This paper was peer-reviewed for scientific content.
Pages 466-471. In: D.E. Stott, R.H. Mohtar and G.C. Steinhardt (eds). 2001. Sustaining the Global Farm. Selected papers from the 10th International Soil Conservation Organization Meeting held May 24-29, 1999 at Purdue University and the USDA-ARS National Soil Erosion Research Laboratory.

Carbon Sequestration in a Plowed and No-Tillage Chronosequence in a Brazilian Oxisol

João Carlos de M. Sá, Carlos C. Cerri, Warren A. Dick, Rattan Lal,*
Solismar P. Venske Filho, Marisa C. Piccolo and Brigitte E. Feigl

ABSTRACT

No-tillage (NT) adoption is an essential tool for development of sustainable agricultural systems and the amounts and rates of C sequestration under no-tillage are not known for a major ecological region of Southern Brazil. The soil organic carbon (SOC) gains and losses were assessed in a plowed and no-tillage chronosequence in a Brazilian Oxisol, located in South Center quadrant of Paraná State (50º23'W and 24º36'S). The chronosequence involved six treatments: (i) native field (NF); (ii) plow tillage of the native field (PNF-1) involving conversion of natural vegetation to cropland; (iii) no-tillage for 10 years (NT- 10); (iv) no-tillage for 20 years (NT-20); (v) no-tillage for 22 years (NT- 22); and (vi) conventional tillage for 22 years (CT-22) involving plow tillage with an disking after summer harvest and one after winter harvest to 20-cm depth plus two narrow disk. Soil samples were collected from five depths (0- to 2.5-cm, 2.5- to 5-cm, 5- to 10-cm, 10- to 20-cm and 20- to 40-cm) for determining bulk density and SOC. In comparison with NF, long-term no-tillage (NT-20 and NT-22) caused significant increase in SOC storage. More than 60% of this increase occurred in the 0- to 10-cm soil layer. During in the first 10 years of no-tillage the SOC gain was positive only on the top 5-cm layer. In contrast, the second ten years presented positive rates of C sequestration for all depths. Considering SOC pool of the original vegetation (NF) as a base line, analyses of the budget for 0-to 20-cm showed SOC balance at +16.94 Mg ha^{-1} for NT-22 and -1.26 Mg ha^{-1} for CT-22. The C sequestration rate obtained in this paper was 80.6 g C m^{-2} yr^{-1} for 0- to 20-cm and 99.4 g C m^{-2} yr^{-1} for 0- to 40-cm depth. This potential is equivalent to mitigate (1 unit of C convert to 3.67 units of CO_2) 34.3 Tg CO_2 yr^{-1}.

INTRODUCTION

Soil organic matter is the key component of sustainable agricultural systems and is highly dependent on management that influences the intensity of tillage and the amount and placement of crop residues. The steady state of soil organic carbon (SOC) pool is a balance between carbon additions from non-harvested portions of crops and organic amendments, and losses through organic matter decomposition, mineralization with attendant release of CO_2 to the atmosphere, and soil erosion. The impact of agricultural practices on the decline of SOC, coupled with the increased importance of the terrestrial ecosystem in global C budget has stimulated much scientific interest in evaluating the SOC dynamics in relation to land use and management (Lal and Logan, 1995).

Experiments conducted in several agroecoregions have demonstrated higher SOC contents in surface soils of no-tillage compared with conventional tillage (Lal, 1976; Dick, 1983; Dick et al., 1991, Havlin et al., 1990; Rasmussen, 1991; Lal, 1995; Muzilli, 1983; Resck, et al., 1991; Sá, 1993; Bayer, 1996). Comparisons between these systems for SOC pools can also be done considering natural or original vegetation as a base line representing the steady state (Cambardella and Elliot, 1992; 1993; and 1994). Data on a base line SOC pool are essential to understanding the magnitude of the SOC gains or losses from native soils, mainly because of the confounding effect of microbial respiration and soil erosion on SOC pool and fluxes.

Useful comparisons can be made between in SOC pools under forests and when converted to other land uses e.g. grassland (Oades, 1984). Tiessen & Santos (1989) observed 46% loss of SOC in one year on a sloping Alfisol. A rain forest site upper Rio Negro (AM- Brazil) lost most of its SOC from the surface soil only to three years after slash and burn management was started (Uhl, 1987). In a semiarid tropical Oxisol, in Araripe (NE Brazil) was observed 30% SOC was lost within six years of adopting mechanized cultivation (Tiessen et al., 1992) resulting in a mean residence time of less than 15 years for native organic C (Tiessen, 1994). In weathered tropical soils, rates of SOC loss under cultivation are generally higher. Plowing a pasture field in a Brazilian savanna deplete the SOC pool of 49 % within five years in a Typic Hapludox - Red Latosol, with > 30 % of clay content (Resck, et al., 1998). If converted to cropland, natural grasslands can be a major source of atmospheric CO_2, especially during the initial years of conversion. In contrast, Fisher et al. (1997) showed

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*J.C.M.Sá, Universidade Estadual de Ponta Grossa, Cx. Postal 992/3, 84010-330, Ponta Grossa-PR, Brasil; C.C.Cerri and S.P.Venske Filho and M.C. Piccolo and B.E. Feigl, Universidade de São Paulo-Centro de Energia Nuclear na Agricultura, Av. Centenário 303, 13416-970, Piracicaba-SP, Brasil; R. Lal, The Ohio State University, School of Natural Resources, 2021 Coffey Rd., Columbus, OH 43210, USA; and W.A. Dick, The Ohio State University, School of Natural Resources, 1680 Madison Avenue, Wooster 44691, USA. *Corresponding author: jcmsa@uepg.br.

that SOC increased in introduced grass pasture and the rate of enhancement was 1.8 kg m^{-2} C. Adopting best management practices on croplands can render them a net sink for while decreasing emissions of CO_2 from agricultural ecosystems (Lal, et al., 1998).

In Brazil 27% of cropland (13.47 millions hectares) are cultivated using a no-tillage system (Febrapdp, 2000). However, the information about C sequestration potential on no-tillage systems is not available for principal soils and major ecosystems. Therefore, the objective of this paper is to evaluate SOC pool and the carbon sequestration potential in a long-term plow and no-tillage chronosequence comprising a Brazilian Oxisol.

MATERIAL AND METHODS

Site Description

Field experiment was conducted on farmer's fields, located near the town of Tibagi (Santa Branca Farm) and Ponta Grossa City (Frankanna Farm), in the South Center quadrant of Paraná State - Brazil (50º23' W and 24º 36' S; 50º 20' W and 25º 20' S, respectively). These sites are located 880 to 910 meters above the sea level. The climate is mesothermic, wet subtropical, type cfb according koeppen classification (Maack, 1981). The mean annual rainfall is 1545 mm and the mean annual temperature is 18.7°C for Ponta Grossa (IAPAR, 1998), and 1532 mm and 20.7°C for Tibagi (Fundação ABC, 1998). The rainfall is uniformly distributed without a pronounced dry period. The previous land use was natural vegetation dominated by *Andropogon sp.*, *Aristida sp.*, *Paspalum sp.* and *Panicum sp.* (Maack, 1981). The landscape has long gentle slopes ranging from 2 to 7%. The soils at these sites are typical clayey Red Latosol (Typic Hapludox), with a deep and well-drained profile. These soils have high permeability and are located on the shoulder slopes. The geological material was derived from sediments formed in the Devonian period, comprising a reworked material of sandstone and shale. The clay material in these soils is kaolinite and gibbsite, and very rich in hematite and goethite. The chemical analyses and the proportion of the kaolinite and gibbsite are shown in the Table 1.

The choice of these sites was based on the existence of a well-defined chronosequence starting from the original undisturbed conditions (vegetation, soil properties), which provide an opportunity to assess the impact of conventional tillage and no-tillage on SOC pool and fluxes. The sites are developed on the same parent material and the same soil type, and were managed with similar crop rotation and cultural practices.

Experimental Design

These experiment were sited on a farmer's field, where the previous land use was natural vegetation. Theses sites were plowed in autumn of 1975, and 3.5 Mg ha^{-1} of lime and 117 kg ha^{-1} of P_2O_5 (52 kg P) was incorporated into the 20-cm depth only in Santa Branca Farm. The farmers adopted no-tillage system in 1976 and 1979 with gradual conversion

Table 1. Chemical and mineralogical properties of the *Typic Hapludox* (Dak Red Latosol) in the chronosequence.

Property	Depth	Treatments†					
	(cm)	NF	PNF-1	NT-10	NT-20	NT-22	CT-22
Chemical							
pH (1:2.5 soil/water)	0-20	4.9	5.6	6.3	6.3	6.3	6.0
	20-40	5.0	4.7	5.7	5.3	5.2	4.9
Potential Acidity, mmolc kg-1	0-20	97	132	42	62	51	53
	20-40	80	127	47	71	58	80
Exchangeable Al, mmolc kg-1	0-20	13	22	0.7	0.8	0.7	1.5
	20-40	9.7	37	2.0	4.0	3.0	5.0
Exchangeable Ca, mmolc kg-1	0-20	5.4	34	48	53	47	45
	20-40	1.6	3.6	14	12	9	11
Exchangeable Mg, mmolc kg-1	0-20	1.7	22	19	22	21	22
	20-40	1.0	2.0	7.0	5.0	6.0	6.0
Exchangeable K, mmolc kg-1	0-20	1.2	3.4	2.2	3.7	4.6	4.1
	20-40	0.3	1.2	0.7	1.1	2.1	2.2
ECEC, mmolc kg-1	0-20	105	179	109	137	123	124
	20-40	83	134	69	89	75	99
Available P, mg kg-1	0-20	6.3	15	24	35	73	27
	20-40	3.0	5.0	4.0	4.0	4.0	3.0
Mineralogical TDA %‡							
Ap‡‡	Kao§	17.6	16.8	16.0	11.5	14.1	-
	Gib	39.7	17.6	45.2	46.7	44.3	-
Bo1	Kao	16.3	15.5	11.8	10.2	10.9	-
	Gib	39.4	20.8	38.4	46.4	37.4	-

† NF = native field, comprising a natural climax vegetation; PNF-1 = plow tillage of the native field, involving conversion of natural vegetation to cropland; NT-10 = no-tillage for 10 years; NT-20 = no-tillage for 20 years; NT-22 = no-tillage for 22 years; CT-22 = conventional tillage for 22 years.

‡ TDA = Thermal Differential Analyses, results in percentage.

‡‡ The TDA was done in Ap and Bo1 horizons.

§ Kao = Kaolinite, Gib = Gibbsite, Hem = Hematite, Goe = Goethite.

Table 2. Crop rotation, fertilizers used, grain yield, and crop residues amount for the treatments (NT-10; NT-20; NT-22 and CT-22).

Sites	Crop Rotation	Input	Fertilizers			Grain yield	Crop residues		
			N	P_2O_5	K_2O		Above Ground	Roots	Above ground + Roots
			-------------- Kg ha^{-1} ------------			-------------------- Mg ha^{-1} --------------------			
NT-10	O/C/W/S/O/S	Total	407.0	685.0	714.0	47.1	65.3	26.5	91.5
		Annual	40.7	68.5	71.4	4.7	6.5	2.6	9.2
NT-20	O/C/W/S/O/S	Total	643.0	1,472.0	1,361.0	88.9	126.4	50.9	177.3
		Annual	32.0	74.0	68.0	4.5	6.3	2.6	8.9
NT-22	O/C/W/S/O/S	Total	1,478.0	2,596.0	2,578.0	106.7	115.4	37.7	152.8
CT-22		Annual	67.0	118.0	117.0	4.9	5.3	1.7	6.9

O = Oat (*Avena sativa)*; C = Corn; W = Wheat; S = Soybean;

Table 3. The total SOC gain or losses for each treatment compared with native field (NF) for each depth. Numbers in parenthesis refers the percentage of the SOC gain or losses.

Depth	PNF-1	NT-10	NT-20	NT-22	CT-22
(cm)	--------------------------------------- Mg ha^{-1} ---------------------------------------				
0.0-2.5	0.73 (+6.9)	2.09 (+19.6)	4.60 (+43.2)	8.04 (+75.4)	-1.44 (-13.5)
2.5-5.0	2.36 (+26.2)	0.79 (+8.8)	3.16 (+35.1)	5.05 (+56.1)	-0.64 (-7.2)
5.0-10.0	3.91 (+26.1)	-0.37 (-2.5)	2.30 (+15.4)	2.37 (+15.8)	-0.24 (-1.6)
10.0-20.0	8.26 (+32.8)	-3.66 (-14.5)	3.15 (+12.5)	1.48 (+5.9)	1.06 (+4.2)
20.0-40.0	6.67 (+16.8)	-3.67 (-9.3)	4.16 (+10.5)	1.97 (+4.9)	1.06 (+2.7)

over a period of several years. The experimental design involved a chronosequence with six treatments, and duration of plowing and no-tillage were assigned as whole plots and depth of sampling as subplots. The sites are developed on the same parent material, have the same soil type, the same upland position, and were managed with similar rotation and cultural practices. The treatments consisted of: (i) native field (NF) comprising a natural climax vegetation of this region; (ii) plow tillage of the native field (PNF-1) involving conversion of natural vegetation to cropland with lime (3.5 Mg ha^{-1}) and phosphate (117 kg ha^{-1} P_2O_5 or 52 kg P) application of incorporated into 20-cm depth with an disk and twice narrow disk.; (iii) no-tillage for 10 years (NT-10); (iv) no-tillage for 20 years (NT-20); (v) no-tillage for 22 years (NT-22); (vi) conventional tillage for 22 years (CT-22) involving plow tillage with disking after summer and winter harvests to 20 cm depth plus two narrow disk to break the clods. The dimension of each chronosequence area was 200-m x 50-m, with five pseudo-replicates representing a 40-m x 50-m dimension. The choice of theses sites was based on the existence of a well defined chronosequence starting from the original undisturbed conditions (vegetation, soil properties) which provide an opportunity to assess the impact of plowing and no-tillage on C pool and fluxes. Detailed of cultural practices for each experimental site are shows in Table 2.

Soil Sampling and Analyses

Soil samples were collected from four treatments (NF, PNF-1, NT-10 and NT-20) during September 1997 and May 1998. Soil samples for two sites (CT-22 and NT-22) were collected once in November 1998. For each replicate, soil was sampled by digging 9 profiles of 20 cm x 50 cm dimensions and collecting soil for five depths (0- to 2.5-cm, 2.5- to 5-cm, 5- to 10-cm, 10- to 20-cm and 20- to 40-cm). Individual samples from 9 small profiles were composted to obtain a single sample for each depth and pseudo-replicate. Soil samples were air-dried and ground to pass through a 2-mm sieve. A portion of the sample was ground to pass through < 150-µm sieve to determine the total organic carbon by dry combustion method (Nelson & Sommers, 1982) using a Carbon analyzer - LECO® CR-412 (St. Joseph MI, USA). For each layer sampled, bulk density (ρ_b) was measured by the core method (Blake & Hartge, 1986) on a core of 5.0-cm diameter and 5.0-cm deep for the 5- to 10-cm, 10- to 20-cm, and 20- to 40-cm depths, and 5.0-cm diameter and 2.5-cm deep for the 0- to 2.5-cm, and 2.5- to 5-cm depths. Soil texture was measured by the pipette method (Gee & Bauder, 1986), and the pH in a 1:2.5 soil:water ratio (EMBRAPA, 1979). Potential acidity, exchangeable Al, Ca, Mg, K and P available were measured using the cation-anion resin exchange, (Raij and Quaggio, 1987), and x-ray diffraction was measured by the method of Jackson (1966).

Statistical Analyses

Results were analyzed using analysis of variance, and the regression equations were selected by the stepwise procedures (SAS Institute, 1990) to adjust the models. Regressions equations were used to assess the temporal changes in the SOC pool for each depth considering the SOC pool in the native field as the baseline or reference point. Statistical significance were computed at P<0.05 and 0.01, represented by *and**, respectively.

The rate of C sequestration was calculated by computing the slope of the regression line using derivative function (dy/dx) to represent the variation rates with the time. This approach is based on the model of Henin and Dupuis (1945) modified by Greenland (1995).

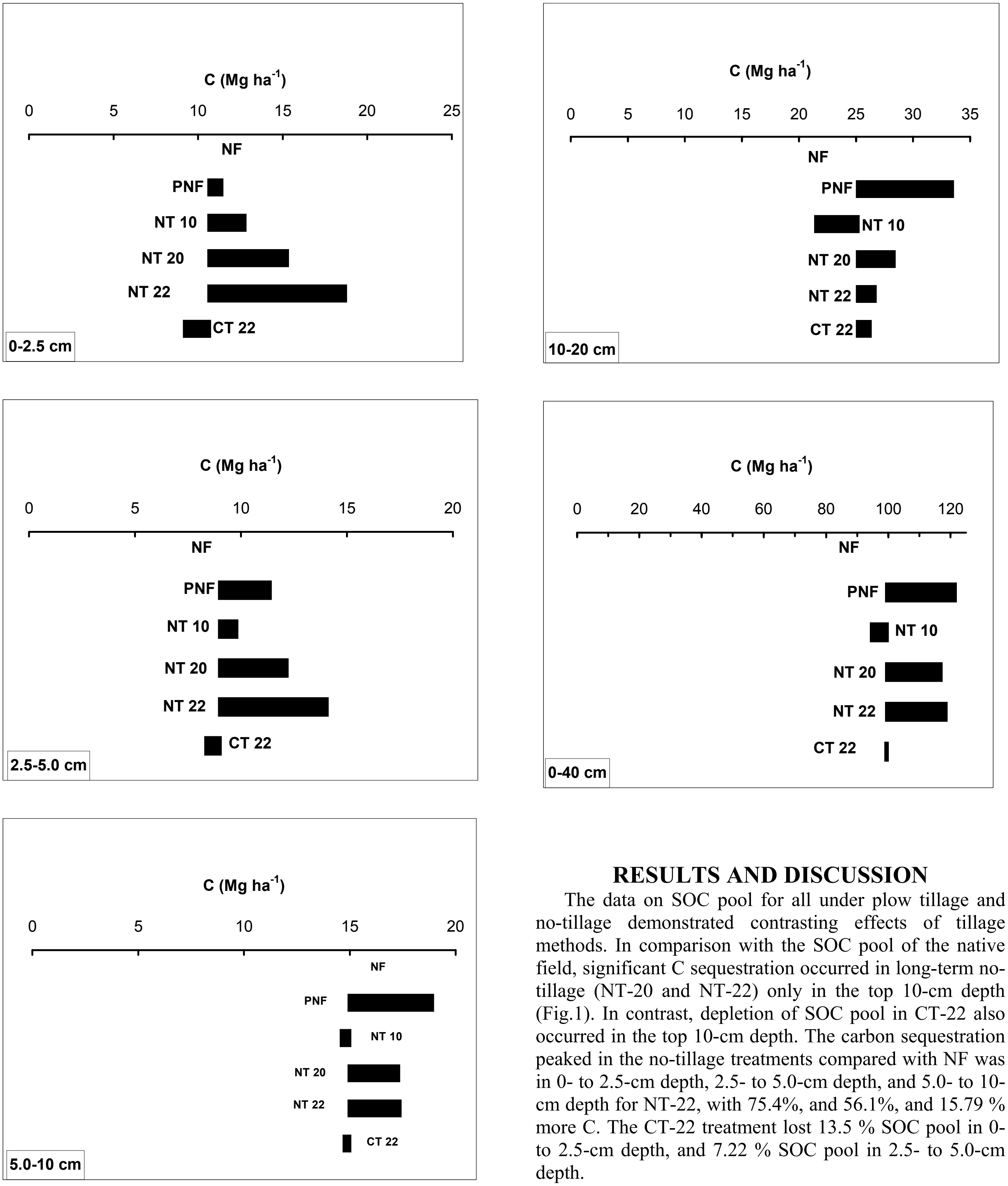

Figure 1. Soil organic carbon pools in the chronosequense. The base line (heavy vertical) is the native field (NF). The bars are the standard deviation and the square brackets refers the LSD=0.05*.

RESULTS AND DISCUSSION

The data on SOC pool for all under plow tillage and no-tillage demonstrated contrasting effects of tillage methods. In comparison with the SOC pool of the native field, significant C sequestration occurred in long-term no-tillage (NT-20 and NT-22) only in the top 10-cm depth (Fig.1). In contrast, depletion of SOC pool in CT-22 also occurred in the top 10-cm depth. The carbon sequestration peaked in the no-tillage treatments compared with NF was in 0- to 2.5-cm depth, 2.5- to 5.0-cm depth, and 5.0- to 10-cm depth for NT-22, with 75.4%, and 56.1%, and 15.79 % more C. The CT-22 treatment lost 13.5 % SOC pool in 0- to 2.5-cm depth, and 7.22 % SOC pool in 2.5- to 5.0-cm depth.

The gain of SOC for the first ten years of no-tillage treatment (NT-10) compared to the native field (NF) was 0.21 Mg ha^{-1} yr^{-1} for the 0- to 2.5-cm depth and 0.08 Mg ha^{-1} yr^{-1} for 2.5- to 5.0-cm depth. In contrast, there was a loss of SOC pool at the rate of –0.037 Mg ha^{-1} yr^{-1} for 5- to 10-cm depth, -0.366 Mg ha^{-1} yr^{-1} for 10- to 20-cm depth and –0.367 Mg ha^{-1} yr^{-1} for 20- to 40-cm depth. During the second decade, there was a gain of SOC pool at all depths at the rate of 0.42 Mg ha^{-1} yr^{-1} for 0- to 2.5-cm depth, 0.32 Mg ha^{-1} yr^{-1} for 2.5- to 5-cm depth, 0.24 Mg ha^{-1} yr^{-1} for 5- to 10-cm depth, 0.51 Mg ha^{-1} yr^{-1} for 10- to 20-cm depth, and 0.57 Mg ha^{-1} yr^{-1} for 20- to 40-cm depth. The gain of SOC in the second decade demonstrated a great storage promoted by long-term no-tillage and associate with crop residues input. The loss in SOC for lower depths in the NT-10 treatment during the first decade is attributed to three factors: (1) this site was cultivated at the same time as the NT-20, cropped for two years and then maintained under fallow for 8 years. Thus, conversion to cropland promoted high microbial activity and released C by respiration. During the fallow period, the residence time of C in the soil profile may have changed, impacting its availability for microbial breakdown (Cihacek & Ulmer, 1997); (2) the inputs of C as crop residue may have been insufficient to maintain the steady state level of SOC; (3) the clay content is lower than others sites resulting in less SOC contents than clayey sites because the SOC residence time in clayey profiles is longer. Also, base line for comparison in this study is NF rather than Conventional field.

While comparing the C budget in the 0- to 20-cm depth with the original vegetation as a base line, the cumulative increase of SOC pool was 16.94 Mg ha^{-1} for NT-22 and -1.29 Mg ha^{-1} for CT-22.

These data show that potential of carbon sequestration in tropical and subtropical ecoregions through adoption at no-tillage systems based on input of crop residue is high. The SOC sequestration rate associated with no-tillage (calculations included NF, NT-10, NT-20 and NT-22 selecting an equation) in this major ecological region of Southern Brazil was calculated to be 80.6 g C m^{-2} yr^{-1} for 0- to 20-cm soil layer and 99.4 g C m^{-2} yr^{-1} for 20- to 40-cm. These data of SOC sequestration are higher than 30 to 70 g C m^{-2} yr^{-1} reported by Lal et al. (1998). In Brazil 27% of cropland (13.4 millions hectares) are cultivated using a no-tillage system (Febrapdp, 2000) of which 70.5 % (i.e. 9.43 millions hectares) is located in South region (Paraná, Santa Catarina and Rio Grande do Sul State). Therefore, the SOC sequestration potential of this region is 9.37 Tg C yr^{-1} (data of this study) to 12.54 Tg C yr^{-1} (data from Bayer et al., 2000). This potential is equivalent to assimilation (1 unit of C convert to 3.67 units of CO_2) of 34.3 Tg CO_2 yr^{-1} to 46.0 Tg CO_2 yr^{-1}.

CONCLUSIONS

Adoption of no-tillage in Southern Brazil can lead to C sequestration in soil. The SOC pool increased with duration of no-tillage adoption compared to the original vegetation, with significant sequestration in to top 10-cm layer. The rate of C system sequestration was less during the first compared to the second decade. The long-term no-tillage sequestered SOC more efficiently than natural vegetation, especially in the surface soil layer. The rate of C sequestration potential of this region is 9.37 Tg C yr^{-1} (data of this study) to 12.54 Tg C yr^{-1}. This potential is equivalent to mitigate (1 unit of C convert to 3.67 units of CO_2) of 34.3 Tg CO_2 yr^{-1}.

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