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


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 (0.0–0.10 m, 14.0 Mg/ha; 0.10–0.20 m, 13.0 Mg/ha) and NT/ORG (0.0–0.10 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, qCO2 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 (Diekow 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 rates of 20% in the last decade, accounting for over 24 Mha worldwide (Willer and Yusufi 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 Yusufi 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; Aparício 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 (CO2) 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 (Trevis 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, Piaui 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 Tropic 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/dm³; Ca²⁺ 2.6 cmol/dm³; Mg²⁺ 1.7 cmol/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. Seven 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 cannauba (Copernicia cerifera Mart.) straw was applied in the NT/ORG and NT/ORG/CHE systems. Compost and cannauba straw properties are showed in Table 1.

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

<table>
<thead>
<tr>
<th>Component</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Compost</strong></td>
<td></td>
</tr>
<tr>
<td>Moisture</td>
<td>380 g/kg</td>
</tr>
<tr>
<td>Density</td>
<td>0.36 g/cm³</td>
</tr>
<tr>
<td>P</td>
<td>7.0 g/kg</td>
</tr>
<tr>
<td>K</td>
<td>26 g/kg</td>
</tr>
<tr>
<td>Ca</td>
<td>10 g/kg</td>
</tr>
<tr>
<td>Mg</td>
<td>4.0 g/kg</td>
</tr>
<tr>
<td>Total N</td>
<td>32 g/kg</td>
</tr>
<tr>
<td>C/N ratio</td>
<td>7</td>
</tr>
<tr>
<td><strong>Cannauba straw (% dry matter)</strong></td>
<td></td>
</tr>
<tr>
<td>Crude protein</td>
<td>14.0</td>
</tr>
<tr>
<td>Ca</td>
<td>0.17</td>
</tr>
<tr>
<td>P</td>
<td>0.10</td>
</tr>
<tr>
<td>Food fibre</td>
<td>51.9</td>
</tr>
<tr>
<td>Acid detergent fibre</td>
<td>76.2</td>
</tr>
<tr>
<td>Neutral detergent fibre</td>
<td>18.1</td>
</tr>
<tr>
<td>Lignin</td>
<td></td>
</tr>
</tbody>
</table>

**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 Brenner 1988). Total nitrogen (TN) was measured in the soil samples by the Kjeldahl method (Brenner 1996).

The free light fraction (FLF) was separated from the soil by flotation in Nal 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 Brenner 1988). Carbon of the FLF was considered labile C (C₀) as proposed by Vieira et al. (2007). The non-labile carbon (Cₐ) was calculated by difference (Cₐ = TOC - C₀). 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 Cₐ (i.e. L = Cₐ/TOC) 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-SCO₂ 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 Wel 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 (CO₂ 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 CO₂-C, were placed in the above containers. On day 7 after the incubation, the glass vial was removed and the CO₂ trapped in NaOH was then determined titrimetrically. The qCO₂ was calculated as the ratio of basal respiration to microbial biomass C and results were expressed as g CO₂-C/g C_MIC/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. CMI 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

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 kg/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.

<table>
<thead>
<tr>
<th>Soil management</th>
<th>C-CO₂ rate (Mg/ha.year)</th>
<th>C_l (Mg/ha)</th>
<th>C_NL (Mg/ha)</th>
<th>C_l/TOC (%)</th>
<th>CPI</th>
<th>L</th>
<th>LI</th>
<th>CMI</th>
</tr>
</thead>
<tbody>
<tr>
<td>NV</td>
<td>–</td>
<td>0.62c</td>
<td>0.05b</td>
<td>7.23c</td>
<td>–</td>
<td>0.08</td>
<td>–</td>
<td>801a</td>
</tr>
<tr>
<td>NT/ORG</td>
<td>+1.22</td>
<td>3.61a</td>
<td>9.04b</td>
<td>28.5a</td>
<td>1.46</td>
<td>0.43</td>
<td>5.49</td>
<td>544b</td>
</tr>
<tr>
<td>NT/CHE</td>
<td>-0.04</td>
<td>2.42b</td>
<td>6.12c</td>
<td>28.3a</td>
<td>0.98</td>
<td>0.43</td>
<td>5.56</td>
<td>424b</td>
</tr>
<tr>
<td>NT/CHE/ORG</td>
<td>+1.63</td>
<td>2.38b</td>
<td>11.6a</td>
<td>17.0b</td>
<td>1.61</td>
<td>0.20</td>
<td>2.63</td>
<td>424b</td>
</tr>
<tr>
<td>CT/CHE</td>
<td>+0.29</td>
<td>0.64c</td>
<td>9.00b</td>
<td>6.61c</td>
<td>1.11</td>
<td>0.08</td>
<td>0.90</td>
<td>100c</td>
</tr>
<tr>
<td>NV</td>
<td>–</td>
<td>0.49b</td>
<td>6.86c</td>
<td>6.63b</td>
<td>–</td>
<td>0.07</td>
<td>–</td>
<td>526a</td>
</tr>
<tr>
<td>NT/ORG</td>
<td>+1.30</td>
<td>2.22a</td>
<td>9.39b</td>
<td>19.1a</td>
<td>1.58</td>
<td>0.24</td>
<td>3.33</td>
<td>370b</td>
</tr>
<tr>
<td>NT/CHE</td>
<td>+0.46</td>
<td>1.55a</td>
<td>7.29bc</td>
<td>17.5a</td>
<td>1.20</td>
<td>0.22</td>
<td>3.08</td>
<td>356b</td>
</tr>
<tr>
<td>NT/CHE/ORG</td>
<td>+1.75</td>
<td>1.69a</td>
<td>11.4a</td>
<td>12.9a</td>
<td>1.78</td>
<td>0.16</td>
<td>2.21</td>
<td>356b</td>
</tr>
<tr>
<td>CT/CHE</td>
<td>+0.53</td>
<td>0.64b</td>
<td>8.46b</td>
<td>7.00b</td>
<td>1.24</td>
<td>0.07</td>
<td>1.04</td>
<td>129c</td>
</tr>
</tbody>
</table>

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 qCO₂ were higher in NT/CHE and CT/CHE, while the C₇₅: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) C₇₅:TC 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.
plots and C additional input from compost (animal manure and canauba 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 polymerisation, 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 changes in climate or land use (Marland et al. 2004). Therefore, in the NT/ORG system, the contribution from residue input, compost, and canauba 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 NT/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 CMI 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 CMI 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 ‘canauba’ straw, which supply available C. Additionally, the increase in C_b(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 Fliibeck 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 $C_{\text{mic}}/\text{TOC}$ 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 $C_{\text{mic}}/\text{TOC}$ 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 Marini and 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.

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