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Organic Matter Dynamics and Carbon Sequestration Rates for a Tillage Chronosequence in a Brazilian Oxisol

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ABSTRACT

Amounts and rates of C sequestration under no-tillage are not known for a major ecological region of south Brazil. These were assessed in a Brazilian Oxisol under a plow and no-tillage chronosequence located in Paraná State. The chronosequence consisted of six treatments: (i) native field (NF); (ii) 1-yr plow conversion of native field to cropland (PNF-1); (iii) no-tillage for 10 yr (NT-10); (iv) no-tillage for 20 yr (NT-20); (v) no-tillage for 22 yr (NT-22); and (vi) conventional tillage for 22 yr (CT-22). Soil samples were collected from five depths. No-tillage, compared with the NF treatment, caused a significant increase in soil organic C (SOC) storage. More than 60% of this increase occurred in the 0- to 10-cm soil layer. There was a decrease in the amount of SOC in the CT-22 compared with the NF soil treatment and 97% of this loss also occurred in the 0- to 10-cm layer. There was a close relationship between the SOC content and the amount of crop residues input ($R^2 = 0.74, P \leq 0.05$). There were increased SOC concentrations in the finer particle-size fractions (<20 μm) of no-tillage surface soil compared with the NF or CT-22 soils. However, the percentage of SOC derived from crop residues in no-tillage treatments, as assessed by 13C natural abundance (δ), was generally greater in the coarse (>20 μm) than in the finer (<20 μm) particle-size fractions. The C sequestration rate for no-tillage was 80.6 g C m^{-2} yr^{-1} for the 0- to 20-cm depth and 99.4 g C m^{-2} yr^{-1} for the 0- to 40-cm depth. The no-tillage C sequestration potential for South Brazil was estimated as 9.37 Tg C yr^{-1}.

THE SOC POOL in the top 1-m depth of world soils ranges between 1462 and 1576 Pg. It is nearly three times that in the aboveground biomass and approximately double that in the atmosphere; 32% of this is contributed by soils in the tropics (Eswaran et al., 1993; Lal et al., 1995; Batjes, 1996).

Agricultural practices can render a soil either a sink or a source of the atmospheric CO_2, with direct influence on the greenhouse effect (Lugo and Brown, 1993; Lal et al., 1995). The CO_2 contribution to radiative forcing is about 50%, and 22.9% of total CO_2 emissions to the atmosphere is attributed to agriculture, deforestation, and land use (Intergovernmental Panel on Climate Change, 1996).

In temperate zones, grassland soils tend to lose 30 to 50% of their original SOC content in the first 40 to 50 yr of cultivation (Campbell and Souster, 1982; Mann, 1985). In contrast, the SOC loss in tropical regions may be several times higher (Lal and Logan, 1995). In Northeast Brazil, Resck (1998) reported a SOC loss of 69% within 5 yr of cultivation by a heavy disk harrow in quartz sand (<15% clay content) and 49% in a Typic Hapludox—Dark Red Latosol (>30% clay content). Plowing decreases aggregate stability, disrupts macroaggregates and exposes SOC to microbial processes (Tisdall and Oades, 1982). As a consequence, the mineralization rates increase due to high aeration, resulting in high CO_2 flux to the atmosphere (Elliot, 1986; Reicosky et al., 1995).

Several reports have shown that crop residue mulch associated with no-tillage management improves soil aggregation and increases SOC content (Havlin et al., 1990; Carter, 1992; Cambardella and Elliot, 1992, 1993). However, this increase is generally restricted to the surface soil. Kern and Johnson (1993) reviewed data from 17 field studies comparing no-tillage with conventional-tillage plots in the USA, and observed that SOC gains

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Abbreviations: CT-22, conventional tillage for 22 yr; NF, native field; NT-10, no-tillage for 10 yr; NT-20, no-tillage for 20 yr; NT-22, no-tillage for 22 yr; PNF-1, 1-yr conversion of native field to cropland by plow tillage; SOC, Soil organic C; TN, total nitrogen; δ, natural abundance; *,**,***, Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

were 27% for the 0- to 8-cm layer, 16% for the 8- to 15-cm layer, and no gains for depths >15 cm. In tropical zones, a significant impact on SOC concentrations has been observed for the 0- to 10-cm layer (Lal, 1976; Sá, 1993, p. 96; Resck, 1998; Bayer et al., 2000b).

The combination of determining size distribution of water stable aggregates, particle-size fractionation, and $\delta^{13}C$ techniques is a useful tool to investigate the relationship between crop-residue management and no-tillage on SOC dynamics (Balesdent et al., 2000; Havlin et al., 1990; Carter, 1992; Christensen, 1992; Cambardella and Elliot, 1994; Beare et al., 1994a; Jastrow et al., 1996; Rasmussen et al., 1998; Bayer et al., 2000a). In soils of the tropics, particle-size fractionation techniques have been used to characterize relationships between SOC and aggregation at the macro and microaggregate scale (Feller et al., 1996). The concept is that soil organic fractions associated with different sized particles differ in structure and function, and therefore play different roles in SOC turnover (Christensen, 1992). Developing such relationships is crucial to understanding the SOC dynamics, the effect of crop residues on the SOC pool and composition, and C-turnover time in soil. Bayer et al. (2000a, 2000b), using a particle-size fractionation technique combined with electron spin resonance and ^{13}C nuclear magnetic resonance showed that, in southern Brazil, crop residues input from no-tillage and cropping systems resulted in a SOC sequestration rate of 1.33 Mg C ha^{-1} yr^{-1}. They also reported that SOC associated with sand and silt fractions was less humified than that associated with the finer-size fractions. Nevertheless, there are also studies (Balesdent et al., 1987; Anderson and Paul, 1984; Oades et al., 1987; Six et al., 2000) reporting that the most humified or oldest faction is associated with silt particles.

There are few comparison between plow and no-tillage systems for SOC dynamics in oxisols that consider soil under natural vegetation as a base line representing the steady-state level. Obtaining data on base-line SOC pool is essential for understanding the magnitude of the SOC gain or losses because of the confounding effects of microbial respiration and soil erosion on SOC pool and fluxes. Information about SOC sequestration potential in a no-tillage chronosequence is rarely available, yet it is important for developing strategies for sustainable management of soils. In this study, a chronosequence is understood to mean a series of similar soils that differ from each other in certain properties primarily as a result of time.

This study evaluated the effects of a long-term no-tillage chronosequence in a Brazilian Oxisol on (i) SOC and total N (TN) contents in whole soil and in particle-size fractions, (ii) the amount of soil C derived from crop residues using the $\delta^{13}C$ technique, and (iii) SOC sequestration rates.

MATERIALS AND METHODS

Site Descriptions

Field experiments were conducted at two research sites located near the towns of Tibagi (Santa Branca Farm) and Ponta Grossa (Frankanna Farm), in the South Center quadrant of Paraná State, Brazil (Table 1). The natural vegetation is a subtropical prairie dominated by C_4 species, i.e., some fire-resistant grasses such as *Andropogon* sp., *Aristida* sp., *Paspalum* sp., *Panicum* sp., and by subtropical gallery forests generally located in natural drainage channels (Maack, 1981). The landscape has long gentle slopes ranging from 2 to 7%. The parent material is comprised of clastic sediments of the Devonian period characterized by a mixture of Ponta Grossa shale and Furnas formation sandstone. These soils, classified as oxisols (Typic Hapludox), have a deep and very well structured profile, high porosity (with equal proportion of macro and microporosity) and very good internal drainage. The choice of these sites was based on the existence of a well-defined tillage chronosequence including the original undisturbed conditions (natural vegetation and soil properties). This chronosequence provided an opportunity to assess the impact of plowing and no-tillage on SOC dynamics. The sites were developed on the same parent material, soil type, landscape position (Table 1); have similar soil characteristics (Table 2); and have been managed with similar rotation and cultural practices.

Conversion of Natural Vegetation to Agricultural System and Treatments Description

A summary of when the Tibagi and Ponta Grossa sites were converted to cropland and the subsequent cropping history at each site is provided in Fig. 1.

The native grassland field at the Tibagi site, comprising of natural climax vegetation of the region, represents the NF treatment. In 1969, some of the NF area was converted to cropland by plowing to a 20-cm depth, and then tilling twice with a disk to break the clods. The acidity was corrected with application of 3.5 Mg ha^{-1} of dolomite limestone (85% equivalent to pure $CaCO_3$) and P deficiency was corrected by addition of 117 kg ha^{-1} of P_2O_5 (52 kg P). For 3 yr, this

Table 1. Location, climate, and soil of the two tillage chronosequence study sites.

		Sites	
Description	**Parameters**	**Tibagi**	**Ponta Grossa**
Location	**Latitude**	**24°36′S**	**25°20′S**
	Longitude	**50°23′W**	**50°20′W**
	Altitude	**880 m**	**910 m**
Climate	**Type**	**mesothermic, wet subtropical, type cfb**	**mesothermic, wet subtropical, type cfb**
	MAT†	**20.7°C**	**18.7°C**
	MAP‡	**1532 mm**	**1545 mm**
Soil	**Type**	**Dark Red Latosol, Typic Hapludox**	**Dark Red Latosol, Typic Hapludox**
	Texture	**Clayey**	**Clayey**
	Parent Material	**Shale + Sandstone (Reworked material)**	**Shale + Sandstone (Reworked material)**

† MAT, Mean Annual Temperature.
‡ MAP, Mean Annual Precipitation.

Table 2. Chemical and mineralogical properties of the Brazilian oxisol (Dark Red Latosol) soil in the tillage chronosequence.

Property		Depth	NF	PNF-1	NT-10	NT-20	NT-22	CT-22
			Treatments†					
		cm						
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, $mmol_c$ kg^{-1}		0–20	97	132	42	62	51	5.3
		20–40	80	127	47	71	58	80
Exchangeable Al, $mmol_c$ 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, $mmol_c$ kg^{-1}		0–20	5.4	34	48	53	47	45
		20–40	1.6	3.6	14	12	9.0	11
Exchangeable Mg, $mmol_c$ 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, $mmol_c$ 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
Effective cation-exchange capacity, $mmol_c$ 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								
Clay fraction types, x-ray‡		Bo1	Kao§	Kao	Kao	Kao	–	
			Gib	Gib	Gib	Gib	Gib	–
			Hem	Hem	Hem	Hem	Hem	–
			Goe	Goe	Goe	Goe	Goe	–
TDA, %¶	Kao	Ap	17.6	16.8	16.0	11.5	14.1	–
	Gib		39.7	17.6	45.2	46.7	44.3	–
	Kao	Bo1	16.3	15.5	11.8	10.2	10.9	–
	Gib		39.4	20.8	38.4	46.4	37.4	–

† NF, native field; PNF-1, 1 yr of conventional tillage of native field; NT-10, 10 yr of continuous no-tillage application; NT-20, 20 yr of continuous no-tillage application; NT-22, 22 yr of continuous no-tillage application; and CT-22, 22 yr of continuous application of conventional tillage.

‡ x-ray analyses were applied to samples from the Bo1 horizon only.

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

¶ TDA = Thermal Differential Analyses results are given in percentages and are reported for the Ap and Bo1 horizons.

Table 3. Total fertilizer inputs for each crop, total biomass, and percentage of total biomass from various crops compared with the total dry biomass production for the no-tillage treatments in a Brazilian oxisol.

Treatments	Crops	N	P_2O_5	K_2O	Total	Relative
		Total Fertilizer†			Dry Mass	
		kg ha^{-1}				%
NT-10‡	Soybean	–	285	326	21 900	23.9
	Oat§	–	–	–	25 500	27.8
	Corn	269	216	228	31 700	34.7
	Wheat	138	184	160	12 400	13.6
	Lupine§	–	–	–	–	–
	Lolium¶	–	–	–	–	–
	B. Bean	–	–	–	–	–
	Total	407	685	714	91 500#	100
	Annual input	40.7	68.5	71.4	9 150	–
NT-20††	Soybean	38	611	625	48 400	27.3
	Oat§	–	–	–	48 100	27.1
	Corn	383	350	363	55 700	31.5
	Wheat	222	511	333	20 200	11.4
	Lupine§	–	–	–	4 780	2.7
	Lolium¶	–	–	–	–	–
	B. Bean	–	–	–	–	–
	Total	643	1 470	1 320	177 000#	100
	Annual input	32.2	73.6	66.1	8 860	–
NT-22‡‡	Soybean	100	730	730	51 200	30.6
	Oat§	–	–	–	14 300	8.5
	Corn	541	531	513	55 900	33.4
	Wheat	190	735	735	32 200	19.2
	Lupine§	–	–	–	4 380	2.6
	Lolium¶	225	450	450	7 180	4.3
	B. Bean	55	75	75	2 380	1.4
	Total	1 110	2 521	2 503	167 000#	100
	Annual input	50.5	115	114	7 610	–

† Total fertilizer used for each crop.

§ Cultivated only for cover crop.

¶ Cultivated for silage.

Sum of aboveground biomass plus roots of each crop.

‡ NT-10, 10 yr of continuous no-tillage application.

†† NT-20, 20 yr of continuous no-tillage application.

‡‡ NT-22, 22 yr of continuous no-tillage application.

area was planted to rice (*Oryza sativa* L.) with plow tillage. Following for the next 7 yr, a rotation of soybean [*Glycine max* (L.) Merr.] in summer and wheat [*Triticum aestivum* L.] in winter was followed. During this total 10-yr period, lime was incorporated in the 0- to 20-cm soil layer three times at the rate of 2 Mg ha^{-1}. In 1979, 20 to 30% of the total area was converted to no-tillage and part of this area represents the NT-20 treatment. From 1979 to 1998, cropping during the summer season involved 15 crops of soybean and five of corn (*Zea mays* L.). During the winter season, wheat was cultivated six times, black oat (*Avena sativa* L.) 11 times and lupine (*Lupinus angustifollios* L.) twice. Both black oat and lupine were grown as cover crops.

In 1989 a border area, which had been converted to cropland at the same time as the NT-20 treatment, but after 2 yr was reverted back to fallow, was converted to no-tillage. This area represents the NT-10 treatment with prior history being 2 yr of cultivation and 8 yr of fallow prior to adoption of no-tillage. The fallow period represented a time when nothing was done to the soil. For the NT-22 treatment, lime was broadcast four times (two times for the NT-10 treatment) on the soil surface at a rate of 1.5 Mg ha^{-1}. Cropping during the summer season in this area consisted of seven crops of soybean and three of corn. Cropping during the winter season comprised of four crops of wheat and six of black oat.

Another site was converted to cropland in June 1996 and represents the plow tillage conversion of the native field (PNF-1). The conversion involved application of lime (3.5 Mg ha^{-1}) and triple superphosphate (140 or 72 kg ha^{-1} of P) incorporated to 20-cm depth by three separate disking operations. The conversion began 18 mo prior to sampling. The crops sown were soybean (October 1996), black oat (May 1997), and corn (September 1997).

The previous land use at the Ponta Grossa site (Frankanna Farm) was also natural vegetation and the conversion to agriculture was initiated in 1961 (Fig. 1). Soil management practices used during 1961 to 1976 were similar to those of the

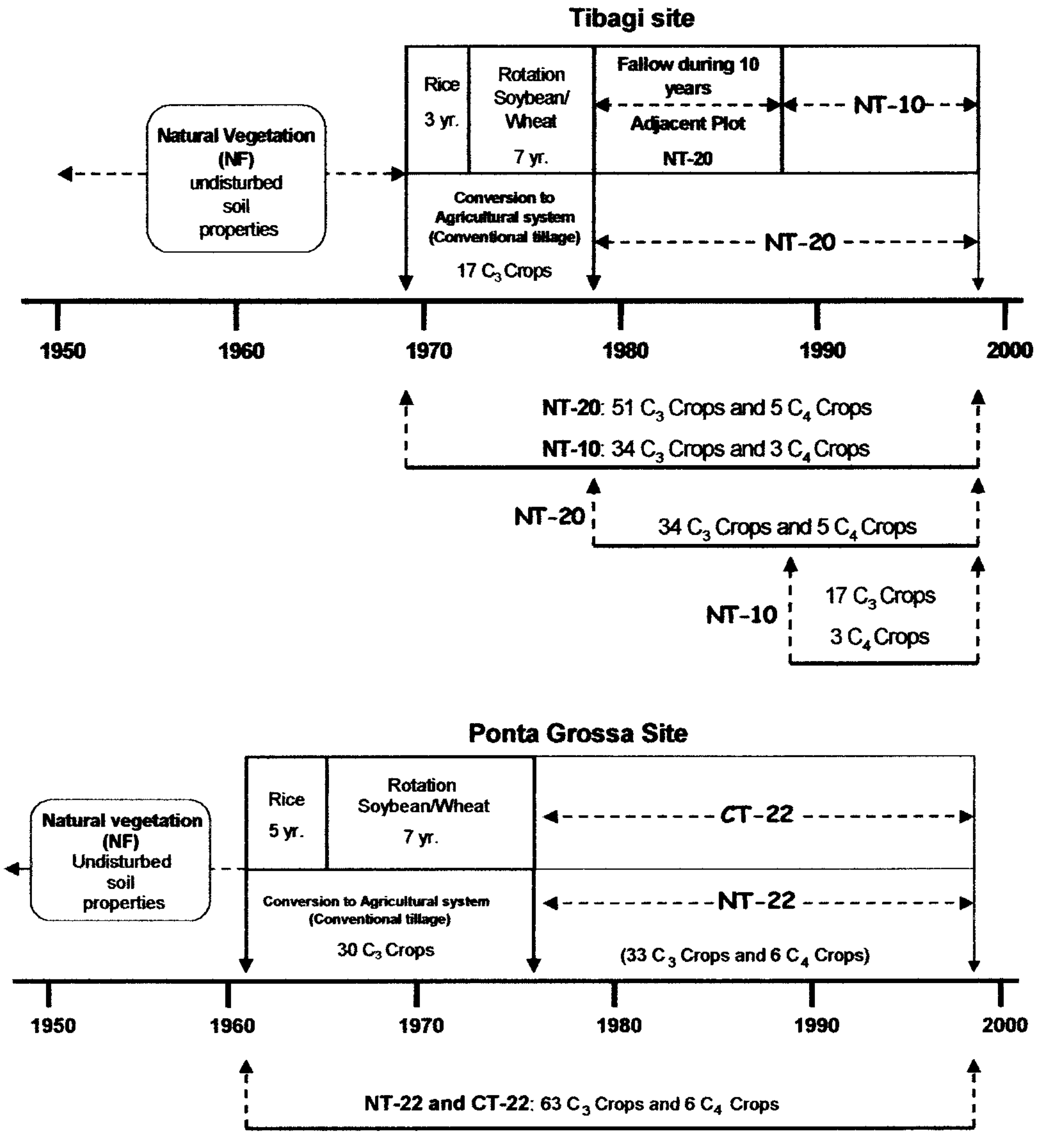

Fig. 1. Schematic summarizing the various treatments applied to the soil at the Tibagi and Ponta Grossa sites, Brazil. Conventional tillage, CT and no-tillage, NT.

Tibagi site with the exception of two more years of rice crop before changing to a soybean–wheat rotation. In 1976, a tillage variable was imposed thus permitting comparison of NT-22 with CT-22. The latter involved plow tillage after summer harvest and again after winter harvest followed by two diskings to break the clods. Cropping during the summer season between 1976 until 1998 comprised of 15 crops of soybean, six of corn, and two of black bean (*Phaseolus vulgaris* L.). Black bean was not considered part of the regular rotation. Cropping during the winter season was comprised of 10 crops of wheat, four of black oat and one of lupine. Winter ryegrass (*Lolium multiflorum* Lam.) was sown during the last four seasons and removed as forage. Also, this area received liquid cattle manure at the rate of 15 to 20 m^3 ha^{-1} in 1996 and 1997.

At both sites, the 3-yr crop rotation generally was as follows: wheat–soybean—Year 1; black oat–soybean—Year 2; and black oat–corn—Year 3. Two crops per each year corresponded to winter and summer seasons, respectively. Specific details of no-tillage treatments, fertilizers used, total dry biomass (aboveground + root dry biomass) production, and the percentage of dry biomass contributed by each crop in the crop rotation are summarized in Table 3. The aboveground dry biomass was estimated from an index based on the grain yield/shoot ratio. The index was 0.9 for soybean, 1.0 for corn, and 1.0 for wheat. The aboveground biomass for each crop was estimated by multiplying the grain yield by the respective index. The same technique was used to estimate the root dry biomass. The index to obtain root dry biomass for each crop was 0.2 for soybean, 0.25 for corn, 0.2 for wheat, and 0.3 for oat. The data obtained from the grain yield was multiplied by the root index to estimate total root biomass. Total biomass was calculated as the sum of shoot and root biomass.

Experimental Design and Sampling

The experimental design consisted of six treatments in a no-tillage chronosequence. Duration of plow tillage and no-tillage were assigned as whole plots and the sampling depth as subplots as per a split-plot. The chronosequence treatments were: (i) NF, (ii) PNF-1, (iii) NT-10, (iv) NT-20, (v) NT-22, and (vi) CT-22. The dimension of each chronosequence area was 200 by 50 m. Five subareas, each 40 by 50 m, were marked for subsequent sampling. Soil samples were collected from four sites (NF, PNF-1, NT-10, and NT-20) in May 1998 and from two sites (CT-22 and NT-22) in November 1998. Soil samples for each subarea were obtained by digging nine profiles of 20 by 50 (surface area) by 50 cm deep. Samples were collected from five depths (0–2.5, 2.5–5, 5–10, 10–20, and 20–40 cm) and a composite sample from all subareas was obtained for each depth.

Soil Chemical and Mineralogical Analyses for Characterization of Soil Profiles

Soil pH was measured using a 1:2.5 ratio of soil/0.01 *M* $CaCl_2$ solution (EMBRAPA, 1979). The potential acidity was determined using a 0.01 *M* calcium acetate solution buffered at pH 7.0 (EMBRAPA, 1979). The exchangeable Al^{3+}, Ca^{2+}, Mg^{2+}, K^+, and available P were extracted using a cation- and anion-exchange resin (Raij and Quaggio, 1983, p. 31). The cation-exchange capacity (CEC) was obtained by summing the value of potential acidity and the exchangeable cations. The Bo1 horizon was sampled for each site to identify the clay material by x-ray diffraction (Jackson, 1966, p. 849). Relative quantities of kaolinite and gibbsite were determined using the thermal differential analysis (Jackson, 1966, p. 849) in Ap and Bo1 horizons. The soil texture of all horizons was measured by the pipette method (Gee and Bauder, 1986).

Carbon and Nitrogen Analyses in a Whole Soil Layer

Soil samples from each depth were air dried and ground to pass through a 2-mm sieve. A portion of each sample was ground to pass through 150-μm sieve to determine the SOC and TN contents. The latter was determined by micro Kjeldahl, and SOC by the loss-on-ignition method (Nelson and Sommers, 1982) using a C analyzer. Soil bulk density for each layer was measured by the core method (Blake and Hartge, 1986) using cores of 5.0-cm diam. and 5.0 cm deep for the 5- to 10-, 10- to 20-, and 20- to 40-cm depths. Cores of 5.0-cm diam. by 2.5-cm deep were used for the 0- to 2.5-, and 2.5- to 5-cm depths. The core was taken in the middle of the layer for the 10- to 20- and 20- to 40-cm depths. The SOC and TN pools, expressed as megagrams per hectare for a specific depth, were computed by multiplying the SOC and TN content (g kg^{-1}) with bulk density (g cm^{-3}) and depth (cm).

Particle-Size Fractionation

The particle-size fractionation was done according to Feller (1994). A 40-g oven dry subsample sieved through a 2-mm screen, from each treatment and each depth, was prewetted overnight at 4°C in 200 mL of deionized H_2O. Aggregate disruption was accomplished by rotary shaking at a frequency of 50 rpm with three agate balls (10-mm diam.) for 2 h. The amount of soil that did not pass through a 200-mm sieve was used to estimated the 200- to 2000-μm fraction. The soil that passed through the 200-μm sieve was ultrasonicated using a probe-type ultrasonic unit at 240 W for 10 min. This energy level was determined to be the minimum required for the breakdown of macroaggregates into sand- and silt-sized microaggregates, associated organic matter, and primary particles. A suspension sample was taken after each sonication to check the degree of disruption under a microscope. The disrupted soil suspension was passed through two sieves (53- and 20-μm) to obtain the 53- to 200-μm and 20- to 53-μm size fractions. The material remaining on the each sieve was washed and added to the corresponding suspension. The silt (2–20 μm) and clay (<2 μm) fractions were obtained by six to seven centrifugations of the soil suspension that passed through 20-mm sieve. The centrifuge was calibrated to 90 × *g* (700 rpm) and each centrifugation duration was 3 min. The supernatant liquid from each centrifugation was siphoned and stored in a 1-L glass cylinder and 10 mL of deionized H_2O was added in each tube. The procedure was repeated until the supernatant in the tube was clear. The soil pellet in each tube was recovered, and it represented the 2- to 20-μm size fraction. The clay suspension in the 1-L glass cylinder was flocculated with 0.77 g $CaCl_2$, and it represented the <2-μm size fraction.

The Natural Abundance of ^{13}C, Carbon, and Nitrogen Analyses in the Particle-Size Fractions

Natural abundance stable isotope ratios were measured in different particle-size fractions for each depth, based on the method of Cerri et al. (1985), Balesdent et al. (1987), and Angers and Giroux (1996). The $^{13}C/^{12}C$ ratio and SOC and TN contents were determined by a Mass Spectrometer (Delta Plus, Finnigan Mat; Finnigan Corp., Cincinati, OH) equipped with a gas chromatograph model EA 1110 CHN. The $\delta^{13}C$ value was calculated from the measured C isotope ratio (R) of the sample and standard gas was calibrated versus the Pee Dee Beleminite (PDB) standard (Eq. [1]) available from the National Bureau of Standards.

$$\delta^{13}C(‰) = [(R_{sample} - R_{standard})/R_{standard}] \times 10^3 \quad [1]$$

The proportion of C derived from crop residues (X) was calculated according to the method of Angers and Giroux (1996) (Eq. [2]):

$$X = (\delta_{cs} - \delta_{nf})/(\delta_{cr} - \delta_{nf}) \quad [2]$$

where δ_{cs} equals the ^{13}C value of sample fraction of cropped soil (measured in each particle-size fraction for each depth in PNF-1, NT-10, NT-20, NT-22, and CT 22 treatments); δ_{nf} equals the ^{13}C value of the NF treatment for each particle-size fraction and for each depth (which represented the natural vegetation dominated by C_4 species); and δ_{cr} equals the measured $\delta^{13}C$ value of the crop residues. The $\delta^{13}C$ value of crop residues (−23.8 ± 0.26‰) was based on the average of 10 subsamples of all the aboveground biomass collected before the harvest of corn in the NT-20 treatment. These residues represented a mixture from all of the previous crops grown in rotation although it was dominated by black oat, the most recent rotational crop.

Statistical Analyses

The data were statistically analyzed for ANOVA, and means were compared using the Tukey test ($LSD_{0.05}$). The regression equations were developed by the stepwise procedures (SAS Institute, 1990). Pearson correlation coefficients were used to assess the degree of relationships among variables. Regression equations were used to assess the temporal changes in SOC and TN pools for each soil depth considering the native field as the baseline or the reference point. The rates of SOC sequestration were calculated by determining the slope of the regression line (dy/dx) for each depth for the NT-10, NT-20, and NT-22 treatments. Statistical significance were computed at $P \leq 0.05$ and $P \leq 0.01$, and $P \leq 0.001$ represented by *, **, and ***, respectively.

RESULTS AND DISCUSSION

Soil Organic Carbon, Total Nitrogen, and Carbon/Nitrogen Ratio in the Whole Soil

Tillage treatments had significant effects on SOC and TN contents and pools. The average SOC and TN contents were significantly higher ($P \leq 0.05$) in soils under long-term no-tillage than those for the NF and CT-22 treatments in the top 0- to 5-cm layer (Table 4). In contrast, depletion of SOC and TN contents in the long-term conventional tillage soil (i.e., the CT-22 treatment) as compared with the NF treatment occurred in the top 0- to 5-cm depth. These data are similar to those reported by Bayer et al. (2000b) for a soil in southern Brazil and by Kern and Johnson (1993) and Dick et al. (1998) in different ecoregions in the USA.

The C/N ratios (Table 4) were significantly lower ($P \leq 0.05$) for the surface layers of the no-tillage soils compared with the NF soil and the ratios increased with depth for all treatments except for the PNF-1 treatment. This suggests that the availability of N in the surface soil layers was greater and that the N supply is a key component to reduce C losses and increase the SOC content (Ismail et al., 1994).

The significant increase of SOC and TN contents upon initial conversion to cropland (i.e., comparing the PNF-1 and NF treatments) for all depths may be because of rapid mineralization of the biomass in natural vegetation stimulated by soil chemical amelioration by liming and P application (Fox, 1980). In addition, the inputs of C and N in crop residue from soybean, black oat, and corn cultivated prior to soil sampling may have also enhanced SOC and TN contents.

The decrease in SOC and TN contents in the NT-10 treatment is thought to be because of the following factors: (i) 2 yr of cultivation and 8 yr of fallow prior to adopting no-tillage may have enhanced microbial activity and released C by respiration; (ii) the residence time of C in the soil profile may have also changed during the fallow period impacting its availability for microbial breakdown (Cihacek and Ulmer, 1997); and (iii) the rate of residue inputs during this period under no-tillage did not compensate high losses due to mineralization.

In comparison with NF treatment, changes in the SOC pools for the 0- to 40-cm soil layer were +21.9 Mg C ha^{-1} for PNF-1, −4.83 Mg C ha^{-1} for NT-10, +17.4 Mg C ha^{-1} for NT-20, +18.9 Mg C ha^{-1} for NT-22, and −0.13 Mg C ha^{-1} for CT-22 (Fig. 2). The gains and losses of the SOC and TN pools for the different treatments varied with depth of soil layer (Fig. 3), and were determined taking into account bulk density differences which were higher in the no-tillage treatments than in the NF and CT-22 treatment. Most of the increased SOC found in the no-tillage profiles, as compared with that in the NF treatment, was found in the 0- to 5-cm layer for the NT-10 treatment (59%), in the 0- to 10-cm soil layer for the NT-20 treatment (57.9%), and in the 0- to 10-cm soil layer for the NT-22 treatment (81.8%). In contrast, the same comparison of SOC increase for the PNF-1 treatment in the 0- to 10-cm soil layer was only 31%.

Regression analyses between SOC and the amount (Mg ha^{-1}) of crop-residue (CR) input for the 0- to 10-cm soil layer showed a significant relationship ($P \leq 0.05$) among these parameters:

$$\text{SOC (Mg ha}^{-1}) = 26.6 + 0.265\text{CR} \ (R^2 = 0.74) \quad [3]$$

Table 4. Changes in soil organic carbon (SOC) concentrations, total nitrogen (TN) concentrations, and C/N ratios for a tillage chronosequence in a Brazilian oxisol.

		Treatments†					
Variable	Depth	NF	PNF-1	NT-10	NT-20	NT-22	CT-22
	cm						
SOC, g kg^{-1}	0–2.5	34.5Ac‡	38.4Ab	36.3Ab	45.9Aa	52.8Aa	30.1Ad
	2.5–5.0	29.5Bb	37.2Aa	25.7Bb	34.6Ba	35.1Ba	28.0Ab
	5.0–10.0	25.3Bb	35.5Aa	18.9Cc	24.7Cb	25.1Cb	25.9Ab
	10.0–20.0	21.6Cb	31.2Ba	14.6Dc	21.6Cb	20.7Db	23.5Bb
	20.0–40.0	16.9Db	22.0Ca	12.7Dc	17.9Db	16.9Db	19.3Ca
TN, g kg^{-1}	0–2.5	2.3Ac	2.6Ab	3.0Ab	3.7Aa	4.0Aa	2.1Ad
	2.5–5.0	1.9Bb	2.5Aa	2.1Bb	2.7Ba	2.6Ba	1.8Ab
	5.0–10.0	1.6Bb	2.3Aa	1.4Cc	1.8Cb	1.7Cb	1.6Ab
	10.0–20.0	1.4Bb	2.1Aa	0.9Dc	1.4Db	1.2Db	1.3Bb
	20.0–40.0	1.0Cb	1.5Ba	0.8Dc	1.1Db	1.0Db	1.0Bb
C/N Ratio	0–2.5	15.2Aa	14.6Aa	12.1Ab	12.3Ab	13.2Ab	14.6Aa
	2.5–5.0	15.3Aa	14.9Aa	12.2Ab	12.6Ab	13.4Ab	15.5Aa
	5.0–10.0	15.9Aa	15.5Aa	13.1Ab	13.8Ab	14.8Aa	16.3Aa
	10.0–20.0	16.0Ab	15.0Ab	15.4Bb	15.8Bb	17.2Ba	18.0Ba
	20.0–40.0	16.6Bb	14.4Ac	16.3Bb	16.6Bb	17.3Bb	18.9Ba

† Treatments are defined as follows: NF, native field; PNF-1, 1 yr of conventional tillage of native field; NT-10, 10 yr of continuous no-tillage application; NT-20, 20 yr of continuous no-tillage application; NT-22, 22 yr of continuous no-tillage application; CT-22, 22 yr of continuous application of conventional tillage.

‡ Means followed by the same letters in a column (uppercase) and in a row (lowercase) do not differ according to the Tukey test at $P \leq 0.05$.

In comparison with the no-tillage treatments, a highly significant ($P \leq 0.05$) loss of SOC in the CT-22 occurred in the top 10-cm layer. The percentage of the total SOC loss associated which each soil layer, as compared with the NF treatment, was 62.1% for the 0- to 2.5-cm soil layer, 27.6% for the 2.5- to 5-cm layer, and 10.3% for 5- to 10-cm layer. The comparison between NT-22 and CT-22 for 0- to 40-cm layer showed that no-tillage had 19.0 Mg ha^{-1} more SOC and 1.91 Mg ha^{-1} more TN (Fig. 4). Although soil erosion was not measured, the visual observations of these plots, sited on about a 1% slope, showed minimal erosion. Because the annual input of crop residues was similar for the NT-22 and CT-22 treatments, the difference in SOC and TN content may be attributed to differences in the rates of assimilation and decomposition of residues for the two tillage treatments.

Soil Organic Carbon and Total Nitrogen Changes in the Particle-Size Fractions

The particle-size fractions >53 μm accounted for 24 to 54% of the total sample weight and the <53 μm fraction represented 45 to 75% of the total sample weight for all depths except for soil obtained from the PNF-1 treatment (Fig. 5). The 200- to 2000-μm and 53- to 200-μm size fractions are comprised mainly of sand and its associated organic matter which is coarse undecomposed-plant residues and debris representing different stages of decomposition. The high C/N ratio observed for the organic matter associated with the 200- to 2000-μm size fraction supports the argument that the SOC in this fraction was comprised of fresh or little altered plant material.

The SOC concentrations in all depths increased in the fractions with size <20 μm (Fig. 5) indicating associations such as organo-silt complex and organo-clay frac-

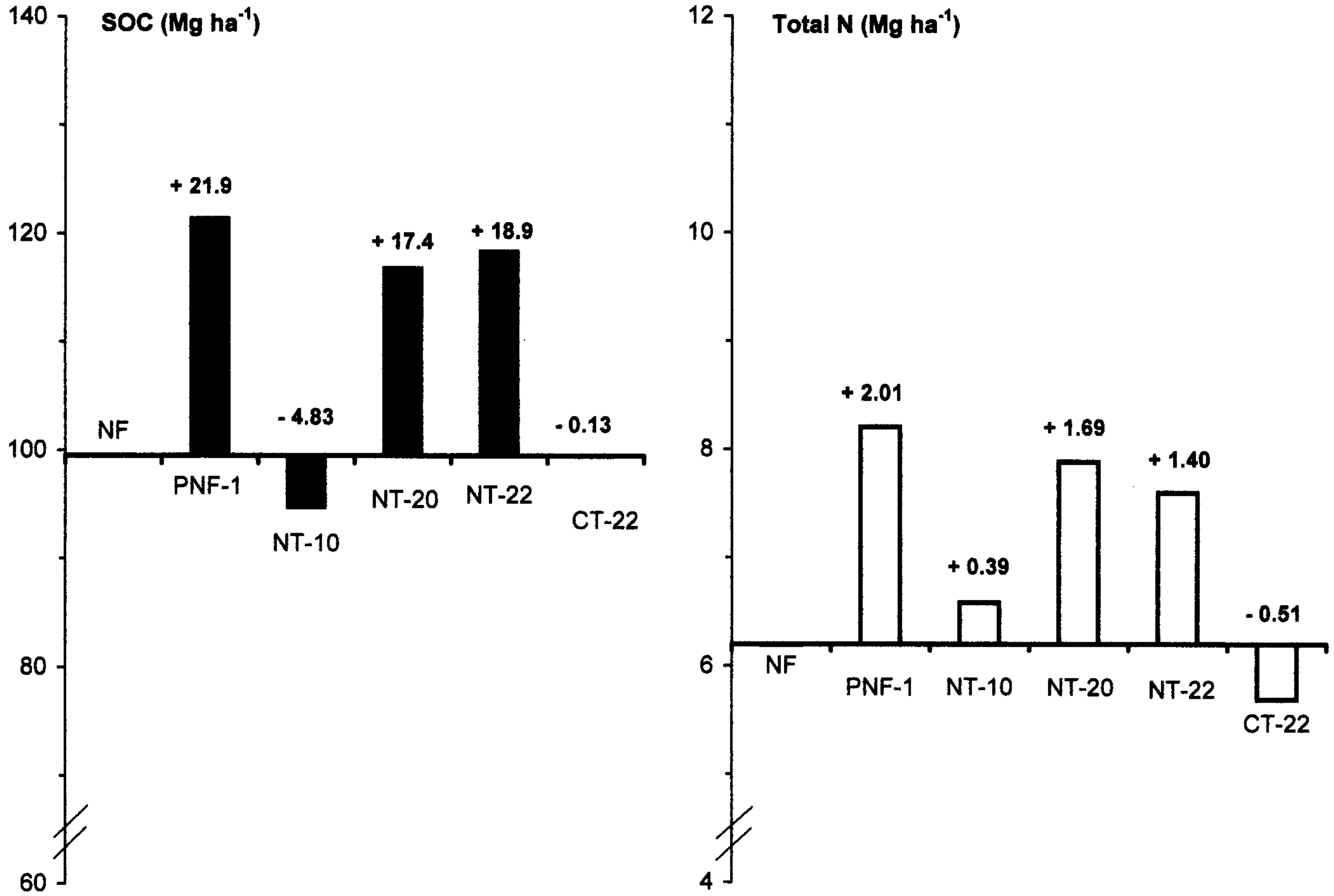

Fig. 2. Soil organic C (SOC) and total N (TN) stored in a 0- to 40-cm layer as affected by the various tillage chronosequence treatments. The heavy horizontal line represents the Native Field (NF) treatment. Treatments are defined as follows: NF, native field; PNF-1, 1 yr of conventional tillage of native field; NT-10, 10 yr of continuous no-tillage application; NT-20, 20 yr of continuous no-tillage application; NT-22, 22 yr of continuous no-tillage application; CT-22, 22 yr of continuous application of conventional tillage.

tions (Feller, 1994). This trend was similar for the NF and no-tillage treatments, and the enrichment of SOC in the clay fraction compared with the sand fraction (i.e., the particle-size fraction >53-μm) ranged from 1.72 to 2.75 times for the 0- to 2.5-cm layer, 2.4 to 4.6 times for the 2.5- to 5-cm layer, 2.72 to 12.5 times for the 5- to 10-cm layer, 3.68 to 16.2 times for the 10- to 20-cm layer, and 3.84 to 14.5 times for the 20- to 40-cm layer. The organic matter in the coarser size fractions (i.e., >53 μm) acts as an energy source for the microbial biomass and the stable organic compounds released from this process bind together the finer-size fractions (Angers and Giroux, 1996; Six et al., 1999). Golchin (1994) found that a continuous flux of organic compounds, released during the mineralization of crop residues, coupled with the activity of soil fungi can, indeed, lead to formation of stable organo-mineral complexes.

In the 0- to 2.5-cm and the 2.5- to 5-cm soil layers of the no-tillage treatments, the peak SOC concentrations were observed in 20- to 53-μm size fraction. This is an indication that long-term no-tillage with high crop residues input improved the protection and concentration of organic C through formation of silt-sized mineral-organo complexes. This protection may be because of the accumulation of fungal hyphae debris when crop residues are left on the soil surface. Fungi dominate microbial communities in no-tillage systems (Doran, 1980; Hendrix et al., 1986).

It is well known that microorganisms secrete large amounts of polysaccharides that can serve as a strong binding agent (Greenland et al., 1962). According to Baldock et al. (1992) the organic matter in the silt-sized fraction is less decomposed, with higher C/N ratio and higher O–alkyl C concentrations, than organic matter in the <20-μm fraction. In contrast, the silt- (2- to 20-μm) and clay- (<2-μm) sized fractions had much lower C/N ratios than observed for the larger sized fractions. This is because of microbial alterations of soil organic matter and the stabilization of the finer fractions by microbial products including polysaccharides, fungal hyphae, and bacterial cells or colonies encrusted with clay particles (Oades and Waters, 1991). As much as 40 to 60% of the microbial biomass may be associated with microaggregates 2 to 20 μm, depending on the amount and type of clay (Monrozier et al., 1991). Under tropical forest or savanna conditions, bacterial cell walls or colonies at different stages of decomposition can be observed in fractions <20 μm. The amorphous organic matter of microbial origin in clay fractions is indicated by very low xylose/mannose ratios (Feller et al., 1996).

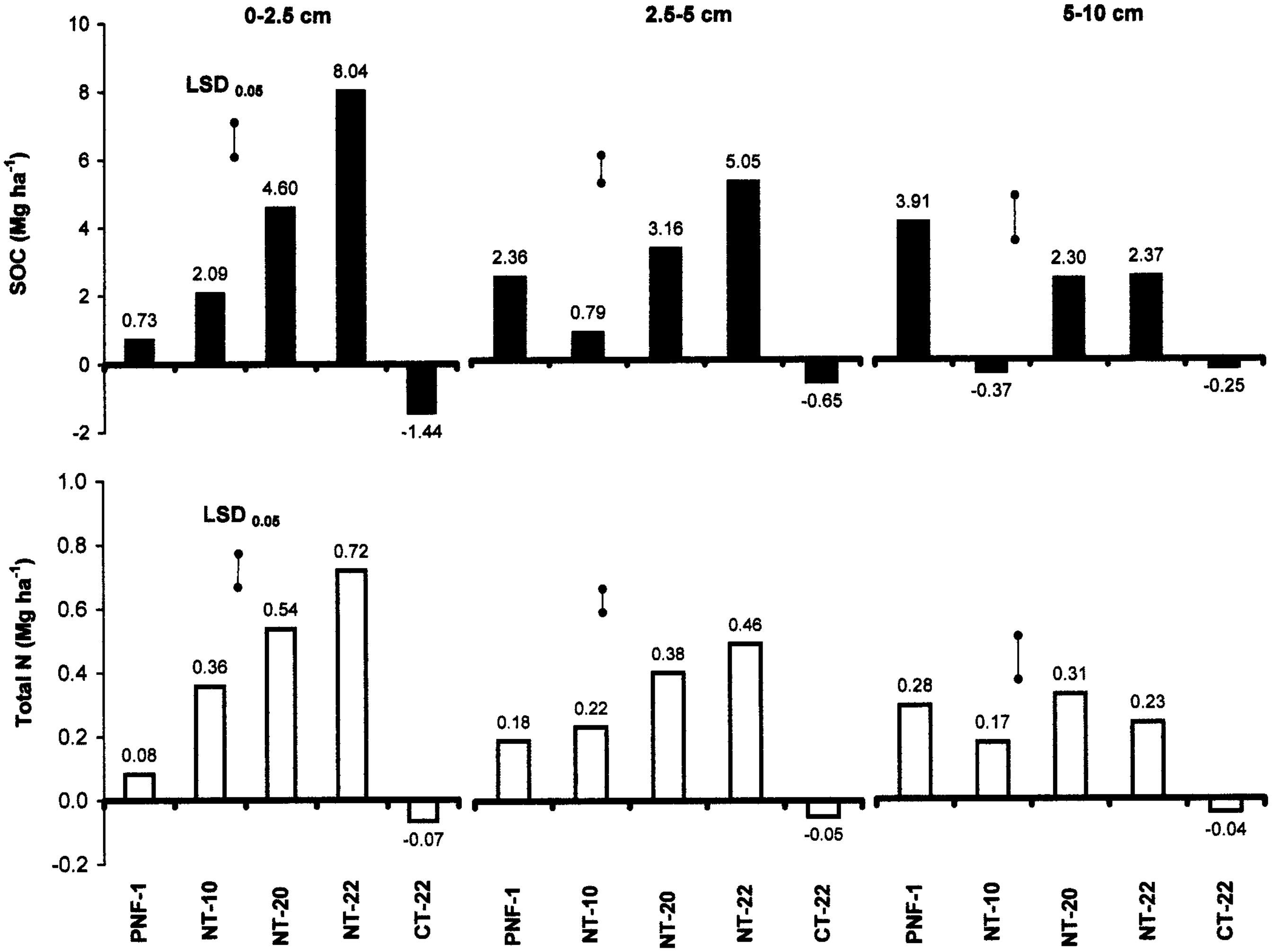

Fig. 3. Soil organic C (SOC) and total N (TN) gains or losses in the top three layers of soil (0–10-cm depths) under various tillage chronosequence treatments compared with the Native Field (NF) treatment (heavy horizontal line). The LSD$_{0.05}$ value determined by the Tukey Test is provided for mean comparison. Treatments are defined as follows: NF, native field; PNF-1, 1 yr of conventional tillage of native field; NT-10, 10 yr of continuous no-tillage application; NT-20, 20 yr of continuous no-tillage application; NT-22, 22 yr of continuous no-tillage application; CT-22, 22 yr of continuous application of conventional tillage.

The low C/N ratio observed in the finer-size fractions is an indication that the SOM is more stabilized and more aromatic (Bayer et al., 2000b).

Conversion to cropland caused a significant decrease in concentration of SOC in the 200- to 2000-μm size fraction for all depths in the PNF-1 treatment (Fig. 5). This size fraction is easily mineralizable because it is composed of fresh plant residues and debris, a potential source of energy for the microbial biomass.

The trends for TN, although not shown, were found to be similar in all cases to those of SOC. This is because of the highly significant correlation between SOC and TN ($r = 0.97$, $n = 150$, $P \leq 0.001$) in these surface soils.

Effect of Crop Residues and Long-Term No-Tillage on Soil Organic Carbon Assessed by ^{13}C Natural Abundance and Sequestration Rates

The conversion of natural C_4 vegetation to C_3 dominant species resulted in significant changes in the δ^{13}C signature for the various treatments in the chronosequence (Fig. 6). The degree of ^{13}C enrichment remained greater in the deeper layers and finer fractions. These results confirm that the crop-residue input with predominant C_3 species changed the organic matter composition and suggest different degrees of humification in different particle-size fractions in the top layers.

In the 0- to 10-cm layer, the no-tillage treatments had vastly different δ^{13}C values compared with the NF treatment. The introduction of C_3 carbon with its unique δ^{13}C signature, to the organic C originally present in the soil of the NF treatment, was especially evident in the coarsest particle-size fractions. The differences in δ^{13}C values were −6.83 to −4.77‰ for the 0- to 2.5-cm layer, −5.54 to −4.08‰ for the 2.5- to 5-cm layer, and −4.0 to −3.05‰ for the 5- to 10-cm layer (Fig. 6). There were no significant differences amongst treatments below 0- to 10-cm depth, suggesting that the crop residues maintained on the surface contributed a greater amount to the SOC than did the root system. The δ^{13}C values in CT-22 were generally between the no-tillage and NF treatments.

The effect of C_3 species in the crop rotation is diluted

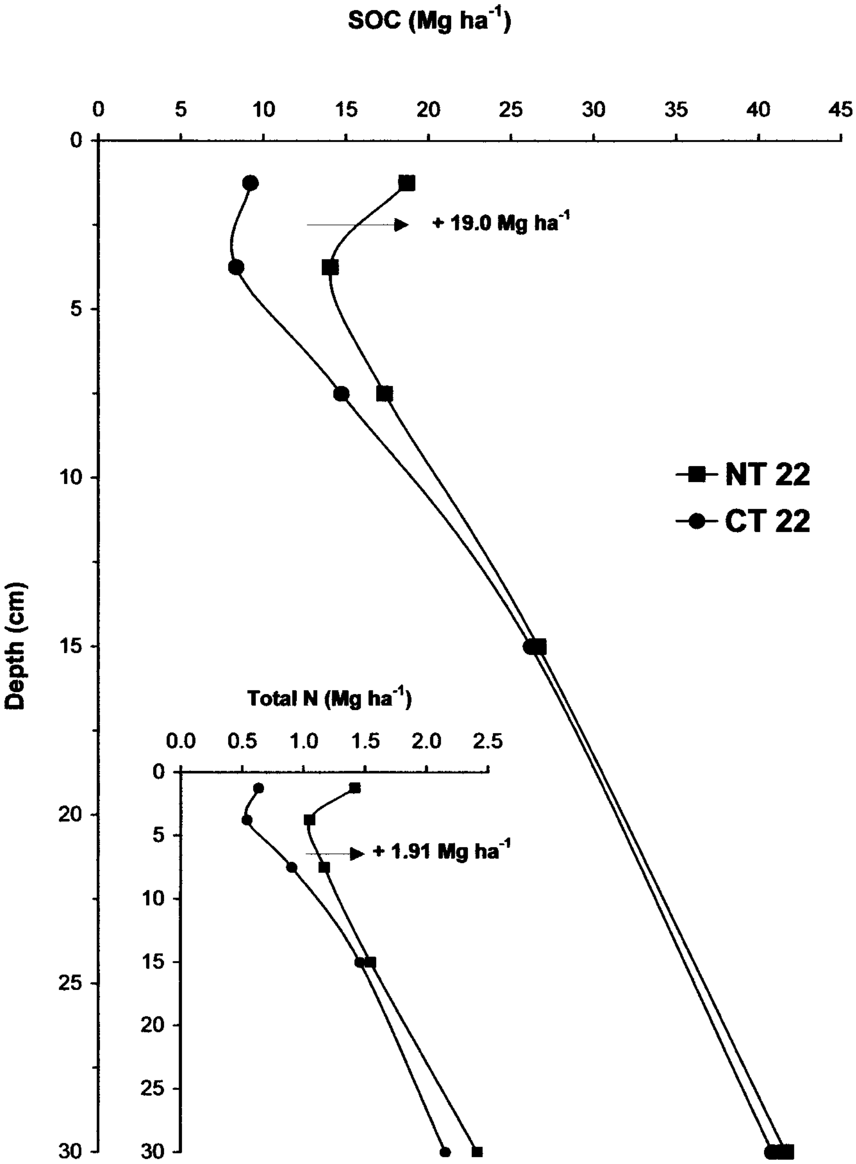

Fig. 4. Soil organic C (SOC) and total N (TN) stored in the 0- to 40-cm soil layer as affected by 22 yr of no-tillage (NT-22) and conventional tillage (CT-22) treatments.

by the $\delta^{13}C$ corn signal. However, the ratio of C_3/C_4 species was 7:1, and we did not attempt to isolate the source of error caused by the $\delta^{13}C$ corn signal in the rotation. Both the crop in rotation and the mineralization of the crop residues control the $\delta^{13}C$ signal and the mineralization of organic residues is greatly affected by the C/N ratio of the residues. The C/N ratio of crop residues estimated by Derpsch (1983) was 13 to 16 for soybean, 28 to 32 for black oat, 34 to 42 for wheat, and 64 to 68 for corn. These ratios suggest that the rate of mineralization can increase after soybean harvest and the influence of the soybean residues can extend to black oat residues, i.e., the N supplied by the soybean residues can also stimulate high biological activity in C-rich crops that the follow in the rotation. Corn residues provide high C input for microbial biomass. The crop residues with a high C/N ratio, when followed by a crop with a low C/N ratio, may be used by the microbial biomass thus stabilizing this C in soil (Smith et al., 1992).

In the 0- to 10-cm soil layer under no-tillage treatments, the estimate of SOC derived from crop residues was significantly greater in the coarse (200–2000, 53–200, and 20–53 μm) than the fine particle-size fractions (Fig. 7). The SOC derived from crop residues in these coarse-sized fractions ranged from: (i) 59.2 to 100% for the 0- to 2.5-cm layer, 76.1 to 78.4% for the 2.5- to 5-cm layer, and 48.2 to 96.8% for the 5- to 10-cm layer of the NT-10 treatment; (ii) 52.8 to 100% for the 0- to 2.5-cm layer, 55.7 to 68.2% for the 2.5- to 5-cm layer, and 40.4 to 49.0% for the 5- to 10-cm layer of the NT-20 treatment; and (iii) 69.7 to 100% for the 0- to 2.5-cm layer, 57.8 to 71.7% for the 2.5- to 5-cm layer, and 32.9 to 45.5% for the 5- to 10-cm layer of the NT-22 treatment. In the PNF-1 treatment a significant increase in SOC from crop residues occurred in the coarser fraction and in 0- to 10-cm layer.

Comparison between no-tillage and NF treatments showed significantly more crop-residues derived C in the

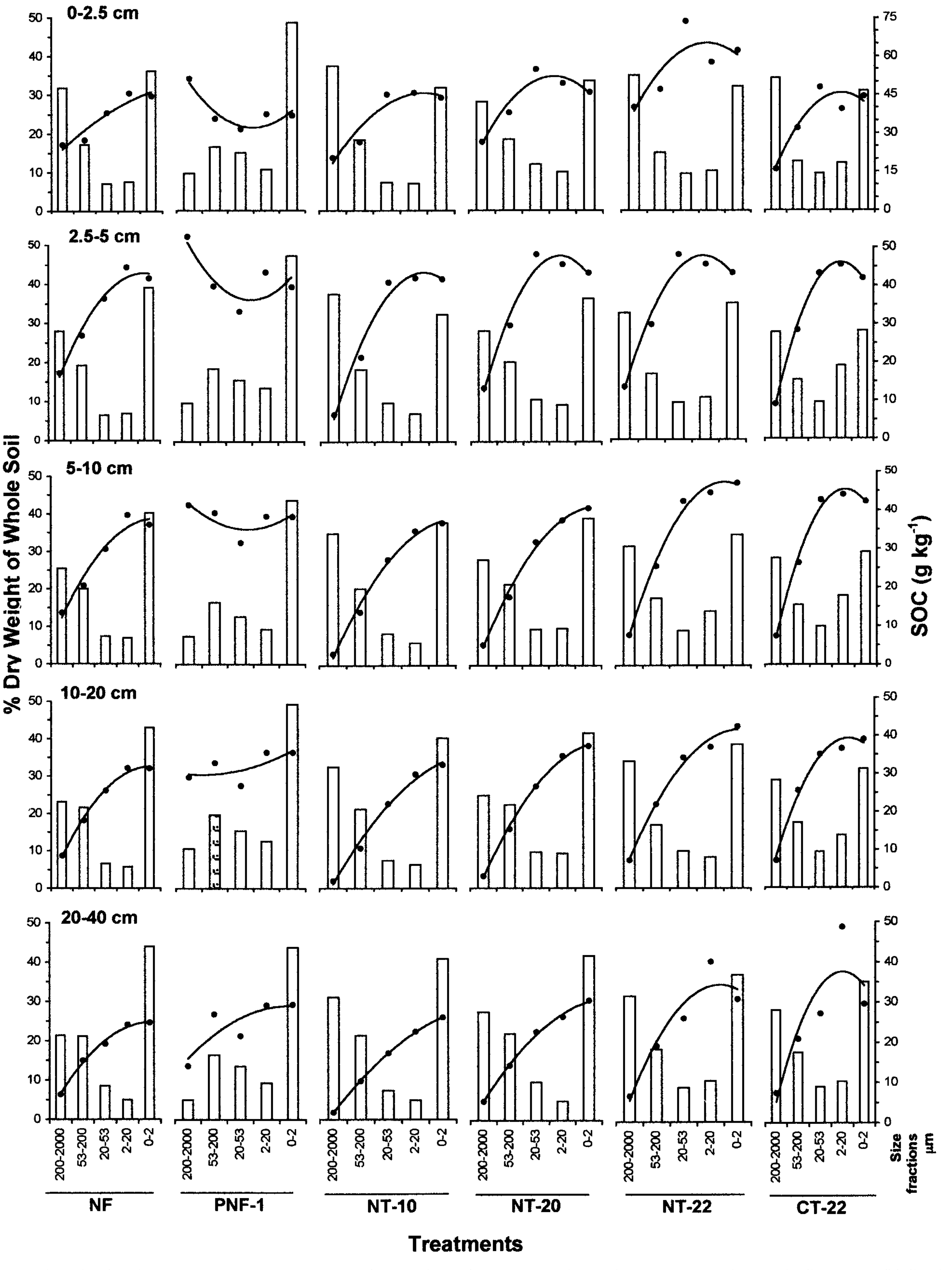

Fig. 5. Particle-size fractions expressed as a percentage of dry weight of the whole soil (vertical bars) and soil organic C content (SOC) (lines) for each particle-size fraction in the 0- to 2.5-, 2.5- to 5-, 5- to 10-, 10- to 20-, and 20- to 40-cm soil layers. Treatments are defined as follows: NF, native field; PNF-1, 1 yr of conventional tillage of native field; NT-10, 10 yr of continuous no-tillage application; NT-20, 20 yr of continuous no-tillage application; NT-22, 22 yr of continuous no-tillage application; CT-22, 22 yr of continuous application of conventional tillage.

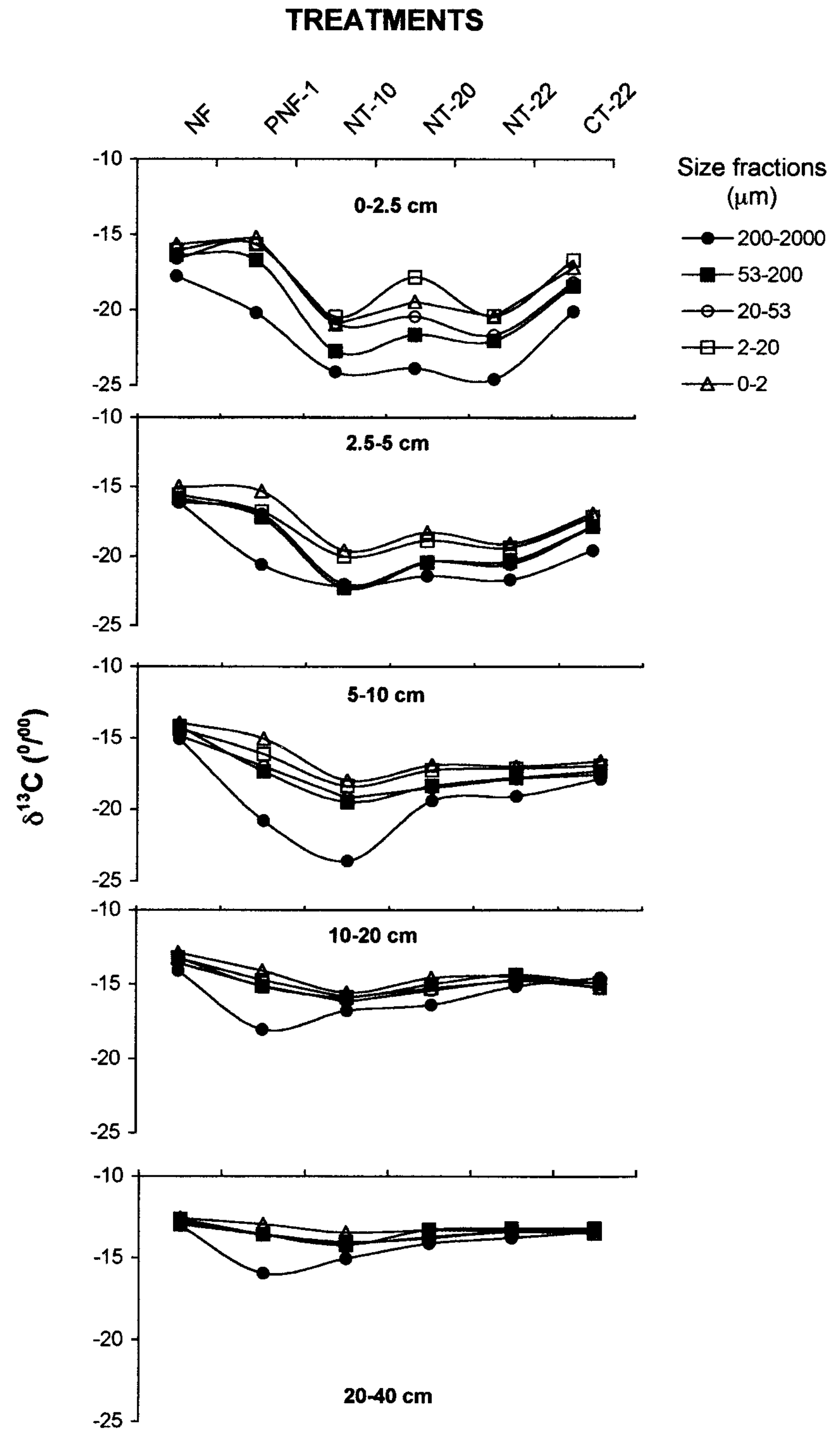

Fig. 6. The natural abundance (δ) of ^{13}C values in various particle-size fractions for each depth as affected by the various tillage chronosequence treatments. Treatments are defined as follows: NF, native field; PNF-1, 1 yr of conventional tillage of native field; NT-10, 10 yr of continuous no-tillage application; NT-20, 20 yr of continuous no-tillage application; NT-22, 22 yr of continuous no-tillage application; CT-22, 22 yr of continuous application of conventional tillage.

soil from the no-tillage treatments in the 2- to 20-μm and the 0- to 2-μm size fractions. The continuous C flux caused by mineralization and humification of organic compounds in the long-term no-tillage treatments may be a key factor that influences associations of SOC with the aggregates and the particle-size fractions. Balesdant et al. (2000) reported a strong relationship of SOC dynamics and the physical protection for temperate soils.

The decline in SOC concentrations by conversion from natural to agricultural ecosystems attains a new equilibrium level in 30 to 50 yr (Wagner, 1981). The SOC loss in the present study during 20 yr (representing the first

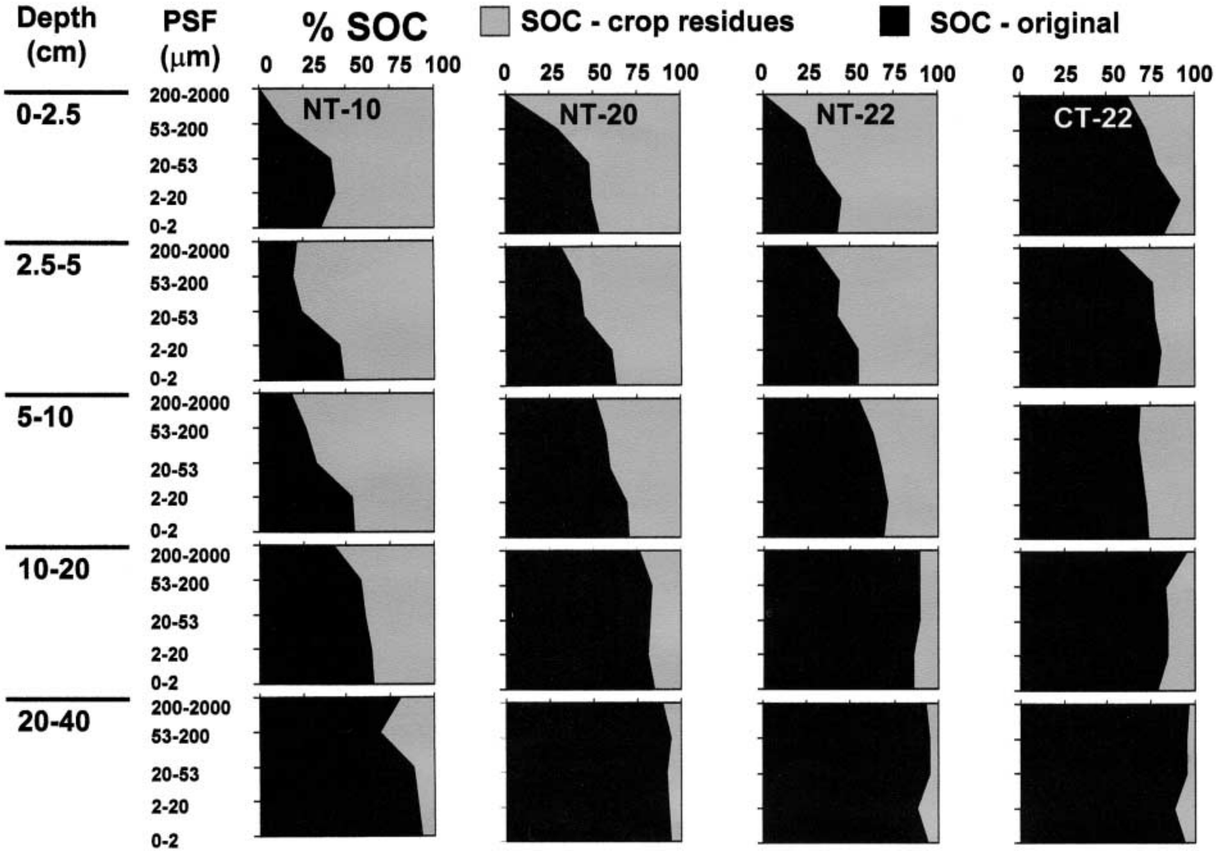

Fig. 7. Percentage of soil organic C (SOC) for each particle-size fraction and each depth that is derived from C originally present in the soil from the various treatment sites and C that is derived from crop residues. PSF, particle-size fraction. The treatment abbreviations are NT-10, no-tillage for 10 yr; NT-20, no-tillage for 20 yr; NT-22, no-tillage for 22 yr; CT-22, conventional tillage for 22 yr.

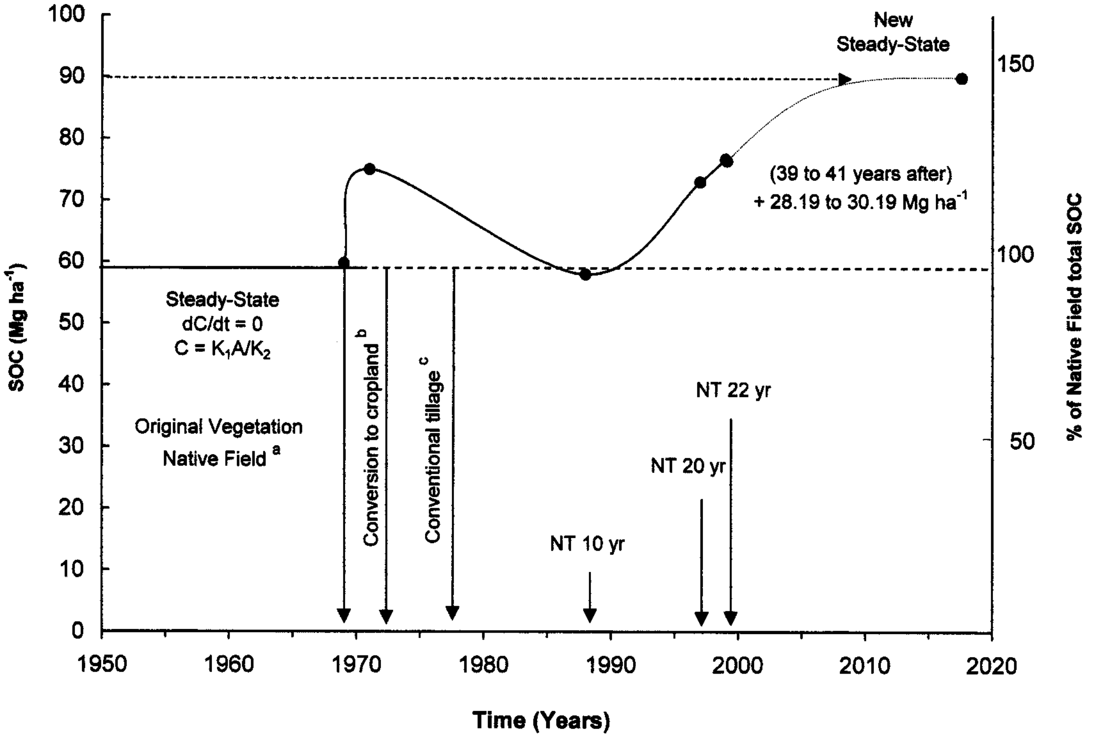

Fig. 8. Representation of soil organic C (SOC) changes in a tillage chronosequence and the prediction of the new steady-state for no-tillage in the 0- to 20-cm soil layer.

phase of cropping comprising 10 yr with plow tillage and 10 yr of no-tillage) was 1.09 Mg ha^{-1} yr^{-1}. The new equilibrium or steady-state level was predicted to occur ~40 yr after the adoption of no-tillage with high inputs of crop residues (Fig. 8). The new equilibrium SOC content estimate for the 0- to 20-cm layer ranged from 88.0 to 90.0 Mg ha^{-1} and represented an increase of 47.1 to 50.5% from the original SOC content in the native field.

The δ^{13}C technique developed by Cerri et al. (1985) and Balesdant et al. (1987) can be used to assess C input and turnover as affected by crop rotation and tillage (Huggins et al., 1998). The δ^{13}C variation between native prairie and no-tillage crop rotation in this study were similar to that reported by Balesdent et al. (1988).

The SOC sequestration rate associated with no-tillage in this major ecological region of south Brazil was calculated using the NF treatment as a benchmark. The sequestration rate was 80.6 g C m^{-2} yr^{-1} for the 0- to 20-cm layer and 99.4 g C m^{-2} yr^{-1} for the 0- to 40-cm layer. The largest contribution to the total sequestration rate was associated with the 0- to 5-cm layer. The contribution of different depths was 31.9 g C m^{-2} yr^{-1} for the 0- to 2.5-cm layer, 21.2 g C m^{-2} yr^{-1} for the 2.5- to 5-cm layer, 12.5 g C m^{-2} yr^{-1} for the 5- to 10-cm layer, 15.1 g C m^{-2} yr^{-1} for the 10- to 20-cm layer, and 18.7 g C m^{-2} yr^{-1} for the 20- to 40-cm layer. These results of SOC sequestration are higher than the 30 to 70 g C m^{-2} yr^{-1} reported by Lal et al. (1998).

In Brazil, 27% of cropland (13.4 million hectares) are cultivated using a no-tillage system (Febrapdp, 2000) of which 70.5% (i.e., 9.43 million 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 b). 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

A significant increase in the SOC content in the upper 10-cm layer in no-tillage soils compared with soils under natural vegetation and long-term conventional tillage (CT-22) occurred because of high crop-residue input and the lack of soil disturbance. These effects were pronounced in the silt-sized or larger particle-size fractions, although the finer fractions were also enriched in the surface layers. The significant contribution of crop residues to SOC in the soil surface layers assessed by δ^{13}C, was evident in the 200- to 2000-, 53- to 200-, and 20- to 53-μm particle-size fractions. These trends imply that long-term no-tillage systems protect soil organic matter through formation of stable sand- and silt-sized particles. The C sequestration rate for the top 40-cm layer was 99.4 g m^{-2} yr^{-1}, and the C sequestration potential for south Brazil is estimated at 9.37 Tg C yr^{-1}.

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