the tillage systems and organic management on total organic carbon (TOC), labile C (C_L), and biological indicators in an Acrisol in north-eastern Brazil. Five systems were studied: NV, native vegetation; NT/ORG, no-tillage plus organic fertiliser; NT/CHE, no-tillage plus chemical fertiliser; NT/CHE/ORG, no-tillage plus organic and chemical fertiliser; CT/CHE, conventional tillage plus chemical fertiliser. Soil samples were collected in the 0–0.10 and 0.10–0.20 m depths. TOC stocks were higher in NT/CHE/ORG (0–0.10 m, 14.0 Mg/ha; 0.10–0.20 m, 13.0 Mg/ha) and NT/ORG (0–0.10 m, 12.6 Mg/ha; 0.10–0.20 m, 11.6 Mg/ha) than in CT/CHE and NV systems. C_L stocks were higher in NT/ORG (3.61 Mg/ha) at 0–0.10 m and in NT/ORG, NT/CHE, and NT/CHE/ORG at 0.10–0.20 m. At 0–0.10 m, microbial biomass C content was higher in the NT/CHE/ORG (190 mg/kg) and NT/ORG (155 mg/kg). Soil microbial respiration rate was similar in all systems. However, qCO_2 was higher in the NT/CHE and CT/CHE systems, suggesting a stress in the soil microbial biomass. No-tillage and organic management promoted positive changes in soil organic carbon and soil microbial properties and improved soil quality.

Additional keywords: carbon sequestration, microbial activity, microbial biomass, no-tillage, fertiliser.

Introduction

Farming methods that use mechanical tillage and excessive synthetic fertiliser can promote soil degradation. Therefore, soil management regimes based on conservation tillage (no-tillage or reduced tillage) or organic management are essential to sustainable land use (Lal 2004; Tejada *et al.* 2006).

No-tillage minimises soil organic matter losses and is a promising strategy to maintain and even increase soil C and N stocks (Dickow *et al.* 2005; Moebius-Clune *et al.* 2008). The widespread use of the no-tillage in Brazil is characterised by sowing onto the crop residues from the previous cultivation, without any soil preparation. The dead biomass formed by the crop residues accumulated on the topsoil can help reduce erosion, and temperature and moisture fluctuations at the surface and the crops exposure to drought. These characteristics result in chemical, biological, and physical alterations in soil properties (Leite *et al.* 2003).

Organic management is gaining worldwide acceptance and has been expanding at annual rate of 20% in the last decade, accounting for over 24 Mha worldwide (Willer and Yussefi 2004). Brazil is one of the leading countries worldwide in organic farming (~850 000 ha) and occupies the 6th position in the world (Willer and Yussefi 2007). In the north-eastern region, Piauí State, organic fruit production has intensified to meet market demands over recent years. Organic practices for fruit production avoid applications of synthetic fertilisers and

pesticides, rely on organic inputs and recycling for nutrient supply, and emphasise cropping system design and biological processes for pest management, as defined by organic farming regulations (Araújo *et al.* 2008). They may thus reduce some negative effects attributed to conventional farming and have potential benefits in enhancing soil quality (Mader *et al.* 2002).

Tillage systems and organic management can be evaluated by soil quality, which is considered a necessary indicator of sustainability land management (Herrick 2000; Marinari *et al.* 2006). Several studies establish that soil organic matter (SOM) is an essential soil quality indicator especially by its effects on soil structure, water retention, nutrient availability, and soil microorganisms (Galantini and Rosell 2006; Aparicio and Costa 2007; Leite *et al.* 2007). More recently, SOM has attracted great interest because of the phenomenon of global warming and the prospect of using soil as a reservoir of carbon released to the atmosphere (CO_2) from human activity. The best strategies to build up carbon stocks in the soil are those that increase crop residue addition to the soil or decrease soil organic matter decomposition rate (Lal 2004).

Microbial processes are directly interlinked with SOM and also are important for the management of farming systems and to improve soil quality. The maintenance of the ecosystem productivity depends mainly on the organic matter transformation and, consequently, soil microbial biomass (Valpassos *et al.* 2001). Microbial biomass has been suggested as an integrative signal of

the microbial significance in soils because it is one of the few fractions of SOM that is biologically meaningful, easily measurable, and sensitive to management or pollution (Powlson 1994). It is both a source and sink for nutrients, it participates in the main biogeochemical transformation of C, N, P, and S, and it contributes to soil structure and stabilisation. For these reasons, microbial biomass is widely used as indicator in many soil-monitoring programs (Winding *et al.* 2005).

Moreover, enzyme activities can be used as early indicators of changes in SOM dynamics (Andersson *et al.* 2004). The activities of most enzymes increase as native SOM content increases, reflecting larger microbial communities and stabilisation of enzymes on humic materials (Bending *et al.* 2002). Dehydrogenase and fluorescein diacetate hydrolysis (FDA) activity typically occurs in all intact, viable microbial cells. Its measurement is usually related to the presence of viable microorganisms and their oxidative capability (Trevors 1984) and soil microbial activity (Araújo *et al.* 2003).

In Brazil, and specifically the north-eastern region, the number of studies comparing the effect of different tillage systems and organic and conventional farming systems on soil quality is limited (Araújo *et al.* 2008). Our study aimed to quantify, in a long-term experiment, the effects of tillage systems and organic management on total organic carbon and biological indicators in an Acrisol cultivated with watermelon in north-eastern Brazil.

Materials and methods

Study area

The field study was carried out in Jatobá, Piauí State, north-eastern Brazil (04°46'16"S, 41°49'04"W; 240 m). The mean annual air temperature and average rainfall are 30°C and 1000 mm/year, respectively. Two-thirds of the rain falls during the warmest season, from October to April. The soil is a Typic Hapludults (Argissolo Vermelho-Amarelo, Brazilian Soil Classification) showing the following chemical and physical characteristics at 0–0.20 m depth: pH(H₂O) 4.9; Al³⁺ 0.6 cmol_c/dm³; Ca²⁺ 2.6 cmol_c/dm³; Mg²⁺ 1.7 cmol_c/dm³; P 4 mg/dm³; K 58 mg/dm³; SOM 14 g/kg. Coarse sand, fine sand, silt, and clay were 80, 60, 160, and 700 g/kg, respectively. Soil bulk density was 1.1 Mg/m³.

The area, used by small farmers, has been cultivated for 12 years, with watermelon and maize–bean intercrop, under conventional and organic farming system. Five land-use systems, under the same type of soil, were selected: NV, native vegetation; NT/ORG, no-tillage plus organic fertiliser (compost); NT/CHE, no-tillage plus chemical fertiliser (120, 120, 100 kg/ha of N-P₂O₅-K₂O, respectively); NT/ORG/CHE, no-tillage plus organic fertiliser (compost) and chemical fertiliser (120, 120, 100 kg/ha of N-P₂O₅-K₂O, respectively); CT/CHE, conventional tillage plus chemical fertiliser (120, 120, 100 kg/ha of N-P₂O₅-K₂O, respectively). The compost was applied yearly at 40 m³/ha shortly before sowing time and was partially air-dried to enable manual application. Annually, 2 Mg/ha of carnauba (*Copernicea cerifera* Mart.) straw was applied in the NT/ORG and NT/ORG/CHE systems. Compost and carnauba straw properties are showed in Table 1.

Table 1. Chemical characteristics of the compost and carnauba straw added to organic plots

Component	Content
<i>Compost</i>	
Moisture	380 g/kg
Density	0.36 g/cm ³
P	7.0 g/kg
K	26 g/kg
Ca	10 g/kg
Mg	4.0 g/kg
Total N	32 g/kg
C/N ratio	7
<i>Carnauba straw (% dry matter)</i>	
Crude protein	14.0
Ca	0.17
P	0.10
Food fibre	
Acid detergent fibre	51.9
Neutral detergent fibre	76.2
Lignin	18.1

Soil sampling and analyses

Soil sampling was carried out after watermelon harvest, in an area of ~1 ha in each land use, after subdivision into 4 plots (replicates). In each plot, 8 subsamples were collected in the 0–0.10 and 0.10–0.20 m layers to form a composite sample. The samples were passed through a 2-mm sieve and a 300-g aliquot of each sample was separated, placed in plastic bags, and stored in refrigerator at 4–8°C for later determination of microbial biomass and activity. The remaining soil samples were air-dried. Soil samples were ground and passed through a 0.21-mm sieve to determine total organic carbon (TOC) by wet combustion using a mixture of potassium dichromate and sulfuric acid under heating (Yeomans and Bremner 1988). Total nitrogen (TN) was measured in the soil samples by the Kjeldhal method (Bremner 1996).

The free light fraction (FLF) was separated from the soil by flotation in NaI solution (SG 1.8 ± 0.01) as proposed by Freixo *et al.* (2002). The siphoned FLF was dried at 80°C for 72 h and the carbon of the FLF was determined by wet combustion using a mixture of potassium dichromate and sulfuric acid under heating (Yeomans and Bremner 1988). Carbon of the FLF was considered labile C (C_L) as proposed by Vieira *et al.* (2007). The non-labile carbon (C_{NL}) was calculated by difference (C_{NL} = TOC – C_L). Based on the difference between the TOC of native vegetation and the TOC of the cultivated systems, a carbon pool index (CPI) was calculated as CPI = TOC cultivated / TOC native vegetation. According to changes in the proportion of C_L (i.e. L = C_L / C_{NL}) in the soil, a lability index (LI) was calculated as LI = (L in cultivated) / (L in native vegetation). These indices were used to calculate the carbon management index (CMI) by the following formula: CMI = CPI × LI × 100 (Blair *et al.* 1995). C-CO₂ emission or sequester rate was estimated using native vegetation as a reference (TOC stocks NV – TOC stocks cultivated systems / 12 years). A conversion factor of C to CO₂ of 3.67 (molar mass of CO₂ / molar mass of C) was used.

The microbial biomass was determined by the irradiation–extraction method by microwave (Islam and Weil 1998) using 0.5 mol/L of K_2SO_4 as extractant, quantifying the C content by wet combustion (Yeomans and Bremner 1988). The conversion factor (K_C) used to convert the flow of C for the microbial biomass C (C_{MIC}) was 0.38 (Sparling and West 1988). Soil respiration (CO_2 emission), FDA hydrolysis, and dehydrogenase (DH) activity were measured as indication of soil microbial activity. Soil respiration was determined according to Alef (1995). Soil samples (100 g) were placed in 300-mL glass containers closed with rubber stoppers, moistened at 60% of the maximum water-holding capacity, and incubated for 7 days at 25°C. Glass vials holding 10 mL of NaOH (0.5 mol/L), to trap the evolved CO_2 -C, were placed in the above containers. On day 7 after the incubation, the glass vial was removed and the CO_2 trapped in NaOH was then determined titrimetrically. The qCO_2 was calculated as the ratio of basal respiration to microbial biomass C and results were expressed as $g\ CO_2\text{-C}/g\ C_{MIC}/\text{day}$. FDA hydrolysis was quantified according to the method of Schnurer and Rosswall (1982). Dehydrogenase activity was determined using method described in Casida *et al.* (1964) and based on the spectrophotometric determination of triphenyl tetrazolium formazan (TTF) released by 5 g of soil during 24 h at 35°C.

Statistical analyses

The study was carried out in a completely randomised design with 4 replicates. Analyses of variance (ANOVA) and a *t*-test were used to detect significant differences between the areas studied. When a significant *F* value was detected, the means were compared by the Tukey test ($P < 0.05$). All the statistical analyses were performed with the SPSS (version 15.0) software package.

Results

Total organic carbon and total nitrogen stocks

TOC stocks at 0–0.10 and 0.10–0.20 m depths were higher ($P < 0.05$) in NT/CHE/ORG (14.0 and 13.1 Mg/ha) and NT/ORG (12.6 and 11.6 Mg/ha), respectively (Fig. 1a); likewise for TN stocks (NT/CHE/ORG 0.97 and 0.90 Mg/ha; NT/ORG 1.05 and 0.82 Mg/ha) (Fig. 1b). Higher potential for C sequestration was observed in NT/CHE/ORG (1.63 and 1.75 Mg/ha.year) and NT/ORG (1.22 and 1.30 Mg/ha.year) systems at 0–0.10 and 0.10–0.20 m, respectively. On the other hand, C emission in NT/CHE (0.04 Mg/ha.year), at 0–0.10 m, was verified (Table 2).

Soil labile C and CMI

At 0–0.10 m depth, C_L stocks were highest ($P < 0.05$) in NT/ORG (3.61 Mg/ha, 28.5% of the TOC); at 0.10–0.20 m, NT/ORG (2.22 Mg/ha, 19.5% of the TOC), NT/CHE/ORG (1.69 Mg/ha, 12.9% of the TOC), and NT/CHE (1.55 Mg/ha, 17.5% of the TOC) were higher than CT/CHE (Table 2). In relation to native forest, C_L stocks had increased by 482, 290, 283, and 3% at 0–0.10 m and by 353, 216, 244, and 30% at 0.10–0.20 m depth in NT/ORG, NT/CHE, NT/CHE/ORG, and CT/CHE, respectively. CPI values varied from 1.61 (NT/CHE/ORG) to 0.98 (NT/CHE) at 0–0.10 m and from 1.78 (NT/CHE/ORG) to 1.20 (NT/CHE) at 0.10–0.20 m depth. CMI increased

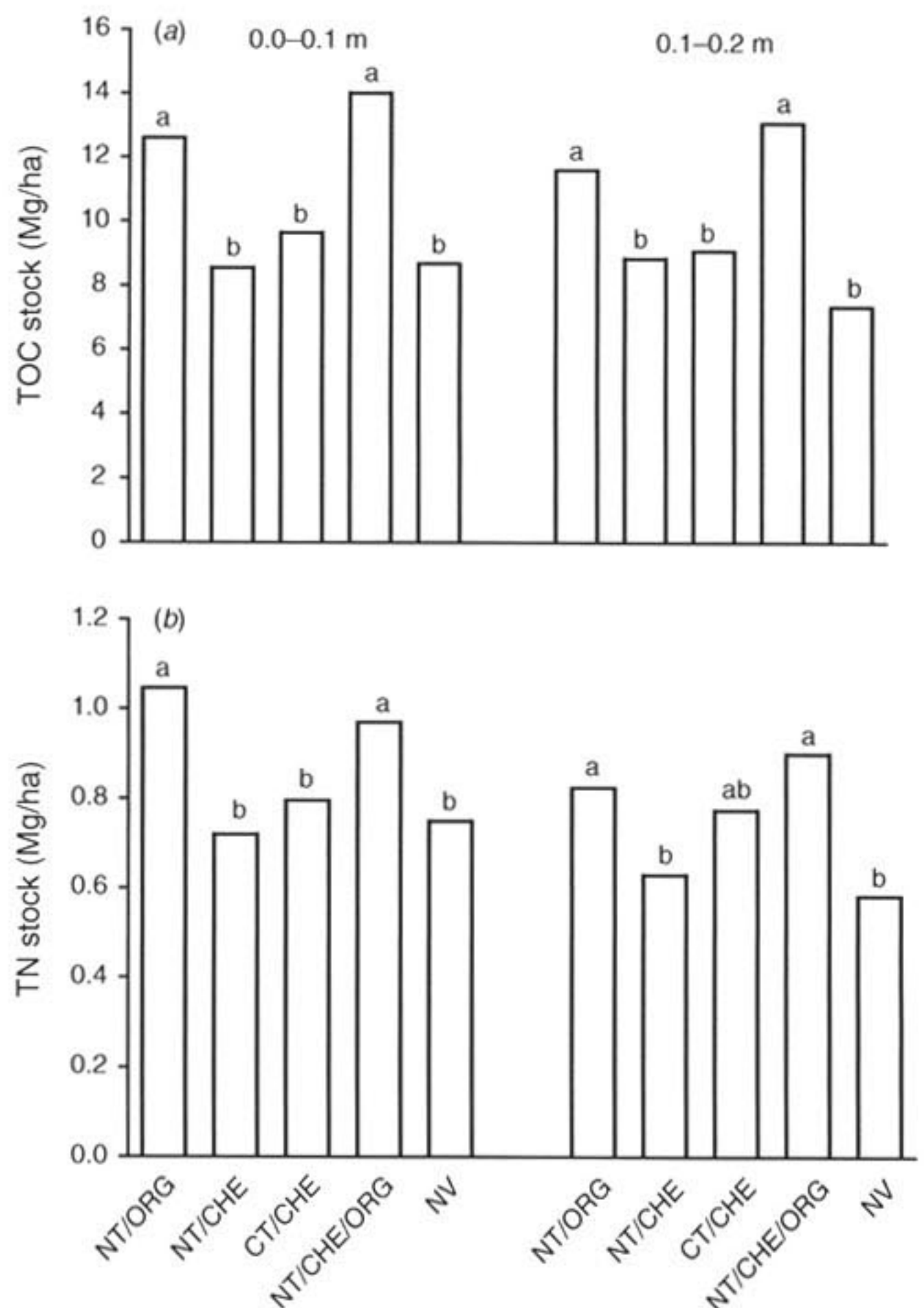


Fig. 1. Soil management systems and its effects on (a) total organic carbon (TOC) and (b) total nitrogen (TN) stocks at 0.0–0.1 and 0.10–0.2 m soil depths. NT/ORG, No-tillage plus organic fertiliser; NT/CHE, no-tillage plus chemical fertiliser; CT/CHE, conventional tillage plus chemical fertiliser; NT/CHE/ORG, no-tillage plus chemical and organic fertilisers; NV, native vegetation. Means within columns followed by the same letters are not different by Tukey test at $P = 0.05$.

with the adoption of the no-till systems and application of compost and varied from 100 (CT/CHE) to 801 (NT/ORG) at 0–0.10 m and from 129 (CT/CHE) to 526 (NT/ORG) at 0.10–0.20 m depth (Table 2).

Soil microbial biomass and activity

Soil microbial respiration rate can measure microbial activity. It was similar in all systems at 0–0.10 m and 0.10–0.20 m depths (Fig. 2a), showing that different land management promoted no changes in soil respiration.

Practices in the organic farming system, such as use of organic compost only or with chemical fertiliser, profoundly affected the size of the soil microbial biomass (Fig. 2b). At 0–0.10 m depth, the C_{MIC} was highest in NT/CHE/ORG and NT/ORG plots with 190 and 155 mg/kg, respectively, while lowest C_{MIC} was observed in the conventional plot (CT/CHE), with 75 mg/kg at 0–0.10 m and 80 mg/kg at 0.10–0.20 m depth. The results showed an increase of ~100–120% from conventional farming to organic farming.

Table 2. Rates of C-CO₂ emission (–) or sequester (+), labile carbon (C_L) stocks, and carbon management index (CMI) for soil management systems. Means within columns followed by the same letters are not different by Tukey test at *P* = 0.05. CMI = CPI × LI × 100, where CPI (carbon pool index) = TOC (total organic carbon) cultivated/TOC native vegetation, LI (lability index) = L (lability of carbon) cultivated/L native vegetation, and L = C_L/C_{NL}. NT/ORG, No-tillage plus organic fertiliser; NT/CHE, no-tillage plus chemical fertiliser; CT/CHE, conventional tillage plus chemical fertiliser; NT/CHE/ORG, no-tillage plus chemical and organic fertilisers; NV, native vegetation

Soil management	C-CO ₂ rate (Mg/ha.year)	C _L (Mg/ha)	C _{NL}	C _L /TOC (%)	CPI	L	LI	CMI
<i>0–0.10 m</i>								
NV	–	0.62c	8.05b	7.23c	–	0.08	–	–
NT/ORG	+1.22	3.61a	9.04b	28.5a	1.46	0.43	5.49	801a
NT/CHE	–0.04	2.42b	6.12c	28.3a	0.98	0.43	5.56	544b
NT/CHE/ORG	+1.63	2.38b	11.6a	17.0b	1.61	0.20	2.63	424b
CT/CHE	+0.29	0.64c	9.00b	6.61c	1.11	0.08	0.90	100c
<i>0.10–0.20 m</i>								
NV	–	0.49b	6.86c	6.63b	–	0.07	–	–
NT/ORG	+1.30	2.22a	9.39b	19.1a	1.58	0.24	3.33	526a
NT/CHE	+0.46	1.55a	7.29bc	17.5a	1.20	0.22	3.08	370b
NT/CHE/ORG	+1.75	1.69a	11.4a	12.9a	1.78	0.16	2.21	354b
CT/CHE	+0.53	0.64b	8.46b	7.00b	1.24	0.07	1.04	129c

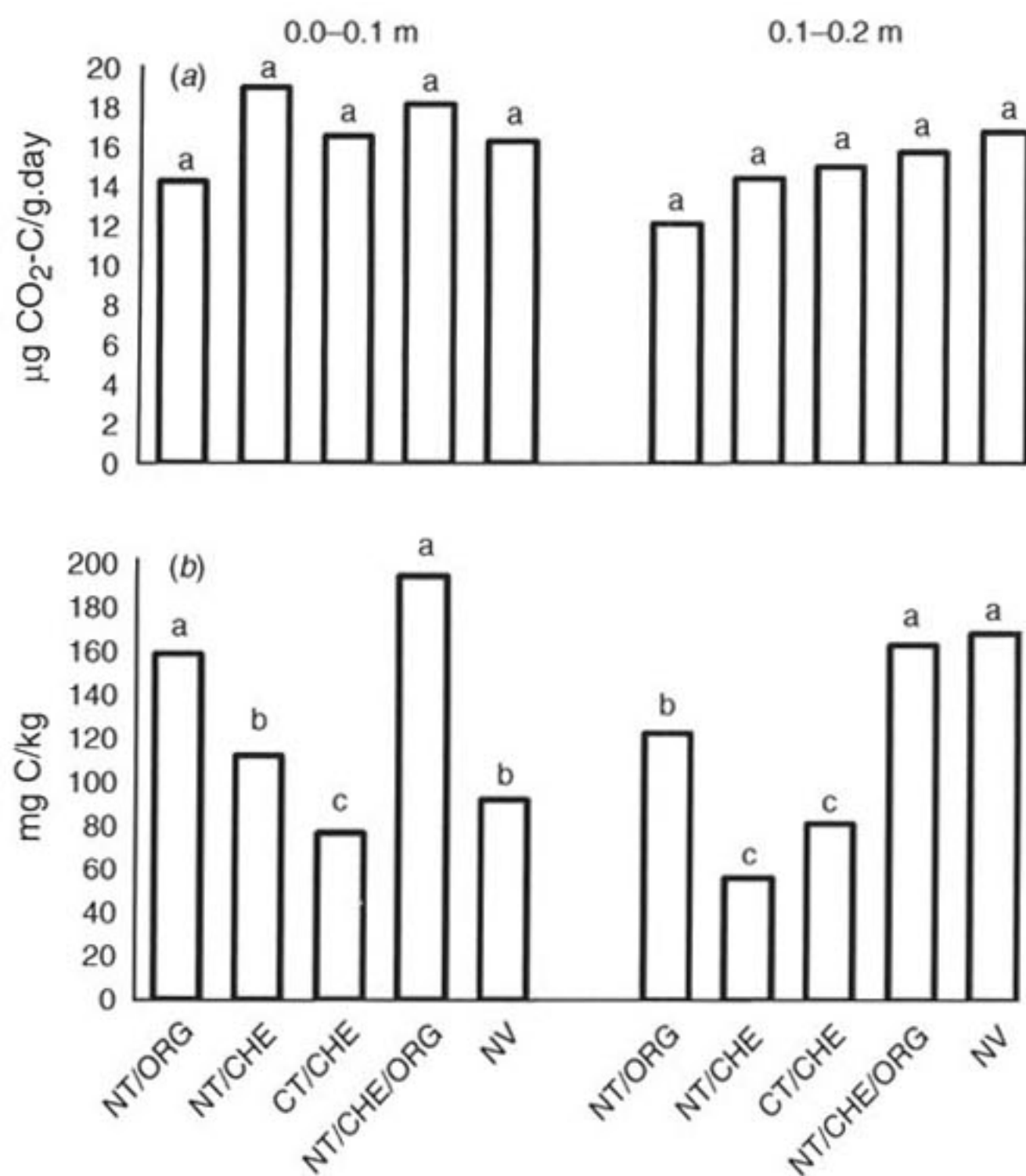


Fig. 2. Soil management systems and its effects on (a) soil respiration and (b) C-microbial biomass at 0.0–0.1 and 0.1–0.2 m soil depths. NT/ORG, No-tillage plus organic fertiliser; NT/CHE, no-tillage plus chemical fertiliser; CT/CHE, conventional tillage plus chemical fertiliser; NT/CHE/ORG, no-tillage plus chemical and organic fertilisers; NV, native vegetation. Means within columns followed by the same letters are not different by Tukey test at *P* = 0.05.

The values of $q\text{CO}_2$ were higher in NT/CHE and CT/CHE, while the $\text{C}_{\text{MIC}}:\text{TOC}$ ratio was higher in NT/CHE/ORG (Fig. 3a, b). The activities of FDA and dehydrogenase were significantly higher in NT/ORG at 0–0.10 m depth and NT/ORG and NT/CHE/ORG at 0.10–0.20 m depth (Fig. 4a, b).

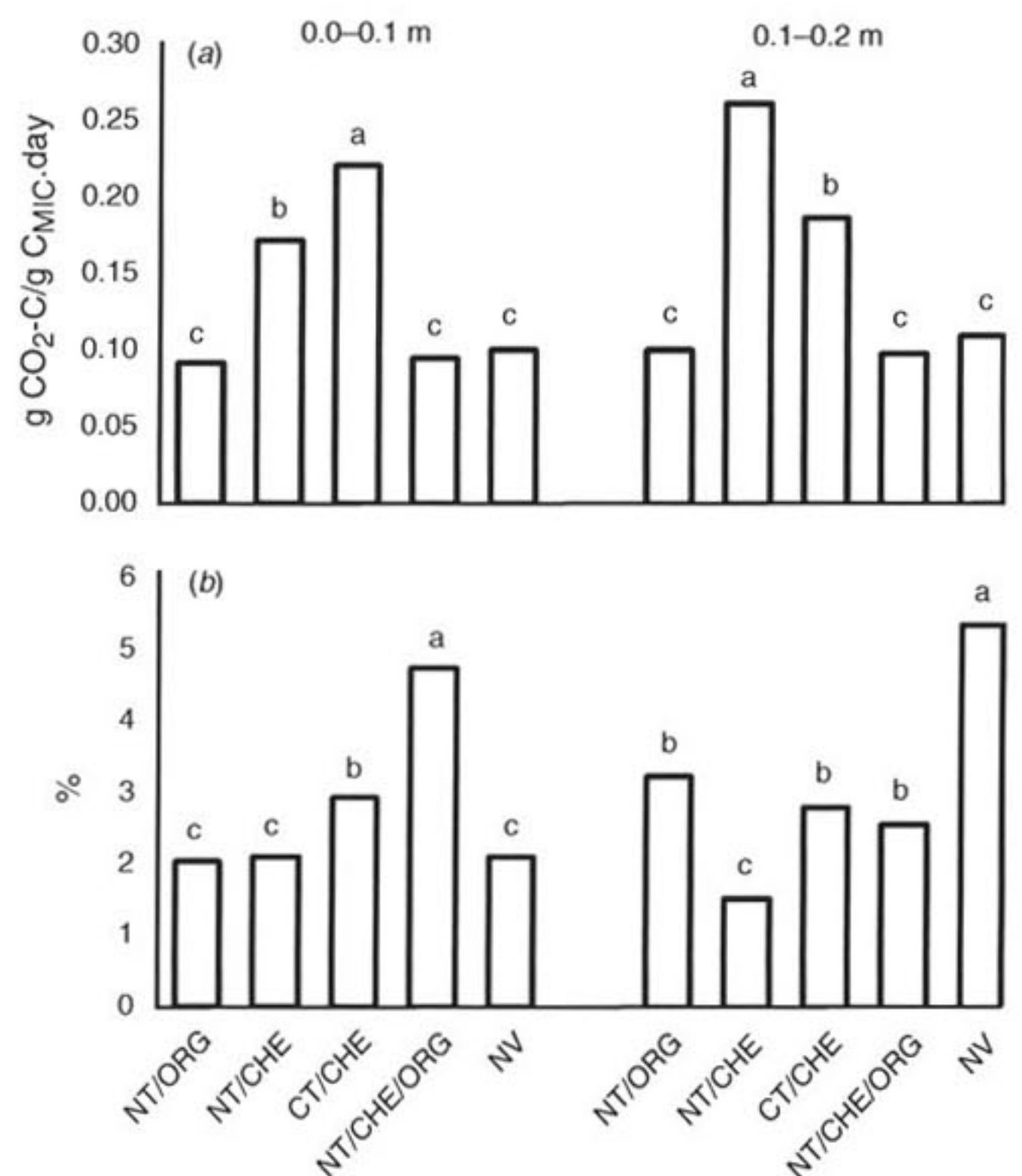


Fig. 3. Soil management systems and its effects on (a) metabolic quotient and (b) $\text{C}_{\text{MIC}}:\text{TOC}$ ratio at 0.0–0.1 and 0.1–0.2 m soil depths. NT/ORG, No-tillage plus organic fertiliser; NT/CHE, no-tillage plus chemical fertiliser; CT/CHE, conventional tillage plus chemical fertiliser; NT/CHE/ORG, no-tillage plus chemical and organic fertilisers; NV, native vegetation. Means within columns followed by the same letters are not different by Tukey test at *P* = 0.05.

Discussion

Total organic carbon and nitrogen stocks

Higher TOC and TN stocks in NT/CHE/ORG and NT/ORG can be attributed to the large amount of plant residues left on the field

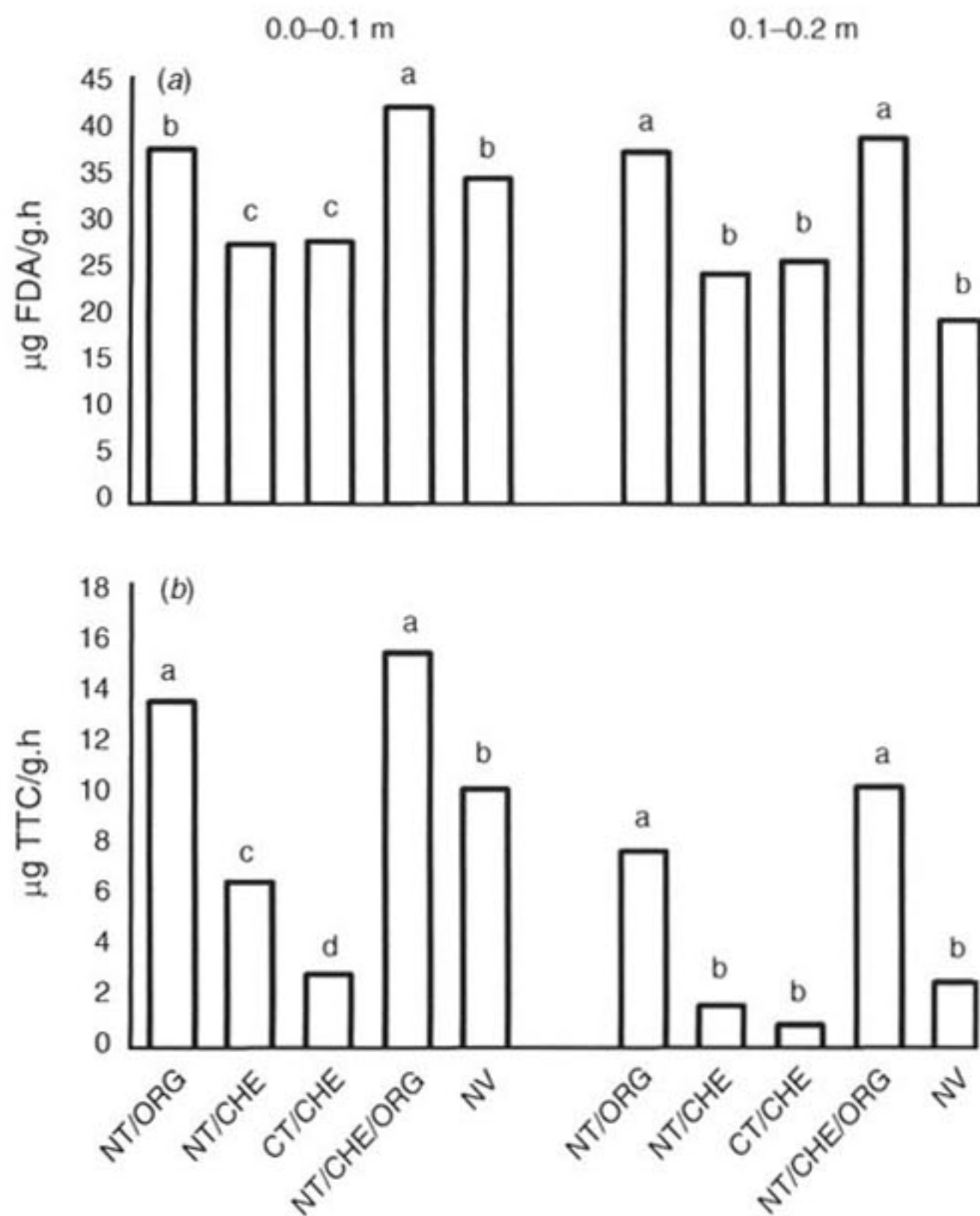


Fig. 4. Soil management systems and its effects on (a) FDA hydrolysis and (b) dehydrogenase at 0.0–0.1 and 0.1–0.2 m soil depths. NT/ORG, No-tillage plus organic fertiliser; NT/CHE, no-tillage plus chemical fertiliser; CT/CHE, conventional tillage plus chemical fertiliser; NT/CHE/ORG, no-tillage plus chemical and organic fertilisers; NV, native vegetation. Means within columns followed by the same letters are not different by Tukey test at $P=0.05$.

plots and C additional input from compost (animal manure and carnauba straw), as reported by other authors (Sherrod *et al.* 2005; Berner *et al.* 2008). These practices ensure greater amounts of organic matter causing a net buildup of the TOC stock (Kong *et al.* 2005; Majumder *et al.* 2008).

Animal manure, which has humic compounds with a high degree of polycondensation, can have provided great resistance to microbial attack (Nannipieri 1993; Triberti *et al.* 2008). Moreover, in the NT/CHE/ORG system, when crop residues from no-tillage are incorporated, N fertilisation can improve TOC stocks indirectly by increasing crop biomass production (Hati *et al.* 2006; Triberti *et al.* 2008). On the other hand, in the NV system, low residue input from species of savannah vegetation in the north-eastern region of Brazil associated with higher moisture and temperature regimes of the tropics, which contribute to enhanced decomposition of organic matter, has led to a decrease in TOC and TN stocks.

Higher C sequestration rates, observed in NT/CHE/ORG and NT/ORG, were higher than those observed in other studies under no-tillage in Brazil. In the southern region, Sá *et al.* (2001) estimated higher sequestration rates of 0.8 Mg C/ha.year at 0–0.20 m and 1.0 Mg C/ha.year at 0–0.40 m depth after 22 years under no-tillage compared with soils under conventional tillage over the same period. Amado *et al.*

(2006), in the same region, studied several soil management and crop systems and reported that no-tillage showed a range of 0.12–0.43 Mg C/ha.year of C accumulation compared with conventional tillage. In the central region, Bayer *et al.* (2006) reported that changes in soil management from conventional to no-tillage resulted in an C sequestration rate of 0.30 Mg C/ha.year in the sandy clay loam Oxisol and of 0.60 Mg C/ha.year in the clayey Oxisol and calculated an average C sequestration rate of 0.35 Mg C/ha.year in the 0–0.20 m layer of Brazilian tropical no-till soils. These results can be explained because we had included, besides no-tillage, compost, which increases TOC stocks in the soil as established by several authors (Leite *et al.* 2007; Triberti *et al.* 2008).

Soil labile C and CMI

The rapid turnover time of labile soil C make this labile pool particularly important in the response to environmental changes, such as changes in climate or land use (Marland *et al.* 2004). Therefore, in the NT/ORG system, the contribution from residue input, compost, and carnauba straw applied annually can increase C_L stocks. Bayer *et al.* (2002) verified that cropping systems with annual C addition showed more labile organic matter, as detected through spectroscopic techniques, compared with the cropping systems under lower C input. Also, Leite *et al.* (2007) observed that soils with the application of compost under no-tillage system had higher C_L stocks of than those with the application of mineral fertiliser alone or the control treatment. However, high amounts of labile organic carbon indicate that the soil shows good quality only if this fraction is able to provide plant nutrients and interfere with soil aggregate stability (Whitbread *et al.* 1998). On the other hand, the decrease in the C_L stocks observed in the CT/CHE system can be associated with aggregate disruption and greater organic matter oxidation after forest conversion into conventional agriculture based on soil ploughing and harrowing as established by Leite *et al.* (2003) and Bayer *et al.* (2006).

Higher CPI values in NT/CHE/ORG reflect the high potential in restoring the original soil organic C stocks. In a study with no-till cropping systems, Vieira *et al.* (2007) reported that N application (180 kg N/ha.year) was important to increase CPI and to recover soil C content as observed in the black oat/maize and black oat + vetch/maize systems. CMI values were higher in NT/ORG at 0–0.10 and 0.10–0.20 m depths. This result shows that adoption of no-tillage and application of compost can be viewed as an efficient way to recycle nutrients and organic matter which can support crop production and maintain or improve soil quality (Whalen *et al.* 2001; Morris *et al.* 2004).

Soil microbial biomass and activity

Our data indicate that microbial biomass C was significantly and rapidly enhanced in the organic system due to annual input of organic compost and 'carnauba' straw, which supply available C. Additionally, the increase in C_{MIC} in organic systems is, probably, also due to the microbial biomass contained in the organic amendments. Others studies show positive influence of inputs of organic residues, with high C content, on soil microbial biomass (Melero *et al.* 2006; Tu *et al.* 2006; Araújo *et al.* 2008), where the microbial biomass content is related to C inputs.

For example, in a long-term field experiment established in the USA, Tu *et al.* (2006) evaluated the effect of transitional practices from conventional to organic farming on the size of the soil microbial communities. The microbial biomass C was higher in the organic plots than conventional plots. According to the authors, the significant differences in microbial biomass C between the organic and conventional farming likely reflect the accumulative impact of organic C inputs during 2000 and 2002, in organic farming, on the size of microbial biomass.

According to Fließbach and Mader (2000), over the long-term, microbial biomass C is significantly affected by the long-term management as well as by its intensity. The same author observed that microbial biomass C in the organic plots was 45–64% higher than in the respective conventional plots with manure amendment.

The $C_{MIC}:TOC$ ratio is an indicator of the availability of carbon to microorganisms, input of organic matter to soil, conversion efficiency to microbial biomass, and stabilisation of carbon in soil. This higher $C_{MIC}:TOC$ ratio observed in NT/CHE/ORG can be due to the higher soil microbial biomass C content observed in the soil under NT/CHE/ORG and indicates an organic matter that is very active and subject to changes (Hart *et al.* 1989).

High soil respiration indicates high biological activity and decomposition of organic residues. However, soil respiration can also be interpreted as an indication of stress in the soil microbial biomass (Anderson and Domsch 1990). To interpret these results, qCO_2 , an index which measures the respiration per biomass unit (Anderson 2003), was determined and compared in all areas (Fig. 4a). Thus, our results show that NT/CHE and CT/CHE have increased qCO_2 , suggesting a stress on soil microbial biomass.

On the other hand, the lower qCO_2 observed in NT/ORG and NT/CHE/ORG indicates high efficiency of soil microbial biomass under the organic system in the use of available C for biosynthesis. According to Behera and Sahani (2003), higher efficiency of the microbial biomass indicates more incorporation of C and less losses of C through the respiration.

Enzyme activities respond immediately to changes in soil environment (Kandeler and Murer 1993; Dodor and Tabatabai 2003) because they are highly correlated with microbial biomass. This suggests that microbial activity, measured by enzymatic activity, was increased in organic farming soils, as reported by Marinari *et al.* (2006) and Lagomarsino *et al.* (2009). According to Aon and Colaneri (2001), an enhancement of soil enzymatic activity is generally expected in response to: (i) increased microbial synthesis and release of extracellular enzymes, and (ii) improved environmental conditions induced by changes of soil physicochemical properties (Aon and Colaneri 2001). Our results show that the enzyme activities responded to the organic management, suggesting that, in NT/ORG and NT/CHE/ORG, the increase in enzymatic activities was related to a larger microbial biomass present in this system.

Conclusions

Higher total organic carbon and labile C were observed in the no-tillage and organic management plots. Microbial biomass

C and enzymatic activities responded rapidly to organic management. This was caused by the higher inputs of organic matter, an energy-rich substrate for the microbial communities present, which were activated to ensure the turnover of applied nutrients. Therefore, soil microbial biomass C and enzymatic activity can be confirmed as useful indicators of changes in C cycling.

No-tillage and organic management promoted, in a long-term experiment under tropical conditions, positive changes in soil organic carbon and soil microbial properties and improved the soil quality.

Acknowledgments

Authors acknowledge CNPq (National Council of Research and Development, Brazil) for the respective fellowship awarded to Luiz F. C. Leite and Ademir S. F. Araújo.

References

- Alef K (1995) Estimation of soil respiration. In 'Methods in soil microbiology and biochemistry'. (Eds K Alef, P Nannipieri) pp. 464–470. (Academic Press: New York)
- Amado TJC, Bayer C, Conceição PC, Spagnollo E, Campos BHC, Veiga M (2006) Potential of carbon accumulation in no-till soils with intensive use and cover crops in Southern Brazil. *Journal of Environmental Quality* **35**, 1599–1607. doi:10.2134/jeq2005.0233
- Anderson JM, Domsch KH (1990) Application of ecophysiological quotients (qCO_2 and qD) on microbial biomass from soils of different cropping histories. *Soil Biology & Biochemistry* **22**, 251–255. doi:10.1016/0038-0717(90)90094-G
- Anderson TH (2003) Microbial eco-physiological indicators to assess soil quality. *Agriculture, Ecosystems & Environment* **98**, 285–293. doi:10.1016/S0167-8809(03)00088-4
- Andersson M, Kjoller A, Struwe S (2004) Microbial enzyme activities in leaf litter, humus and mineral soil layers of European forests. *Soil Biology & Biochemistry* **36**, 1527–1537. doi:10.1016/j.soilbio.2004.07.018
- Aon MA, Colaneri AC (2001) Temporal and spatial evolution of enzymatic activities and physico-chemical properties in an agricultural soil. *Applied Soil Ecology* **18**, 255–270. doi:10.1016/S0929-1393(01)00161-5
- Aparicio V, Costa JL (2007) Soil quality indicators under continuous cropping systems in the Argentinean Pampas. *Soil & Tillage Research* **96**, 155–165. doi:10.1016/j.still.2007.05.006
- Araújo ASF, Monteiro RTR, Abarkeli RB (2003) Effect of glyphosate on soil microbial activity of two Brazilian soils. *Chemosphere* **52**, 799–804. doi:10.1016/S0045-6535(03)00266-2
- Araújo ASF, Santos VB, Monteiro RTR (2008) Responses of soil microbial biomass and activity for practices of organic and conventional farming systems in Piauí state, Brazil. *European Journal of Soil Biology* **44**, 225–230. doi:10.1016/j.ejsobi.2007.06.001
- Bayer C, Martin-Neto I, Mielniczuk J, Pavinato A, Dieckow J (2006) Carbon sequestration in two Brazilian Cerrado soils under no-till. *Soil & Tillage Research* **86**, 237–245. doi:10.1016/j.still.2005.02.023
- Bayer C, Mielniczuk J, Martin-Neto L, Ermani PR (2002) Stocks and humification degree of organic matter fractions as affected by no-tillage on a subtropical soil. *Plant and Soil* **238**, 133–140. doi:10.1023/A:1014284329618
- Behera N, Sahani U (2003) Soil microbial biomass and activity in response to Eucalyptus plantation and natural regeneration on tropical soil. *Forest Ecology and Management* **174**, 1–11. doi:10.1016/S0378-1127(02)00057-9
- Bending GD, Turner MK, Jones JE (2002) Interactions between crop residue and soil organic matter quality and the functional diversity of soil microbial communities. *Soil Biology & Biochemistry* **34**, 1073–1082. doi:10.1016/S0038-0717(02)00040-8

- Berner A, Hildermann I, Fließbach A, Pfinner L, Mader P (2008) Crop yield and soil fertility response to reduced tillage under organic management. *Soil & Tillage Research* **101**, 89–96. doi:10.1016/j.still.2008.07.012
- Blair GJ, Lefroy RDB, Lisle L (1995) Soil carbon fractions based on their degree of oxidation, and development of a carbon management index, for agricultural systems. *Australian Journal of Agricultural Research* **46**, 1459–1466. doi:10.1071/AR9951459
- Bremner JM (1996) Nitrogen total. In 'Methods of soil analysis'. (Ed. DL Sparks) pp. 1085–1121. (SSA: Madison, WI)
- Casida LE Jr, Klein DA, Santoro T (1964) Soil dehydrogenase activity. *Soil Science* **98**, 371–376. doi:10.1097/00010694-196412000-00004
- Diekow J, Mileniczuk J, Knicker H, Bayer C, Dick DP, Kogel-Knaber I (2005) Soil C and N stocks as affected by cropping system and nitrogen fertilization in a southern Brazil Acrisol managed under no-tillage for 17 years. *Soil & Tillage Research* **81**, 87–95. doi:10.1016/j.still.2004.05.003
- Dodor DE, Tabatabai MA (2003) Amidohydrolases in soils as affected by cropping systems. *Applied Soil Ecology* **24**, 73–90. doi:10.1016/S0929-1393(03)00067-2
- Fließbach A, Mader P (2000) Microbial biomass and size–density fractions differ between soils of organic and conventional agricultural systems. *Soil Biology & Biochemistry* **32**, 757–768. doi:10.1016/S0038-0717(99)00197-2
- Freixo AA, de Machado PLOA, de Santos HP, Silva CA, de Fadigas FS (2002) Soil organic carbon and fractions of a Rhodic Ferrasol under the influence of tillage and crop rotation systems in southern Brazil. *Soil & Tillage Research* **64**, 221–230. doi:10.1016/S0167-1987(01)00262-8
- Galantini J, Rosell R (2006) Long-term fertilization effects on soil organic matter quality a dynamics under different production systems in semiarid Pampean soils. *Soil & Tillage Research* **87**, 72–79. doi:10.1016/j.still.2005.02.032
- Hart PBS, August JA, West AW (1989) Long-term consequences of topsoil mining on select biological and physical characteristics of two New Zealand loessial soils under grazed pasture. *Land Degradation* **1**, 77–88. doi:10.1002/ldr.3400010202
- Hati KM, Swarup A, Singh D, Misra AK, Ghosh PK (2006) Long-term continuous cropping, fertilization and manuring effects on physical properties and organic carbon content of a sandy loam soil. *Australian Journal of Soil Research* **44**, 487–495. doi:10.1071/SR05156
- Herrick JE (2000) Soil quality: an indicator of sustainable land management? *Applied Soil Ecology* **15**, 75–83. doi:10.1016/S0929-1393(00)00073-1
- Islam KR, Weil RR (1998) Microwave irradiation of soil for routine measurement of microbial biomass carbon. *Biology and Fertility of Soils* **27**, 408–416. doi:10.1007/s003740050451
- Kandeler E, Murer E (1993) Aggregate stability and soil microbial processes in a soil with different cultivation. In 'International Workshop on Methods of Research on Soil Structure/Soil Biota Interrelationships'. (Eds L Brussard, MJ Kooistra). *Geoderma* **56**, 503–513.
- Kong AYY, Six J, Bryant DC, Denison RF, Van Kessel C (2005) The relationship between carbon input, aggregation, and soil organic carbon stabilization in sustainable cropping systems. *Soil Science Society of America Journal* **69**, 1078–1085.
- Lagomarsino A, Moscatelli MC, Di Tizio A, Mancinelli R, Marinari S (2009) Soil biochemical indicators as a tool to assess the short-term impact of agricultural management on changes in organic C in a Mediterranean environment. *Ecological Indicators* **9**, 518–527. doi:10.1016/j.ecolind.2008.07.003
- Lal R (2004) Soil carbon sequestration to mitigate climate change. *Geoderma* **123**, 1–22. doi:10.1016/j.geoderma.2004.01.032
- Leite LFC, Mendonça ES, Machado PLOA (2007) Influence of organic and mineral fertilisation on organic matter fractions of a Brazilian Acrisol under maize/common bean intercrop. *Australian Journal of Soil Research* **45**, 25–32. doi:10.1071/SR06029
- Leite LFC, Mendonça ES, Machado PLOA, Matos ES (2003) Total C and N storage and organic C pools of a Red-Yellow Podzolic under conventional and no tillage at the Atlantic Forest Zone, south-eastern Brazil. *Australian Journal of Soil Research* **41**, 717–730. doi:10.1071/SR02037
- Mader P, Fließbach A, Dubois D, Gunst L, Fried P, Niggli U (2002) Soil fertility and biodiversity in organic farming. *Science* **296**, 1694–1697. doi:10.1126/science.1071148
- Majumder B, Mandal B, Bandyopadhyay PK, Gangopadhyay A, Mani PK, Kundu AL, Mazundar D (2008) Organic amendments influence soil organic carbon pools and rice–wheat productivity. *Soil Science Society of America Journal* **72**, 775–785. doi:10.2136/sssaj2006.0378
- Marinari S, Mancinelli R, Campiglia E, Grego S (2006) Chemical and biological indicators of soil quality in organic and conventional farming systems in Central Italy. *Ecological Indicators* **6**, 701–711. doi:10.1016/j.ecolind.2005.08.029
- Marland G, Garten CT Jr, Post WM, West TO (2004) Studies on enhancing carbon sequestration in soils. *Energy* **29**, 1643–1650.
- Melero S, Porras JCR, Herencia JF, Madejon E (2006) Chemical and biochemical properties in a silty loam soil under conventional and organic management. *Soil & Tillage Research* **90**, 162–170. doi:10.1016/j.still.2005.08.016
- Moebius-Clune B, van Es HM, Idowu OJ, Schindelbeck RR, Moebius-Clune DJ, Wolfe DW, Abawi GS, Thies JE, Gugino BK, Lucey R (2008) Long-term effects of harvesting maize stover and tillage on soil quality. *Soil Science Society of America Journal* **72**, 960–969. doi:10.2136/sssaj2007.0248
- Morris DR, Gilbert RA, Reicosky DC, Gesch RW (2004) Oxidation potentials of soil organic matter in Histosols under different tillage methods. *Soil Science Society of America Journal* **68**, 817–826.
- Nannipieri P (Ed.) (1993) 'Ciclo della sostanza organica nel suolo.' (Pàtron: Bologna)
- Powlson DS (1994) The soil microbial biomass: before, beyond and back. In 'Beyond the biomass'. (Eds K Ritz, J Dighton, GE Giller) pp. 3–20. (John Wiley and Sons: Chichester, UK)
- Sá JCM, Cerri CC, Dick WA, Lal R, Venske Filho SP, Piccolo MC, Feigl BE (2001) Organic matter dynamics and carbon sequestration rates for a tillage chronosequence in a Brazilian Oxisol. *Soil Science Society of America Journal* **65**, 1486–1499.
- Schnurer J, Rosswall T (1982) Fluorescein diacetate hydrolysis as a measure of total microbial activity in soil a litter. *Applied and Environmental Microbiology* **43**, 1256–1261.
- Sherrod LA, Peterson GA, Westfall DG, Ahuja LR (2005) Soil organic carbon pools after 12 years in no-till dryland agroecosystems. *Soil Science Society of America Journal* **69**, 1600–1608. doi:10.2136/sssaj2003.0266
- Sparling GP, West AW (1988) A direct extraction method to estimate soil microbial C: Calibration *in situ* using microbial respiration and ¹⁴C labelled cells. *Soil Biology & Biochemistry* **20**, 337–343. doi:10.1016/0038-0717(88)90014-4
- Tejada M, Hernandez MT, Garcia C (2006) Application of two organic amendments on soil restoration: Effects on the soil biological properties. *Journal of Environmental Quality* **35**, 1010–1017. doi:10.2134/jeq.2005.0460
- Trevors JT (1984) Effect of substrate concentration, inorganic nitrogen, O₂ concentration, temperature and pH on dehydrogenase activity in soil. *Plant and Soil* **77**, 285–293. doi:10.1007/BF02182931
- Triberti L, Nistri A, Giordani G, Comellini F, Baldoni G, Toderi G (2008) Can mineral and organic fertilization help sequester carbon dioxide in cropland? *European Journal of Agronomy* **29**, 13–20. doi:10.1016/j.eja.2008.01.009
- Tu C, Ristaino JB, Hu S (2006) Soil microbial biomass and activity in organic tomato farming systems: effects of organic inputs and straw mulching. *Soil Biology & Biochemistry* **38**, 247–255.

- Valpassos MAR, Cavalcante EGS, Cassiolato AM, Alves MC (2001) Effects of soil management systems on soil microbial activity, bulk density and chemical properties. *Pesquisa Agropecuaria Brasileira* **36**, 1539–1545. doi:10.1590/S0100-204X2001001200011
- Vieira FCB, Bayer C, Zanatta JA, Dieckow J, Mieleniczuk J, He ZL (2007) Carbon management index based on physical fractionation of soil organic matter in an Acrisol under long-term no-till cropping. *Soil & Tillage Research* **96**, 195–204. doi:10.1016/j.still.2007.06.007
- Whalen JK, Chang C, Olson BM (2001) Nitrogen and phosphorus mineralization potentials of soils receiving repeated annual cattle manure applications. *Biology and Fertility of Soils* **34**, 334–341. doi:10.1007/s003740100416
- Whitbread AM, Lefroy RDB, Blair GJ (1998) A survey of the impact of cropping on soil physical and chemical properties in north-western New South Wales. *Australian Journal of Soil Research* **36**, 669–681. doi:10.1071/S97031
- Willer H, Yussefi M (2004) 'The world of organic agriculture: statistics and emerging trends.' (International Federation of Organic Agriculture Movements: Bonn, Germany)
- Willer H, Yussefi M (2007) 'The World of Organic Agriculture. Statistics and Emerging Trends 2007.' 9th edn (International Federation of Organic Agriculture Movements, IFOAM: Bonn, Germany, & Research Institute of Organic Agriculture, FiBL: Frick, Switzerland)
- Winding A, Hund-Rinke K, Rutgers M (2005) The use of microorganisms in ecological soil classification and assessment concepts. *Ecotoxicology and Environmental Safety* **62**, 230–248. doi:10.1016/j.ecoenv.2005.03.026
- Yeomans JC, Bremner JM (1988) A rapid and precise method for routine determination of organic carbon in soil. *Communications in Soil Science and Plant Analysis* **19**, 1467–1476. doi:10.1080/00103628809368027

Manuscript received 8 July 2009, accepted 17 December 2009