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Organic matter storage in a sandy clay loam Acrisol affected by tillage and cropping systems in southern Brazil

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Abstract

Soil organic matter decline and associated degradation of soil and environmental conditions under conventional tillage in tropical and subtropical regions underline the need to develop sustainable soil management systems. This study aimed first to evaluate the long-term effect (9 years) of two soil-tillage systems (conventional tillage: CT, and no-tillage: NT) and two cropping systems (oat (*Avena strigosa* Schreb)/maize (*Zea mays* L.): O/M; and oat+common vetch (*Vicia sativa* L.)/maize+cowpea (*Vigna unguiculata* (L.) Walp): O+V/M+C without N fertilization on total organic carbon (TOC) and total nitrogen (TN) concentrations in a sandy clay loam Acrisol in southern Brazil. The second objective was to assess soil potential for acting as an atmospheric CO_2 sink. Under NT an increase of soil TOC and TN concentrations occurred, in both cropping systems, when compared with CT. However, this increase was restricted to soil surface layers and it was higher for O+V/M+C than for O/M. The O+V/M+C under NT, which probably results in the lowest soil organic matter losses (due to erosion and oxidation) and highest addition of crop residues, had 12 Mg ha^{-1} more TOC and 0.9 Mg ha^{-1} more TN in the 0–30.0 cm depth soil layer, compared with O/M under CT which exhibits highest soil organic matter losses and lowest crop residue additions to the soil. These increments represent TOC and TN accumulation rates of 1.33 and 0.10 Mg ha^{-1} per year, respectively. Compared with CT and O/M, this TOC increase under NT and O+V/M+C means a net carbon dioxide removal of about 44 Mg ha^{-1} from the atmosphere in 9 years. NT can therefore be considered, as it is in temperate climates, an important management strategy for increasing soil organic matter. In the tropicals and subtropicals, where climatic conditions cause intense biological activity, in order to maintain or increase soil organic matter, improve soil quality and contribute to mitigation of CO_2 emissions, NT should be associated with cropping systems resulting in high annual crop residue additions to soil surface.

Keywords: Soil organic matter; Soil tillage; No-tillage; Cropping systems; Sustainability

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1. Introduction

Conventional tillage with intensive soil disturbance promotes rapid decrease of soil organic matter and subsequent CO_2 emission increase. A chemical, physical and biological soil degradation process then develops, negatively affecting crop productivity. In tropical and subtropical areas, where high temperatures and humidity accentuate soil degradation a main agricultural research goal should be the development of management systems that increase soil conservation and crop productivity. Therefore, knowledge of the main factors involved in soil organic matter increase is fundamental.

Tillage is the principal agent producing soil disturbance and subsequent soil structure modification, increasing potential soil organic matter loss by erosion and biological decomposition (Langdale et al., 1992; Carter et al., 1994). Quantitatively, the latter is thought to be the primary source of organic matter loss triggered by soil tillage (Rasmussen et al., 1998). Cambardella and Elliot (1992) determined that the winter wheat-fallow system after 20 years under no-tillage (NT) resulted in 6.7 Mg ha^{-1} more organic carbon than plow disk. In addition, management systems promoting soil organic carbon accumulation provide an atmospheric CO_2 sink.

The quantity of residue addition by cropping systems can affect soil organic matter accretion in degraded soils. A close relationship between crop residue addition during 5 years and carbon and nitrogen concentrations in an Acrisol under NT in southern Brazil was observed by Testa et al. (1992) and Teixeira et al. (1994). Other authors have also emphasized the great importance of residue addition in restoring soil organic matter (Angers et al., 1997; Larney et al., 1997; Potter et al., 1997; Huggins et al., 1998; Janzen et al., 1998).

Despite general soil organic matter increases under NT and cropping systems having high residue addition, increases also depend on other factors such as climate, mainly temperature and rainfall (Alvarez and Lavado, 1998), soil texture and mineralogy (Sollins et al., 1996; Hassink and Whitmore, 1997; Parfitt et al., 1997). Management systems need to be investigated regionally under different climate and soil conditions to fully clarify both conservation management potential and effect on global changes.

This study aimed at (1) evaluating the long-term effect (9 years) of two soil-tillage systems with different soil disturbance intensities and two cropping systems with different C and N additions on TOC (total organic carbon) and TN (total nitrogen) storage in a sandy clay loam Acrisol in southern Brazil; and (2) assessing soil potential for acting as a C sink, mitigating CO_2 emissions to atmosphere.

2. Material and methods

2.1. Site descriptions

This study was based on a long-term soil management experiment started in September 1985 in an area previously cultivated for 15 years under conventional tillage at the Experimental Station of the Federal University of Rio Grande do Sul, Eldorado do Sul, Rio Grande do Sul State, Brazil. Station area geographic coordinates are 30° 50′ 52″ S and 51° 38′ 08″ W. The soil is a sandy clay loam Acrisol (Dark red podzolic by Brazilian taxonomy and Paleudult by US soil taxonomy) whose physical, chemical and mineralogical characteristics are presented in Table 1.

Regional climate is subtropical, hot and humid, with local annual mean temperature of 19.4°C, varying annually between 13.9 and 24.9°C. Annual mean rainfall is 1440 mm, with monthly variations between 95.7 and 168 mm and occasional water deficiencies in summer (Bergamaschi and Guadagnin, 1990). Experimental area elevation is 96 m.

Table 1
Some chemical, physical and mineralogical characteristics of a sandy clay loam Acrisol from southern Brazil in the 0–20 cm soil depth in 1985

Soil characteristic	
Particle size	
Sand	540 g kg^{-1}
Silt	240 g kg^{-1}
Clay	220 g kg^{-1}
Minerals in clay fraction	
Kaolinite	720 g kg^{-1}
Iron oxides (Fe_2O_3)	109 g kg^{-1}
P	9 mg kg^{-1}
K	78 mg kg^{-1}

2.2. Experimental design and treatments

The original experiment consisted of three soil-tillage and three cropping systems, and two mineral N rates. Randomized block experimental design and three replications were employed with split-plots for tillage and cropping systems. Nitrogen rates were applied in split-blocks. However, in this study only two tillage methods and two of the cropping systems were sampled from the zero N plots.

Soil-tillage systems were applied in 15 m×20 m main plots in spring–summer previously of maize sowing. Tillage systems sampled were defined according to soil disturbance intensity, with total crop residue incorporation to the soil by disk plow and two disking (conventional tillage: CT); and no incorporation,

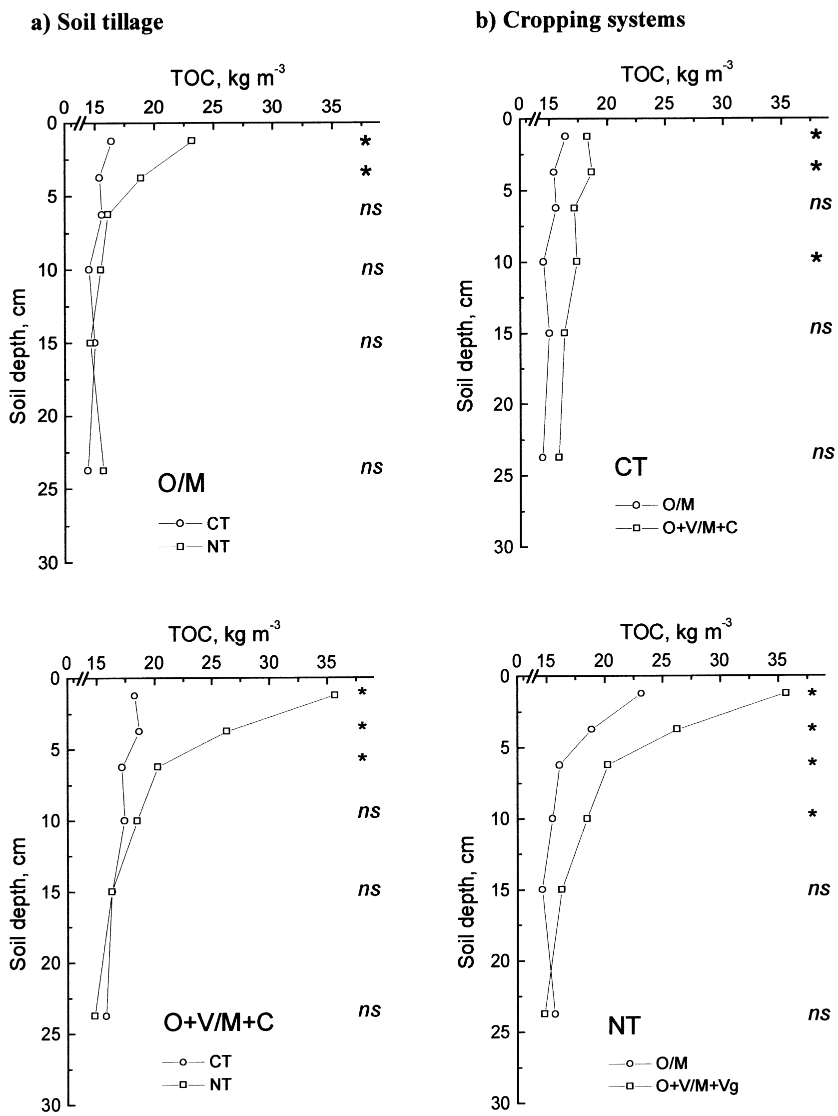

Fig. 1. Effects of soil-tillage (a) and cropping systems (b) on concentration of TOC in a sandy clay loam Acrisol in southern Brazil.

where crop residues are maintained on soil surface (NT). Soil disturbance depth was around 20 cm.

Cropping systems sampled, applied to 5 m×20 m sub-plots, were O/M: oat (*Avena strigosa* Schreb)/ maize (*Zea mays* L.); and O+V/M+C: oat+common vetch/maize+cowpea (*Vigna unguiculata* (L.) Walp). Common vetch replaced subterranean clover in 1990, which presented development problems in some years. Crops were sown at the recommended time, i.e., September (maize) and April (oat and vetch). Winter crops were sown under a NT system, followed in all treatments by shallow disking to provide seed contact with soil. Maize was sown with a manual drill, with 1 m spacing between rows, 0.2 m between holes, and two seeds in each hole. Plant population was adjusted to 50 000 plants per hectare by hand-thinning. About 40 days after maize emergence, cowpea was sown by manual drill between maize rows, with holes spaced at

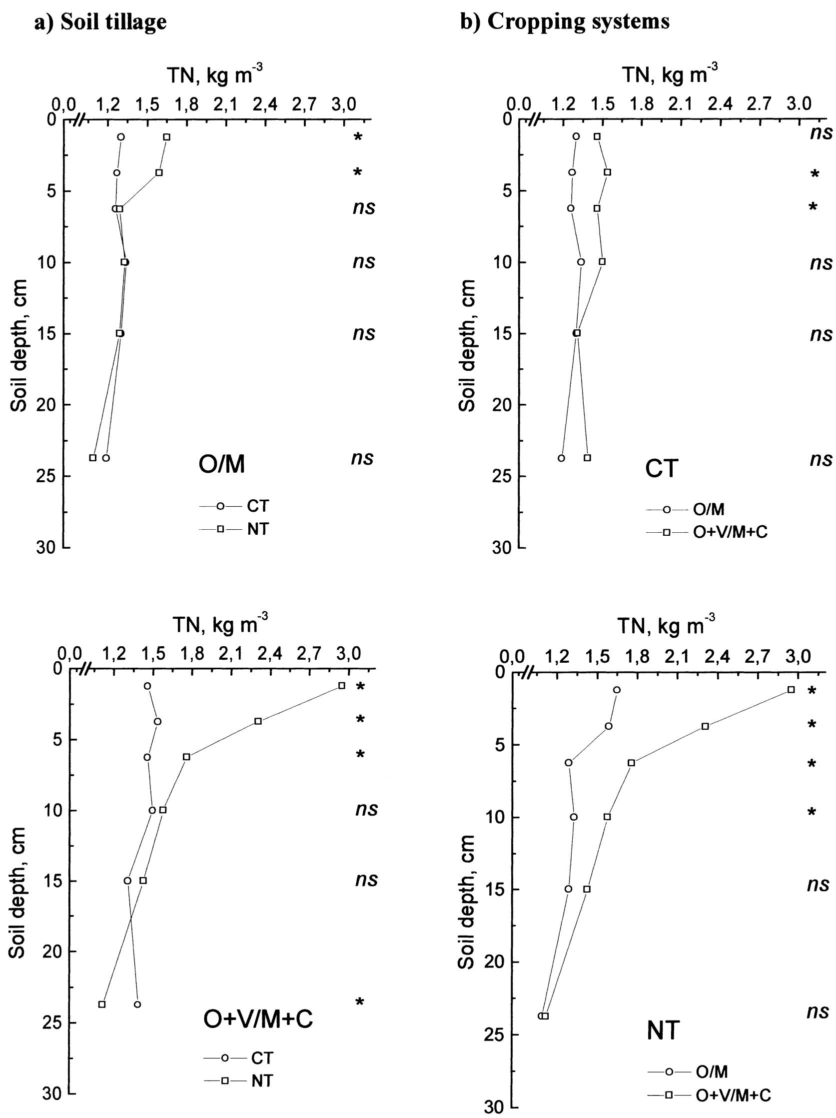

Fig. 2. Effects of soil-tillage (a) and cropping systems (b) on concentration of TN in a sandy clay loam Acrisol in southern Brazil.

0.5 m, three seeds per hole. During maize-growing season, weeds were controlled mechanically by hoeing and chemically using glyphosate-based herbicides. Sprinkler irrigation supplied water in dry seasons.

2.3. Soil sampling and chemical analysis

In September 1994 soil samples were collected at depths 0–2.5, 2.5–5.0, 5.0–7.5, 7.5–12.5, 12.5–17.5 and 17.5–30.0 cm. Samples were taken at random from a 0.10 m×0.50 m area, homogenized and subsampled, air-dried, crushed, and sieved to pass a 2 mm screen. TOC was analyzed by Walkley and Black procedure and TN by Kjeldhal digestion (Page, 1982). The bulk density data reported by Salton (1991) were utilized to calculate organic matter storage based on an equivalent soil mass (Angers et al., 1997; Peterson et al., 1998). TOC and TN levels in an adjacent area under virgin native grassland (Bayer and Mielniczuk, 1997a,b) were used as a comparison for the cultivated sites to evaluate management system effects. The sampled area of native grassland, with 200 identified grass species (*Paspalum notatum* Fl. is found in more than 30% of the area) had been under light grazing pressure for the previous 40 years.

The C and N amounts added or recycled by cropping systems were estimated using data reported by Burle et al. (1997), where C and N content in aboveground parts of winter and summer cover crops and maize residue over a 10-year period were measured. To include C and N from roots and exudates, a 30% mean value was added to the aboveground value (Klepker, 1991).

2.4. Statistics

The statistical analysis of soil-tillage and cropping system effects on TOC and TN concentrations was carried out by variance analysis, following a randomized block design with split-plot. The difference between treatment means was determined by Tukey test at 5% significance level.

3. Results

The O/M and O+V/M+C cropping systems added 4.35 and 7.95 Mg C ha^{-1} per year to soil, respectively (data not shown). The N recycled or added in the same cropping systems was 74 and 213 kg ha^{-1} per year, mainly due to biological fixation by legumes and recycling by crops.

Soil-tillage and cropping systems both affected TOC and TN concentration in soil profile (Figs. 1 and 2). Soil TOC and TN concentration under NT in

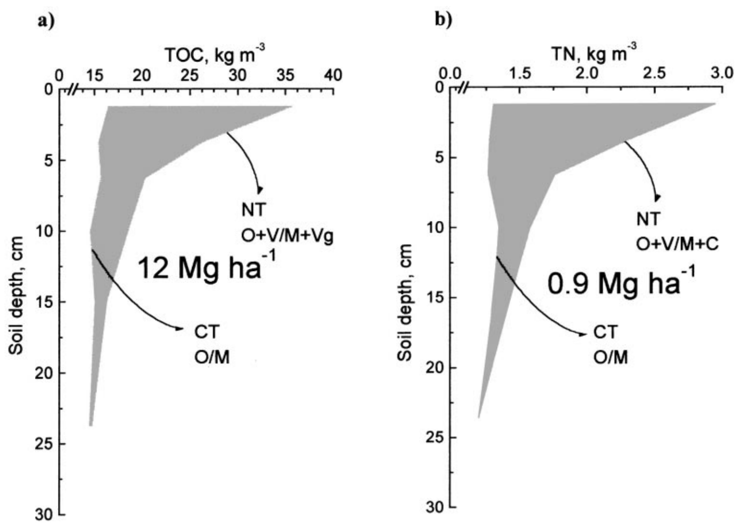

Fig. 3. Concentration of TOC (a) and TN (b) at 0–30 cm depth of a sandy clay loam Acrisol under NT and O+V/M+C compared with CT and O/M in southern Brazil.

both cropping systems (Figs. 1a and 2a) were higher than under CT. However, this effect was restricted to soil surface layers (0–5 cm in O/M; 0–12.5 cm in O+V/M+C). Calculating TOC and TN amounts held in 0–30 cm soil layer showed that the soil under NT had 4.6 and 6.4 Mg ha^{-1} more TOC than under CT in the O/M and O+V/M+C systems, respectively (Table 2). Soil TN contents under NT were 40 and 403 kg ha^{-1} greater than under CT in the same cropping systems (Table 2).

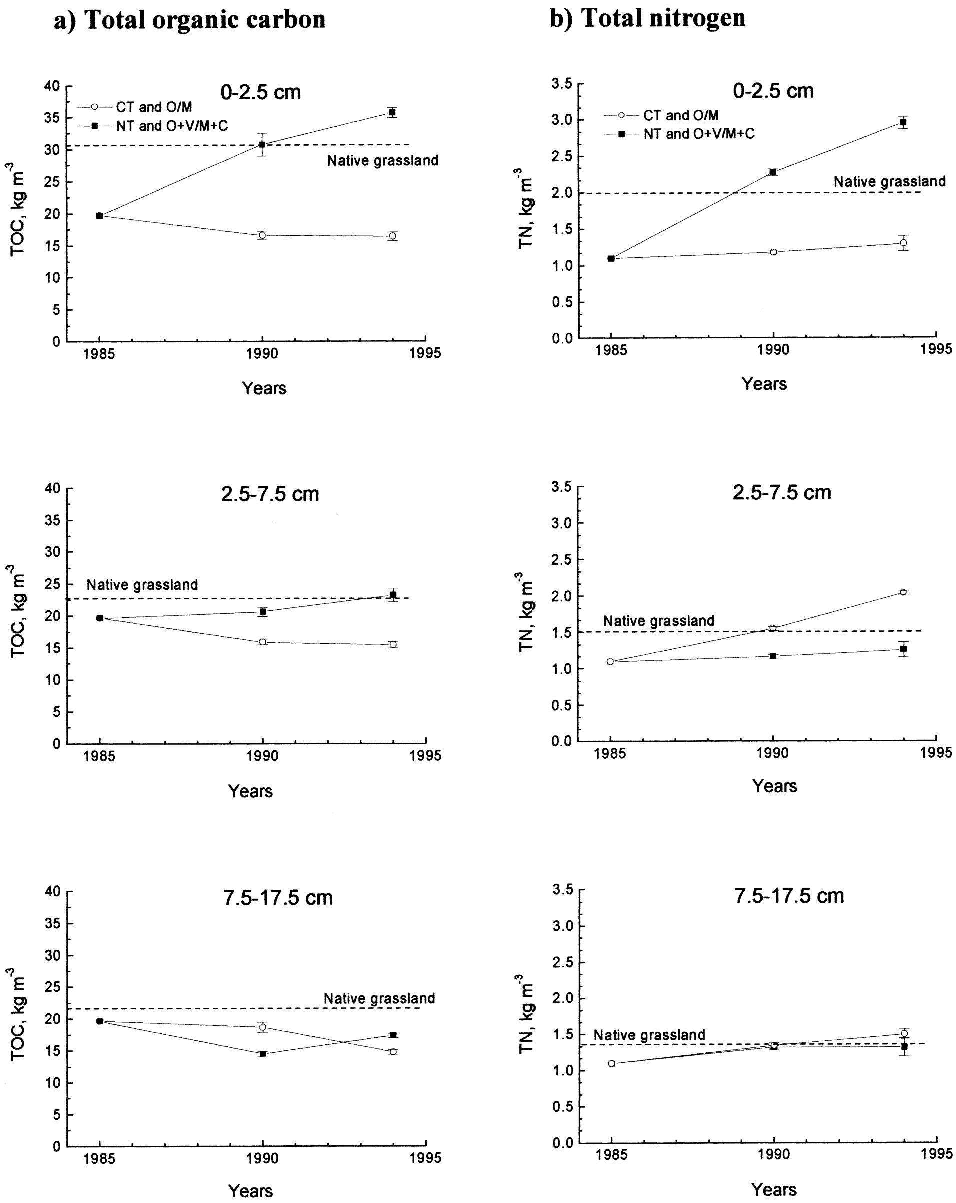

Fig. 4. Changes with time of the concentration of (a) TOC and (b) TN in a sandy clay loam Acrisol in southern Brazil under NT and O+V/M+C, and CT with O/M. Concentration of TOC and TN under adjacent native grassland was included for comparison and was assumed these are at steady state. The error bars represent the standard deviation of mean values.

Table 2
TOC and TN storage in 0–30 cm depth of a sandy clay loam Acrisol affected by management systems in southern Brazil[a]

Cropping system	Tillage system	
	CT	NT
TOC (Mg ha^{-1})		
O/M	44.6 b B	49.2 b A
O+V/M+C	50.2 a B	56.6 a A
TN (kg ha^{-1})		
O/M	3765 b A	3805 b A
O+V/M+C	4262 a B	4665 a A

[a] Tillage means (column) followed by same lower case letters and cropping systems means (row) followed by same capital letters are not different by Tukey test at 5% level.

In both CT and NT systems, soil TOC and TN concentrations were higher under O+V/M+C than under O/M. This effect was also restricted to the first 12.5 cm soil layer and greater under NT (Figs. 1b and 2b). Cropping system O+V/M+C under NT had 7.4 Mg ha^{-1} more TOC and 860 kg ha^{-1} more TN than did O/M. Under CT, these differences were 5.6 Mg ha^{-1} TOC and 497 kg ha^{-1} TN (Table 2).

Nine years of NT and the O+V/M+C cropping system resulted in 12 Mg ha^{-1} more TOC and 0.9 Mg ha^{-1} more TN in the 0–30 cm depth compared with CT and O/M (Fig. 3). These TOC and TN differences represent annual accumulation rates of 1.33 and 0.10 Mg ha^{-1}, respectively. These results are similar to those observed at the end of 5 years in the same experiment: 1.00 Mg ha^{-1} per year TOC and 0.10 Mg ha^{-1} per year TN (Bayer and Mielniczuk, 1997a,b).

The change with time in soil TOC and TN concentrations under NT with O+V/M+C and CT with O/M, at depths of 0–2.5, 2.5–7.5 and 7.5–17.5 cm, is presented in Fig. 4. The initial TOC (20 kg m^{-3}) and TN (1.2 kg m^{-3}) concentrations in 1985 are equal for all depths because soil was cultivated under conventional tillage for 15 years prior to initiation of the experiment and was sampled at 0–20 cm layer. Soil TOC and TN concentrations under adjacent native grassland, assumed to be at steady state, were included in order to compare the effect on TOC and TN after converting this area to use in arable agriculture.

The 15 year previous intensive cultivation significantly reduced the TOC and TN concentrations in all soil layers down to 17.5 cm depth, as observed in 1985 when experiment began (Fig. 4). However, after 9 years under O+V/M+C and NT, TOC concentration was higher than in the native grassland at 0–2.5 cm and equal at 2.5–7.5 cm soil layer, while in these treatments TN was higher than in native grassland in the same soil layers. The O/M under conventional tillage did not increase TOC and TN concentrations to original native grassland levels, with TOC even declining over time after 1985.

4. Discussion

In our experiment, soil organic matter storage in sandy clay loam Acrisol was largely dependent on tillage and cropping systems (Figs. 1 and 2) and their effects on organic matter loss and addition rates. NT resulted in higher soil organic matter content in soil profile (0–30 cm) than CT in both cropping systems (Table 2), an increase occurring mainly on surface layers and when using O+V/M+C system (Figs. 1 and 2).

Long-term experiments connected to studies of C and N storage in agricultural soils are hampered by the difficulties involved in separating C and N losses due to soil erosion from those due to biological oxidation of soil organic matter (Gregorich et al., 1998; Rasmussen et al., 1998). In our experiment, the soil erosion was observed to be very low, even under conventional tillage. The differences in soil TOC accumulation between CT and NT for both cropping systems (Table 2), probably results from higher soil organic matter decomposition rates under CT, providing that carbon additions resulting from cropping systems are virtually equal in both tillage systems. The C high losses from soil after plowing observed by Reicosky and Lindstrom (1993) and Reicosky et al. (1997) give some support to these conclusions.

Under NT, most of the crop residue stays at soil surface, with only a minor amount in close contact with soil. As result, residue decomposes slowly, protecting the soil surface from erosion over time (Pavinato, 1993; Amado, 1997). Under conventional tillage, crop residue incorporated into the soil becomes a readily available food and energy source for microorganisms. Reicosky and Lindstrom (1993) determined that in a 19-day period following soil tillage more C was liberated as CO_2 than was added by crop residue at season's end (1.85 Mg C ha^{-1}), indicating substantial soil organic matter biological oxidation.

Higher TOC and TN storage in soil under O+V/M+C (Figs. 1 and 2) were related to larger rates of C and N addition to soil, compared to results under O/M. Burle et al. (1997) obtained a close relationship of TOC in 0–17.5 cm layer of soil with residue quantity added by 10 different no-till cropping systems. Other strategies to obtain high crop residue addition to soil and subsequent soil organic matter maintenance are intensive cropping with cash or cover crops without fallow periods and animal manure addition (Dick et al., 1998; Janzen et al., 1998; Peterson et al., 1998). Mineral fertilization also may affect soil organic matter storage, depending on increase of crop residue addition (Paustian et al., 1992; Mitchell and Entry, 1998). However, at the end of the 5th year of this experiment the soil TOC and TN contents were unaffected by mineral N addition (Bayer and Mielniczuk, 1997a,b).

The highest soil organic matter storage occurred when the tillage system with the lowest soil disturbance was combined with a cropping system with high residue addition to soil (Figs. 3 and 4). These procedures are very important for organic matter accumulation and amelioration of physical, chemical and biological characteristics of degraded soils in southern Brazil. The magnitude of management system effect on soil organic matter accumulation rates depend mainly on soil components, e.g., clay and Al and Fe oxides (Parfitt et al., 1997), and climatic conditions, such as temperature and precipitation (Alvarez and Lavado, 1998). The combination of these soil and climatic variables with cropping and tillage systems may result in a wide range of soil TOC and TN accumulation rates.

Based on a review of several publications, Reicosky et al. (1995) reported organic matter increase under conservation management systems with rates ranging from 0 to 2300 kg ha^{-1} per year (0–1.15 Mg C ha^{-1} per year). Highest accumulation rates generally occurred in cold weather regions, or where winter cover crops were used, increasing annual residues addition. However, in the tropical West Nigerian, Lal (1997) observed a 1.33 Mg C ha^{-1} increment during 8 years under NT as compared to the conventional tillage of maize, which represents an accumulation rate of 0.17 Mg C ha^{-1} per year. In our experiment, NT and O+V/M+C resulted in accumulation rates of 1.33 Mg ha^{-1} per year TOC and 0.10 Mg ha^{-1} per year TN, compared with O/M under CT. These rates are similar to or even surpassing many obtained in temperate climates. Corazza et al. (1999), in an Oxisol under tropical native savanna vegetation of central Brazil, also observed a relative increase of 26.2 Mg ha^{-1} TOC in soil under crop rotation and NT during 12 years, compared with conventional tillage, representing an annual accumulation rate of 2.18 Mg ha^{-1} per year. Relative to native savanna vegetation, soil TOC decreased 4.8 Mg ha^{-1} under conventional tillage and increased 21.4 Mg ha^{-1} under NT.

These results stress the importance of NT and high crop residue addition for soil C and N storage in wet tropical or subtropical areas of the world. Under these management systems, soil functions as an atmospheric CO_2 sink, thus augmenting their benefits both to agriculture and environment. Increase of 12 Mg ha^{-1} TOC under NT and O+V/M+C observed in this experiment represents a net removal of about 44 Mg ha^{-1} of CO_2 from the atmosphere in 9 years, compared with CT and O/M, both without N fertilization.

5. Conclusions

In tropical and subtropical regions, NT is the primary management strategy for increasing soil organic matter. Large quantities of crop residue additions by cropping systems under NT accentuate soil organic matter accumulation. The highest increase occurs at soil surface layers, but a net increase of soil organic matter storage is observed in total soil profile (0–30 cm). In these management systems, soil acts as a C sink, contributing to mitigating CO_2 emissions to the atmosphere.

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