

Soil organic carbon and fertility interactions affected by a tillage chronosequence in a Brazilian Oxisol

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ABSTRACT

No-till (NT) adoption is an essential tool for development of sustainable agricultural systems, and how NT affects the soil organic C (SOC) dynamics is a key component of these systems. The effect of a plow tillage (PT) and NT age chronosequence on SOC concentration and interactions with soil fertility were assessed in a variable charge Oxisol, located in the South Center quadrant of Paraná State, Brazil (50°23'W and 24°36'S). The chronosequence consisted of the following six sites: (i) native field (NF); (ii) PT of the native field (PNF-1) involving conversion of natural vegetation to cropland; (iii) NT for 10 years (NT-10); (iv) NT for 20 years (NT-20); (v) NT for 22 years (NT-22); and (vi) conventional tillage for 22 years (CT-22) involving PT with one disking after summer harvest and one after winter harvest to 20 cm depth plus two harrow disking. Soil samples were collected from five depths (0–2.5; 2.5–5; 5–10; 10–20; and 20–40 cm) and SOC, pH (in H₂O and KCl), ΔpH, potential acidity, exchangeable bases, and cation exchangeable capacity (CEC) were measured. An increase in SOC concentration positively affected the pH, the negative charge and the CEC and negatively impacted potential acidity. Regression analyses indicated a close relationship between the SOC concentration and other parameters measured in this study. The regression fitted between SOC concentration and CEC showed a close relationship. There was an increase in negative charge and CEC with increase in SOC concentration: CEC increased by 0.37 cmol_c kg⁻¹ for every g of C kg⁻¹ soil. The ratio of ECEC:SOC was 0.23 cmol_c kg⁻¹ for NF and increased to 0.49 cmol_c kg⁻¹ for NT-22. The rates of P and K for 0–10 cm depth increased by 9.66 kg ha⁻¹ yr⁻¹ and 17.93 kg ha⁻¹ yr⁻¹, respectively, with NF as a base line. The data presented support the conclusion that long-term NT is a useful strategy for improving fertility of soils with variable charge.

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1. Introduction

Conversion of natural to cropland ecosystems results in significant changes in soil physical, chemical, and biological properties (Lal, 1976; Oades, 1984; Elliot, 1986; Potter et al., 1998). The plow tillage (PT) system has been used since the dawn of settled agriculture but its use intensified, with the onset of the industrial era in 1850, especially in temperate regions (Lynch, 1984). Principal objectives of PT in high latitudes are to accelerate soil warming during spring, control weeds, and create edaphic conditions conducive to seedling establishment and crop growth.

Most soils in the tropics have low inherent fertility due to low pH, high exchangeable Al³⁺, low base saturation and low available

phosphorus (P) concentration. Some soils also have shallow effective rooting depth due to high subsoil acidity and root-restrictive physical conditions. Thus, PT in the tropics has been used to incorporate lime and alleviate these soil-related constraints (Kamprath, 1977; Ernani et al., 2004; Fageria, 2008). However, the erosion caused by intensive PT, especially in regions of high rainfall erosivity, depletes the soil organic matter (SOM), reduces its fertility and accentuates costs of soil restoration.

Experiments conducted in temperate regions have shown that a continuous use of NT leads to stratification of SOM and plant nutrients in the soil profile with accumulations occurring in the surface soil layer (Triplett and Van Doren, 1969; Blevins et al., 1977; Dick, 1983; Muzilli, 1983; Lal, 1997; Whitbread et al., 2003; Brye et al., 2006; Franzluebbers, 2002; Franzluebbers et al., 2007; Sá and Lal, 2008). However, similar studies for soils of the tropics with variable charge and low effective cation exchange capacity (ECEC) are either lacking or incomplete (Resck, 1998; Sá, 1999;

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Caires et al., 2005; Séguy et al., 2006). Furthermore, the available data do not clearly explain how nutrients, recycled from the crop residues, can be conserved in the surface soil in view of the high losses caused by leaching and runoff/erosion because of intense rains (Resck, 1998). It is widely recognized that an appropriate management strategy for these soils is to increase their net negative charge along with CEC and ECEC (Sanchez, 1976; Uehara and Keng, 1975; Uehara, 1995; Resck, 1998).

In some Oxisols from Brazil (i.e., São Paulo State, Paraná State and Cerrado region), SOM contributes 74–90% of the total CEC, indicating importance of SOM in soils with variable charge (Raij, 1969; Pavan et al., 1985; Lopes and Cox, 1977; Silva et al., 1994; Fontana et al., 2006). Crop residues, with C concentration of 40–50%, have a positive effect on the soil organic carbon (SOC) concentration and the soil's net negative charge (Burle et al., 1997; Bayer and Bertol, 1999). Increasing concentrations of SOC, exchangeable cations (i.e., Ca^{2+} , Mg^{2+} , K^+) released from crop residues by mineralization, along with CEC enhance fertility in soils with variable charge (Bayer and Bertol, 1999). Therefore, the NT systems, which return large amounts of crop residues to the soil surface, are important tools in sustainable management of these soils (Sá et al., 2001; Amado et al., 2006; Bayer et al., 2006; Cerri et al., 2007). Application of lime, gypsum and phosphate are principal means for increasing SOM concentration (Fox, 1980; Resck, 1998; Caires et al., 2005).

Juo and Lal (1979), Dick (1983) and Potter et al. (1998) reported that soil fertility enhancements in NT systems occurs primarily in the surface layers because fertilizers and crop residues are applied onto the soil surface. Strong and positive impact of crop residue mulch on properties of surface soil have been widely reported (Havlin et al., 1990; Buchanan and King, 1993). For a Brazilian Oxisol, Sá (1999) reported a greater decrease in base saturation in the 0–10 cm, than 30–40 cm layer under continuous NT management compared with a PT system. Yet, the acidity level in the 30–40 cm depth neither inhibited root development nor reduced crop yields.

Despite the availability of a large body of data, comparisons of NT and PT systems over an age chronosequence have rarely been done for tropical ecosystems to determine temporal changes in soil properties among tillage systems. Further, quantification of long-term impacts of NT systems on soil properties, especially those related to soil fertility, have not been widely measured for soils of the tropics. Yet, information on SOC concentration/pool and soil fertility dynamics in a long-term NT chronosequence are important to identifying strategies for sustainable management of soils with variable charge. Therefore, the objective of this study was to assess the impact of a tillage chronosequence on SOC concentration and its interactions with some soil fertility attributes in a Brazilian Oxisol.

2. Materials and methods

2.1. Sites description

Field experiments were conducted at two research sites. One site was located near the town of Tibagi (Santa Branca Farm) and the other near Ponta Grossa city (Frankanna Farm), in the South Center quadrant of Paraná State, Brazil (50°23' W and 24°36' S; 50°20' W and 25°20' S, respectively). The experimental sites are located 880–910 m above sea level, and are characterized by a mesothermic, wet subtropical, type cfb (koeppen classification) climate. The mean annual rainfalls of Ponta Grossa (44 years average, IAPAR, 1998) and Tibagi city (24 years average, Fundação ABC, 1998) are 1545 and 1532 mm, respectively. The rainfall is distributed throughout the year and there is no pronounced dry period. The mean temperature is 22 °C during the summer and

15 °C in the winter season with occasional occurrence of frost. The natural vegetation is a subtropical “prairie” dominated by C_4 species represented by 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 reworked material called Ponta Grossa shale and Furnas sandstone formation. These soils are classified as clayey Dark Red Latosols (Typic Hapludox), have a deep and very well structured profile, high porosity (with equal proportion of macro and microporosity) and very good internal drainage. These soils are of low inherent fertility, have high exchangeable Al^{3+} concentration and are located on the shoulder slopes. Soil profile of each site was studied by digging a 1.5 m × 1.5 m pit and samples were obtained for chemical and mineralogical analyses (Table 1). The choice of these sites was based on the existence of a well defined chronosequence starting from the original undisturbed conditions (natural vegetation and soil properties). This chronosequence provided an opportunity to assess the long-term comparative impacts of PT and NT systems on soil fertility. The sites were developed on the same parent material, have the same soil type, the same upland position, and were managed with similar rotation and cultural practices with detailed descriptions given in an earlier report (Sá et al., 2001; Sá and Lal, 2008).

2.2. Conversion of natural vegetation to an agricultural system, crop rotation and cultural practices

At the Tibagi site (Santa Branca Farm) the previous land use was natural vegetation (native field) comprising a climax vegetation of the region, and it represented the NF treatment. In 1969, some of the NF was converted to cropland using a 70 cm disk, plowing to 20 cm depth and tilling twice with 60 cm disk to break the clods. The acidity level was initially corrected with application of 3.5 Mg ha^{-1} of lime, and phosphorus was added at a rate of 117 kg ha^{-1} of P_2O_5 (52 kg P). In 1979, 20–30% of the total area was converted to a NT system and represented the 20 years of NT (NT-20 treatment). From 1979 to 1998, cropping during the summer season involved 15 crops of soybean (*Glycine max.* L. Merrill) and five of corn (*Zea mays* L.). During the winter season, wheat (*Triticum aestivum*) was cultivated seven times, black oats (*Avena strigosa*, Schreb) 11 times and lupine (*Lupinus angustifolios*) twice. Both black oats and lupine were grown as cover crops. In 1989, the border and other tilled areas were converted to NT system and represent the 10 years of NT (NT-10 treatment). Cropping during the summer season 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 oats. Another natural vegetation site was converted to cropland in June 1996, and represents the PT of native field (PNF-1 treatment), with application of lime (3.5 t ha^{-1}) and 140 kg ha^{-1} of superphosphate (67 kg P) initially incorporated to 20 cm depth once with a 70 cm disking, twice 60 cm narrow disking, and the conversion began 1 year and 6 months prior to sampling. The crops sown were soybean (October/96), black oats (May/97) and corn (September/97).

At the Ponta Grossa site (Frankanna Farm), the previous land use was natural vegetation and the conversion to agricultural ecosystem was initiated in 1961. In 1976, two plots were initiated to compare 22 years of NT (NT-22 treatment) and 22 years of conventional tillage (CT-22 treatment—involving PT with a 70 cm disking after summer harvest, and one after winter harvest to 20 cm depth plus two 60 cm narrow disking to break the clods). The management (plowing, crops, lime, and P rates) used during 1961–1976 was similar to that of the Tibagi site. Cropping for the

Table 1

Chemical and mineralogical properties of the Typic Hapludox (Dark Red Latosol) collected from the tillage chronosequence.

Attributes	Depth (cm)	Tillage chronosequence						
		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 (cmol _c kg ⁻¹)	0–20	9.7	13.2	4.2	6.2	5.1	5.3	
	20–40	8.0	12.7	4.7	7.1	5.8	8.0	
Exchangeable Al (cmol _c kg ⁻¹)	0–20	1.3	2.2	0.07	0.08	0.07	0.15	
	20–40	9.7	3.7	0.20	0.40	0.30	0.50	
Exchangeable Ca (cmol _c kg ⁻¹)	0–20	0.54	3.4	4.8	5.3	4.7	4.5	
	20–40	0.16	0.36	1.4	1.2	0.9	1.1	
Exchangeable Mg (cmol _c kg ⁻¹)	0–20	0.17	2.2	1.9	2.2	2.1	2.2	
	20–40	0.10	0.20	0.70	0.50	0.60	0.60	
Exchangeable K (cmol _c kg ⁻¹)	0–20	0.12	0.34	0.22	0.37	0.46	0.41	
	20–40	0.03	0.12	0.07	0.11	0.21	0.22	
CEC (cmol _c kg ⁻¹)	0–20	10.5	17.9	10.9	13.7	12.3	12.4	
	20–40	8.3	13.4	6.9	8.9	7.5	9.9	
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) ^a	Bo1	Kao ^b	Kao	Kao	Kao	Kao	–	
		Gib	Gib	Gib	Gib	Gib	–	
		Hem	Hem	Hem	Hem	Hem	–	
		Goe	Goe	Goe	Goe	Goe	–	
TDA ^c (% of clay fraction)	Ap	Kao ^b	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	–

^a The X-ray analyses was applied to samples from the Bo1 horizon.^b Kao = kaolinite, Gib = gibbsite, Hem = hematite, Goe = goethite.^c TDA = thermal differential analyses, results in percentage. The TDA was applied to samples from the Ap and Bo1 horizons.

summer season between 1976 until 1998 in this area comprised of 15 crops of soybean and six of corn. Cropping for the winter season comprised 10 crops of wheat, four of black oats and one of lupine and for the last four seasons, four crops of winter ryegrass (*Lolium multiflorum*).

At both sites, the 3-year crop rotation model (winter and summer) was: wheat–soybean/black oats–soybean/black oats–corn. The data for NT treatments on fertilizers used, total dry biomass (aboveground + root dry biomass), and percentage of dry biomass compared to total dry biomass for each crop are presented in Sá et al. (2001).

2.3. Experimental design and sampling

The experimental design consisted of six treatments in a NT chronosequence in which duration of plowing and NT 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 treatment was 200 m × 50 m, with five internal replicates (i.e., subareas, Sá et al., 2001) each with an area of 40 m × 50 m. 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 from each replicate were obtained by digging nine pits of 20 × 50 (surface area) × 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 of all replicates was obtained for each depth.

2.4. Sample preparation and analyses

Soil samples were air-dried and ground to pass through a 2 mm sieve. A portion of each sample was ground to pass through 100 mesh sieve to determine the SOC concentrations by the loss on ignition method (Nelson and Sommers, 1982) using a Carbon analyser, LECO[®] CR-412. Soil pH was measured using two procedures: (i) in 1:2.5 soil:water suspension; and in (ii) 1N KCl (EMBRAPA, 1979). The charge status was determined by measuring pH in H₂O and in 1N KCl as described by Mekaku and Uehara (1972). The ΔpH (KCl_{pH}–H₂O_{pH}) corresponds to the sign of the colloidal charge. The negative values of ΔpH correspond to CEC and positive ΔpH values to AEC (anion exchange capacity). The potential acidity was determined by the method of EMBRAPA (1979) and exchangeable Al³⁺, Ca²⁺, Mg²⁺, K⁺ and available P were extracted using a cation and anion exchange resin (Rajj and Quaggio, 1983). The CEC was obtained in buffered solution at pH 7.0 and the ECEC was obtained by summing the exchangeable Al³⁺ and the exchangeable Ca²⁺, Mg²⁺ and K⁺. The ratio of ECEC:SOC was calculated by the following expression: ECEC range/SOC range, where ECEC range is the difference between the average of the values of 0–2.5 cm depth, and those of the 20–40 cm depth. For each site, the Bo1 horizon was sampled to identify the clay minerals by X-ray diffraction (Jackson, 1966). The percentage of kaolinite and gibbsite were determined using the thermal differential analysis (Jackson, 1966) in Ap and Bo1 horizons. The soil texture of all horizons of each profile was measured by the pipette method (Gee and Bauder, 1986).

2.5. Statistical analyses

Results were analyzed for the analysis of variance (ANOVA) and treatments means were compared using the Tukey test (LSD_{0.05}). The regression equations were computed by the stepwise procedures (Sas Institute, 1990) to adjust the models. Pearson correlation coefficients were used to assess the relationships among variables. Regression equations were computed to assess the temporal changes for available K and P for each depth considering the NF as the baseline or reference point. Statistical significance were computed at $P < 0.05$ and $P < 0.01$, and $P < 0.001$ represented by *, ** and ***, respectively. The rate of the temporal changes for P and K was calculated by computing slope at the regression line (dy/dx) for each depth. The temporal changes for P and K estimated by regression analyses were expressed in kg ha⁻¹. Soil bulk density was used to transform the concentration of P (i.e., mg kg⁻¹) and K (i.e., cmol_c kg⁻¹) for kg ha⁻¹.

3. Results and discussion

3.1. Potential acidity and pH in the chronosequence as affected by soil organic carbon

Conversion of NF to cropland under PT or NT systems resulted in a differential response of SOC concentrations. The average SOC concentrations in CT-22 treatment were significantly lower ($P < 0.05$) compared with NF only in the 0–2.5 cm depth. For long-term NT treatments the significant difference in SOC concentration occurred in 0–2.5 and 2.5–5 cm depths (Table 2). For the PNF-1 treatment, the increase in SOC concentration may be due to incorporation of fresh organic material since this treatment had only been established 18 months prior to soil sampling. In this case, the pH and exchangeable bases increased by stimulating mineralization, and these changes were most evident in the surface layers.

For long-term NT treatments, the SOC concentrations were significantly higher in the 0–2.5 and 2.5–5 cm depths than NF and CT-22 treatments. Based on estimate of total annual inputs in the NT treatments, the Pearson correlation coefficient between SOC concentration for NT treatments and input of crop residues (0.40 kg m⁻² yr⁻¹ for NT-10, 0.39 kg m⁻² yr⁻¹ for NT-20 and 0.33 kg m⁻² yr⁻¹ for NT-22) was $r = 0.86^{**}$ for 0–2.5 cm, and $r = 0.99^{***}$ for 2.5–5 cm depths. The responses of potential acidity and pH (Table 2) differed among the chronosequence treatments. For the NF treatment, increase in SOC concentration increased the potential acidity, without change in the pH. Further, the high exchangeable Al³⁺ concentration, and low percentage of base saturation contributed to decline in soil pH (<5.0). Besides, concentration of Al³⁺ and % of base saturation, respectively, 0.95 cmol_c kg⁻¹ and 15.4% for 0–2.5 cm depth, and 1.32 cmol_c kg⁻¹ and 9.6% for 2.5–5 cm depth, 1.41 cmol_c kg⁻¹ and 6.4% for 5.0–10 cm depth, 1.28 cmol_c kg⁻¹ and 5.9% for 10–20 cm depth, and 0.97 cmol_c kg⁻¹ and 3.5% for 20–40 cm depth. Incorporation of lime in the PT treatments (PNF-1 and CT-22) increased soil pH and decreased potential acidity.

Soil acidity and pH in the PNF-1 treatment were both affected by the SOC concentration by depth. In the PNF-1 treatment, in comparison with all other treatments except CT-22, the potential acidity initially increased with increase in SOC concentration and then sharply decreased. Comparison of the PNF-1 and NF treatments indicated an increase in soil pH in the range of SOC from 22.0 to 38.4 g kg⁻¹, with the significant decrease of potential acidity from 14.6 to 7.8 cmol_c kg⁻¹, probably due to the effect of lime application and replacement of Al³⁺ by bases (Ca²⁺, Mg²⁺ and K⁺).

The response of the NT-10, NT-20 and NT-22 treatments differed from that of the CT-22 treatment. There was an increase in pH and a decrease in potential acidity with significant differences ($P < 0.01$) observed in the surface layers (0–2.5, 2.5–5, and 5–10 cm depth, Table 2).

Table 2

Changes of SOC, pH (H₂O), potential acidity (Pac), and ΔpH (KCL_{pH}–H₂O_{pH}) in Typic Hapludox (Dark Red Latosol) profile under a long-term tillage chronosequence (means of five replicates[†]).

Variable	Depth (cm)	Tillage chronosequence					
		NF	PNF-1	NT-10	NT-20	NT-22	CT-22
SOC (g kg ⁻¹)	0–2.5	34.5 B	38.4 C	36.3 C	45.9 D	52.8 D	30.1 A
	2.5–5.0	29.5 A	37.2 B	25.7 A	34.6 B	35.1 B	28.0 A
	5.0–10.0	25.3 B	35.5 C	18.9 A	24.7 B	25.1 B	25.9 B
	10.0–20.0	21.6 B	31.2 C	14.6 A	21.6 B	20.7 B	23.5 B
	20.0–40.0	16.9 B	22.0 C	12.7 A	17.9 B	16.9 B	19.3 B
LSD _{0.05} [§]	(Depth)	4.1	4.9	4.2	5.1	4.3	4.8
pH (H ₂ O)	0–2.5	4.9 A	5.97 BC	6.66 D	6.83 D	6.13 C	5.77 B
	2.5–5.0	4.9 A	5.07 B	6.47 D	6.48 D	6.15 D	5.85 C
	5.0–10.0	4.9 A	4.63 A	6.01 C	6.09 C	6.04 C	5.86 B
	10.0–20.0	4.9 B	4.58 A	5.85 C	5.70 C	5.61 C	5.63 C
	20.0–40.0	5.0 B	4.67 A	5.72 C	5.29 C	5.12 B	5.20 B
LSD _{0.05}	(Depth)	0.45	0.41	0.39	0.34	0.36	0.40
Pac (cmol _c kg ⁻¹)	0–2.5	10.5 D	7.8 C	3.62 A	4.44 B	4.40 B	5.0 B
	2.5–5.0	10.3 C	11.6 C	3.54 A	4.96 B	4.64 B	5.0 B
	5.0–10.0	9.8 C	14.6 D	4.54 A	5.98 B	4.9 B	5.18 B
	10.0–20.0	9.24 C	14.26 D	4.36 A	7.1 C	5.86 B	6.34 BC
	20.0–40.0	8.02 C	12.72 C	4.72 A	7.08 C	6.12 BC	7.52 C
LSD _{0.05}	(Depth)	0.81	1.13	0.47	0.41	0.53	0.72
ΔpH (KCL _{pH} – H ₂ O _{pH})	0–2.5	–0.85 A	–0.66 B	–0.35 C	–0.42 C	–0.32 C	–0.29 D
	2.5–5.0	–0.78 A	–0.57 B	–0.50 BC	–0.53 B	–0.41 C	–0.43 C
	5.0–10.0	–0.79 A	–0.60 B	–0.77 A	–0.74 A	–0.60 C	–0.51 C
	10.0–20.0	–0.82 A	–0.61 B	–0.92 A	–0.98 A	–0.78 B	–0.74 C
	20.0–40.0	–0.87 B	–0.59 C	–1.15 A	–0.92 A	–0.62 C	–0.76 B
LSD _{0.05}	(Depth)	–0.22	–0.14	–0.16	–0.18	–0.12	–0.19

[†] Means followed by the same uppercase (A–D) letters in the rows (comparison among treatments within each depth) do not differ by Tukey test at $P < 0.05$.

[§] Value of Tukey test at $P < 0.05$ for comparison the means among depths within each treatment.

Table 3

Pearson correlation coefficient between potential acidity (PAC) and pH (in H₂O), PAC and effective CEC (ECEC), SOC and ΔpH, ΔpH and ECEC, ΔpH and basis saturation (BS%), ECEC and BS% for all data (n = 150) and within each treatment (n = 25).

Pearson correlation	All data	Tillage chronosequence					
		NF	PNF-1	NT-10	NT-20	NT-22	CT-22
PAC × pH	-0.80***	-0.37*	-0.91***	-0.88***	-0.92***	-0.62**	-0.41*
PAC × CEC	0.13 ^{NS}	0.95***	-0.69**	-0.70**	-0.79***	-0.83***	-0.88***
PAC × ECEC	-0.57***	0.66***	-0.82***	-0.75***	-0.85***	-0.90***	-0.95***
SOC × ΔpH	0.58***	0.15 ^{NS}	-0.08 ^{NS}	0.90***	0.81***	0.79***	0.78***
ΔpH × CEC	0.54***	0.13 ^{NS}	-0.16 ^{NS}	0.82***	0.73**	0.69**	0.73**
ΔpH × ECEC	0.48**	-0.07 ^{NS}	-0.18 ^{NS}	0.84***	0.77***	0.71**	0.74**
ΔpH × BS%	0.51**	0.09 ^{NS}	-0.08 ^{NS}	0.92***	0.86***	0.62**	0.71**
CEC × BS%	0.51**	0.79***	0.86***	0.85***	0.84***	0.94***	0.96***
ECEC × BS%	0.92***						

^{NS} *, **, ***, refer to significance level for test-t: not significant, $P < 0.05$, $P < 0.01$ and $P < 0.001$, respectively.

The Pearson correlation coefficient between potential acidity and pH (in H₂O) within each treatment was high and very significant for all treatments (Table 3). This correlation for the NF although significant at the 5% level, does not reflect the interaction among potential acidity and SOC, and pH observed for the NT treatments. Low soil inherent fertility, high acidity and Al³⁺ concentration may be the reasons for high correlation between potential acidity and pH (Ernani et al., 2004).

The Pearson correlation coefficient between potential acidity and ECEC was positive for the NF treatment and negative for other treatments (Table 3). Such trends in correlation coefficient show that the conversion to cropland and adoption of NT for long time changes the charge sites with displacement of Al³⁺ and hydrogen (H⁺) by exchangeable bases, resulting in an increase in pH and negative charge.

The comparison of pH among NF, NT-22 and CT-22 treatments (Fig. 1) indicate response that long-term NT increased surface pH compared to the CT treatment. These results differ from those of Dick (1983) who observed that NT caused a significant decrease in surface soil pH compared with PT. Blevins et al. (1977) suggested that soil surface acidification in NT was primarily due to nitrification caused by high rate of nitrogen fertilization.

For Oxisols, in general, soil pH and base saturation decrease while the exchangeable Al³⁺ increases with increase in soil depth. Sidiras and Pavan (1985), researching on an Oxisol under long-term NT and PT systems, observed that soil pH (in H₂O) for 0–5 and 5–10 cm depths in NT was more than that in PT. This difference in soil pH was attributed to: (i) more favorable soil moisture in NT compared with PT and diluting acid concentration in the soil solution; and (ii) the slow mineralization rate of NT compared with PT releasing less carboxylic and phenolic groups. However, these causes do not adequately by explain changes in sub-soil layers, where the SOC concentration in NT is similar to or less than that of the PT.

Mineralization of crop residue on the soil surface in NT releases several organic compounds which bind with Al³⁺, thus stabilizing the soil pH. Oades et al. (1989) explained that the interaction between small organic molecules with variable charge clays occurred as a result of electrostatic forces, H-bonds and ligand exchange. The exchange reaction between organic anions, ligands, and OH⁻ charge points on Fe and Al oxides have been suggested as a major reason for the increase in pH by mineralization of crop residues. These arguments are supported by Franchini et al. (1999) for an Oxisol with high exchangeable Al³⁺ and low pH in Paraná State, Brazil. After 90 days of incubation with different crop residues the pH (in 0.01 M CaCl₂ and in H₂O) increased by 2.1–2.4 units with radish (*Raphanus sativus*), by 1.9–2.6 units with soybean and by 0.2–0.4 units for wheat. The

exchangeable Al³⁺ concentrations decreased in all residue management treatments.

Pierre and Banwart (1973) reported that some plants have a high concentration of basic cations in the biomass for maintaining electrical neutrality in the cell. Heylar (1991) observed that some legumes (i.e., *Leucena* spp.) contain high concentrations of organic anions of 100–150 cmol_c kg⁻¹ compared with only 5–10 cmol_c kg⁻¹ in wheat. Consequently, basic cations accumulate in these plants to form cation–anion pairs. Therefore, accumulation of a large amount of crop residues on the soil surface in NT systems results in an increase in concentration of bases. In the previous study (Sá et al., 2001; Sá and Lal, 2008) the total amount of crop residue returned was 91.5 Mg ha⁻¹ for NT-10 (i.e., 0.40 kg C m⁻² yr⁻¹), 177.3 Mg ha⁻¹ for NT-20 (i.e., 0.39 kg m⁻² yr⁻¹), and 167.4 Mg ha⁻¹ for NT-22 (i.e., 0.33 kg m⁻² yr⁻¹).

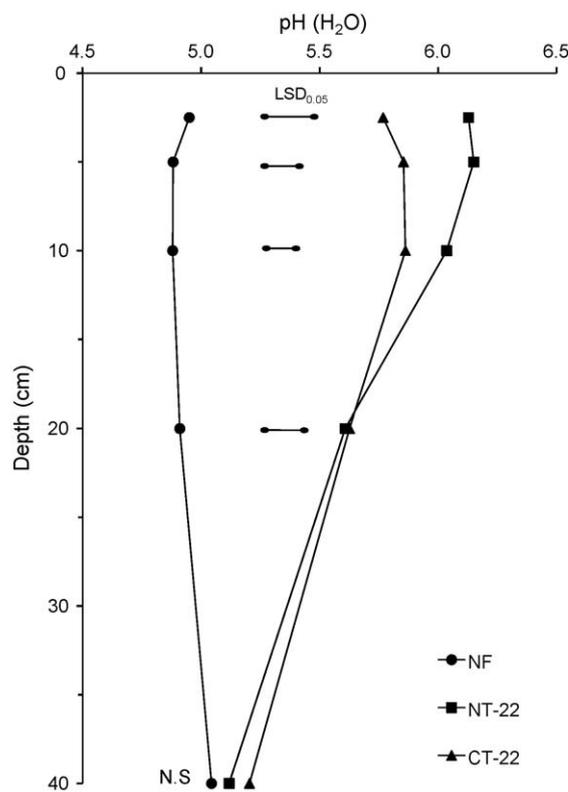


Fig. 1. Comparison of profile pH (H₂O) between native field (NF), no-tillage 22 years (NT-22) and conventional tillage 22 years (CT-22). The bracket shows the LSD_{0.05} compared by Tukey test.

3.2. ΔpH , CEC, ECEC and base saturation in the chronosequence as affected by soil organic carbon

Changes in SOC concentration in the tillage chronosequence increased the negative charge (as evaluated by the ΔpH). There was a significant difference ($P < 0.05$) in ΔpH of the surface layers (0–2.5, 2.5–5 cm depth) of all treatments in comparison with the NF treatment (Table 2). These results suggest the important role of crop residue in affecting ΔpH . The Pearson correlation coefficient between SOC and ΔpH , ECEC and ΔpH , base saturation and ΔpH , and ECEC and base saturation for all data and within each treatment, differed among treatments (Table 3). The low correlation coefficient between SOC concentration and ΔpH for the NF treatment indicates lack of any relationship between these variables. The net negative charge may be due to soil primary particles and the release of many carboxylic and phenolic acids from SOC at the steady state. The high correlation coefficient among ΔpH and ECEC, and ECEC and base saturation support this argument, and show that these properties are moderated by the acidity level.

Conversion of NF to cropland increases the SOC concentration without influencing the negative charge (see ΔpH values in Table 2). The increase in SOC concentration is attributed to liming during the 18 months (the PNF-1 treatment), as is shown by a high correlation coefficient between ECEC and the base saturation (Table 3).

Further, the value of Pearson correlation coefficient in SOC versus ΔpH , ΔpH versus ECEC (i.e., Σ of Ca^{2+} and Mg^{2+} and K^+ concentration), and ΔpH versus BS% (i.e., $\text{BS}\% = [100 \times (\text{Ca}^{2+} + \text{Mg}^{2+} + \text{K}^+)/\text{CEC}]$) increased with time of the age chronosequence (Table 3), indicating a close relationship between crop residues and these parameters, thereby releasing high amount of organic acids (Franchini et al., 1999). Also, the regression analyses showed significant positive relationship between SOC concentration and basis saturation ($\text{BS}\% = 1.44_{\text{SOC}} + 15.5$, $R^2 = 0.60$, $P < 0.05$).

Improvement in soil fertility stimulates the decomposition of new crop residues carrying high charge per unit of C, thereby increasing the CEC. The regression analyses showed high and significant positive relationship between SOC concentration and CEC (Fig. 2) thereby confirming that these two parameters are closely inter-related. As SOM accumulates in the long-term NT, there is an attendant increase in negative charge and CEC. The CEC increased at the rate of $0.37 \text{ cmol}_c \text{ kg}^{-1}$ every g of C kg^{-1} of soil. Our findings is in accord with the previous reports by Resck (1998) in a clayed Red Latosol ($0.42 \text{ cmol}_c \text{ kg}^{-1}$ every g of C kg^{-1} of soil) in Cerrado region (Brazil), and with reported by Burle et al. (1997) in Southern Brazil ($0.57 \text{ cmol}_c \text{ kg}^{-1}$ every g of C kg^{-1} of soil).

The ECEC:SOC ratio for different treatments also definite trends in comparison with using the NF as the base line. The ratio of ECEC:SOC was $0.23 \text{ cmol}_c \text{ kg}^{-1}$ for NF, $0.60 \text{ cmol}_c \text{ kg}^{-1}$ for NT-10, $0.58 \text{ cmol}_c \text{ kg}^{-1}$ for NT-20 and $0.49 \text{ cmol}_c \text{ kg}^{-1}$ for NT-22. The increase in ECEC for each g kg^{-1} of SOC compared to NF, was 2.64 times for NT-10, 2.54 times for NT-20 and 2.16 times more for NT-22. This drastic increase in ECEC was more than that reported by Burle et al. (1997), and Bayer and Bertol (1999) for Oxisols in Southern Brazil.

3.3. Phosphorus and potassium dynamics in a chronosequence as affected by soil organic carbon

Significant increases in P and K were observed in the long-term NT compared with NF and CT-22 treatments (Fig. 3a and b) for 0–2.5 and 2.5–5 cm depths. However, there was no significant difference in P concentration among any treatment for the 20–40 cm depth. The significantly higher concentration of resin-

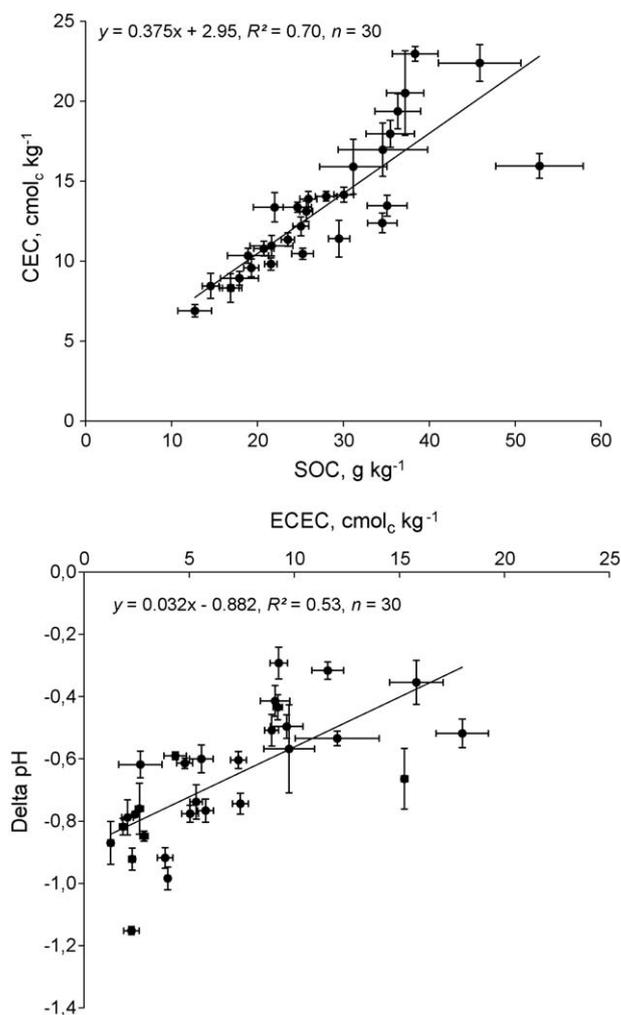


Fig. 2. Regression analyses between soil organic carbon (SOC) and cation exchange capacity (CEC) and Delta pH and effective cation exchange capacity (ECEC). The bars refer the standard deviation of the mean.

exchangeable P in the 0–2.5 cm depth for NT-22 treatment may be due to the application of the liquid cattle manure during the 2 years prior to soil sampling. Similarly, the NT treatments generally had higher K concentrations than in NF or CT-22 treatment.

Enhancement of P in PNF-1 may be due to application of lime and phosphate, resulting in the neutralization of exchangeable Al^{3+} , increase in pH and turnover of the freshly applied organic matter. Mineralization of SOM may be the main reason of increase in K in PNF-1. The P level in CT-22 was significantly different ($P < 0.01$) than those of NF and PNF-1 treatment for 0–2.5, 2.5–5.0 cm and 5.0–10 cm depths. The increase in P was caused by the fact that P released from the crop residues and the fertilizers exceeded the fixation capacity, and thus enhanced the available P level.

The increase in P in the surface layers of the NT plots was greater than those in PNF-1 and CT-22 treatments, and this trend can not be explained merely by the amount of fertilizers and manure applied. The higher P concentration in NT may be attributed to: and (i) the effect of SOC with negative charges maintaining freely available phosphate (Negassa et al., 2008); (ii) the enhancement of organic forms of P, and (iii) low contact of P with primary particles (clay, Fe and Al oxides) in a NT soil, which reduces P fixation. The increase in SOC for the NT treatments was strongly correlated with the available P and the Pearson correlation

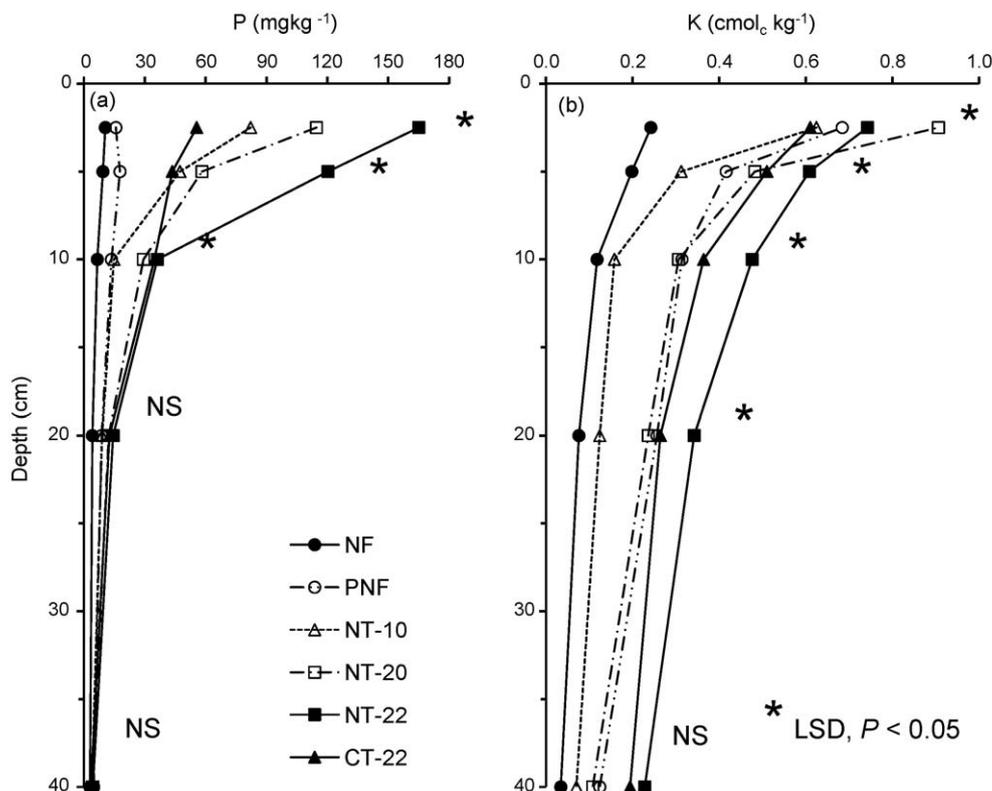


Fig. 3. Changes on profile available phosphorus (a) and exchangeable potassium (b) in the chronosequence. The * refers the comparison of the mean by Tukey test $P < 0.05$ among treatments within each depth.

coefficient supported these observation ($r = 0.95^{***}$, $r = 0.94^{***}$, $r = 0.97^{***}$, for NT-10, NT-20, and NT-22, respectively). The increase in organic P is often an overlooked factor, which enhances soil P availability. For a similar Oxisol from Paraná State, Brazil, Sá (1999) observed strong Pearson correlation coefficient between SOC and organic P ($r = 0.66^{***}$, $n = 25$), and SOC and available P ($r = 0.77^{***}$, $n = 25$), suggesting that organic P and available P are strongly linked.

Regression analyses between SOC and available P showed strong relationship for these parameters (Eq. (1)):

$$P (\text{mg kg}^{-1}) = 94.3 - 9.11(\text{SOC}) + 0.24(\text{SOC})^2 \quad (R^2 = 0.85^{***}) \quad (1)$$

Concentration of K in NT-22 was significantly greater ($P < 0.05$) than that in NF, PNF-1 and CT-22 treatments for all depths,

probably due to the impact of large amount of crop residues and long-term NT. In general, K concentration in the crop residues is 65–75% of the total K absorbed (Malavolta, 2006). Crop residue, therefore, is an important source of K for the next crop. Regression analyses between SOC and K concentration showed strong relationship as shown in Eq. (2):

$$K (\text{cmol}_c \text{ kg}^{-1}) = 0.018(\text{SOC}) - 0.183 \quad (R^2 = 0.69^{***}) \quad (2)$$

The rate of increase in concentration of P and K for each depth in the long-term NT treatments are presented in Table 4. Comparing the P and K budgets for the top 0–10 cm layer with NF as a base line, the rates of increase were $9.66 \text{ kg ha}^{-1} \text{ yr}^{-1}$ for P and $17.93 \text{ kg ha}^{-1} \text{ yr}^{-1}$ for K. The high rate of increase in K than that of P indicates that increase in SOC in the chronosequence increased CEC that leads to retention of K in soil.

Table 4

Regression equations between the age of chronosequence (years) and available phosphorus and potassium (i.e., kg ha^{-1}), determination coefficient (R^2), significant level and rates of changes in P^{\S} and K for each depth.

Nutrient	Depth (cm)	Equation	R^2	Significance level [‡]	Rate (dy/dx) ^{‡‡} ($\text{kg ha}^{-1} \text{ yr}^{-1}$)
Phosphorus	0–2.5	$P = -0.133\text{yr}^2 + 5.1\text{yr} + 2.4$	0.99	***	5.08
	2.5–5	$P = -0.115\text{yr}^2 + 3.57 + 3.33$	0.99	***	3.56
	5–10	$P = 1.018\text{yr} + 8.24$	0.89	***	1.02
Potassium	0–2.5	$K = -0.225\text{yr}^2 + 9.1\text{yr} + 58.1$	0.86	**	9.04
	2.5–5	$K = 3.99\text{yr} + 38.7$	0.79	**	3.99
	5–10	$K = 4.9\text{yr} + 42.2$	0.82	**	4.90

[‡] *, **, ***, refer to significant level for test-t at $P < 0.05$, $P < 0.01$, $P < 0.001$.

^{‡‡} The rate was obtained with (dy/dx) of the equation slope.

[§] P = phosphorus, kg ha^{-1} ; K = Potassium, kg ha^{-1} ; yr = year.

4. Conclusions

An increase in the SOC concentration in the chronosequence reduced the potential acidity, and increased soil pH and the negative charge as evaluated by ΔpH . The increase in ECEC was attributed to an increase in the negative charge, and was strongly correlated with the base saturation. In comparison with NF, the NT treatments increased the ECEC for each g kg^{-1} of SOC in 2.15–2.64 times. The strong relationship demonstrated by the regression equations for P and K indicated the impact of the SOC on these elements. These data support the conclusion that long-term NT is a useful tool to improve soil fertility in soils with variable charge.

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References

- Amado, T.J., Bayer, C., Conceição, P.C., Evandro, S., Campos, B.-H.C., Veiga, M., 2006. Potential of C accumulation in no-till soils with intensive use and cover crops in Brazil. *J. Environ. Qual.* 35, 1599–1607.
- Bayer, C., Bertol, I., 1999. Características químicas de um cambissolo húmico afetadas por sistemas de preparo, com ênfase à matéria orgânica. *R. Bras. Ci. Solo* 23, 687–694.
- Bayer, C., Martin-Neto, L., Mielniczuk, J., Pavinato, A., Dieckow, J., 2006. Carbon sequestration in two Brazilian Cerrado soils under no-till. *Soil Till. Res.* 86, 237–245.
- Blevins, R.L., Thomas, G.W., Cornelius, P.L., 1977. Influence of NT and nitrogen fertilization on certain soil properties after 5 years of continuous corn. *Agron. J.* 69, 383–386.
- Brye, K.R., Cordell, M.L., Longer, D.E., Gbur, E.E., 2006. Residue management practice effects on soil surface properties in a young wheat–soybean double-crop system. *J. Sust. Agric.* 29, 121–150.
- Buchanan, M., King, L.D., 1993. Carbon and phosphorus losses from decomposing crop residues in no-till and conventional till agroecosystems. *Agron. J.* 85, 631–638.
- Burle, M.L., Mielniczuk, J., Focchi, S., 1997. Effect of cropping systems on soil chemical characteristics with emphasis on soil acidification. *Plant Soil* 190, 309–316.
- Caires, E.F., Alleoni, L.R.F., Cambri, M.A., Barth, G., 2005. Surface application of lime for crop grain production under a no-till system. *Agron. J.* 97, 791–798.
- Cerri, C.E.P., Sparovek, G., Bernoux, M., Easterling, W.E., Melillo, J.M., Cerri, C.C., 2007. Tropical agriculture and global warming: impacts and mitigations options. *Sci. Agric.* 64, 83–99.
- Dick, W.A., 1983. Organic carbon, nitrogen and phosphorus concentrations and pH profiles as affected by tillage intensity. *Soil Sci. Soc. Am. J.* 47, 102–107.
- Elliot, E.T., 1986. Aggregate structure and carbon, nitrogen and phosphorus in native and cultivated soils. *Soil Sci. Soc. Am. J.* 50, 627–633.
- EMBRAPA-Empresa Brasileira de Pesquisa Agropecuária, SNLCS, 1979. Manual de métodos de análise do solo. Rio de Janeiro, RJ, 390 p.
- Ernani, P.R., Ribeiro, M.F.S., Bayer, C., 2004. Chemical modifications caused by liming below the limed layer in a predominantly variable charge acid soil. *Commun. Soil Sci. Plant Anal.* 35, 889–901.
- Fageria, N.K., 2008. Optimum soil acidity indices for dry bean plant production on an Oxisol in no-tillage system. *Commun. Soil Sci. Plant Anal.* 39, 845–857.
- Fontana, A., Pereira, M.G., Loss, A., Cunha, T.J.F., Salton, J.C., 2006. Atributos de fertilidade e frações húmicas de um Latossolo Vermelho no Cerrado. *Pesq. Agropec. Bras.* 41, 847–853.
- Fox, R.H., 1980. Soil with variable charge: agronomic and fertility aspects. In: Theng, B.K.G. (Ed.), *Soils with Variable Charge*. New Zealand Society of Soil Science, Lower Hutt, pp. 195–224.
- Franchini, J.C., Malavolta, E., Miyazawa, M., Pavan, M.A., 1999. Chemical changes in acid soils after application of plant residues. *R. Bras. Ci. Solo* 23, 533–542.
- Franzluebbers, A.J., 2002. Soil organic matter stratification ratio as an indicator of soil quality. *Soil Tillage Res.* 66, 95–106.
- Franzluebbers, A.J., Shomberg, H.H., Endale, D.M., 2007. Surface-soil responses to paraplowing of long-term no-tillage cropland in the Southern Piedmont USA. *Soil Tillage Res.* 96, 303–315.
- Fundação, A.B.C., 1998. Dados Climáticos. Castro-PR, Brazil.
- Gee, G.W., Bauder, J.W., 1986. Particle-size analyses. In: Klute, A. (Ed.), *Methods of Soil Analysis*. Part 1, vol. 9. 2nd ed. Agron, pp. 383–412.
- Havlin, J.L., Kissel, D.E., Maddus, L.E., Claassen, M.M., Long, J.H., 1990. Crop rotation and tillage effects on soil organic carbon and nitrogen. *Soil Sci. Soc. Am. J.* 54, 448–452.
- Heylar, K.R., 1991. The management of acid soils. In: Wright, R.J., Bagliar, V.C., Murrinan, R.P. (Eds.), *Plant and Soil Interactions at low pH*. Kluwer Academic Publishers, Dordrecht, pp. 365–382.
- Instituto Agronômico do Paraná-lapar, 1998. Dados climáticos. Área de Ecofisiologia. Instituto Agronômico do Paraná-lapar, Londrina-PR, Brazil.
- Jackson, M.L., 1966. *Soil Chemical Analysis—Advanced Course*, 2nd ed. Madison, Jackson, M.L, p. 894.
- Juo, A.S.R., Lal, R., 1979. Nutrient profile in tropical Alfisol under conventional and no-till systems. *Soil Sci.* 127, 168–173.
- Kamprath, E.J., 1977. Exchangeable aluminum as a criterion for liming leached mineral soils. *Soil Sci. Soc. Am. Proc.* 34, 252–254.
- Lal, R., 1976. No-tillage effects on soil properties under different crops in Western Nigeria. *Soil Sci. Soc. Am. J.* 40, 762–768.
- Lal, R., 1997. Long-term tillage and monoculture effects on a tropical Alfisol in Western Nigeria: II. Soil chemical properties. *Soil Tillage Res.* 42, 161–174.
- Lopes, A.S., Cox, F.R., 1977. A survey of the fertility status of surface soils under “Cerrado” vegetation in Brazil. *Soil Sci. Soc. Am. J.* 41, 742–747.
- Lynch, J.M., 1984. Interactions between biological process, cultivation and soil structure. *Plant Soil* 76, 307–318.
- Maack, R., 1981. Classificação do clima do Estado do Paraná. In: *Livraria José Olímpio Editora, S.A. (Ed.)*, *Geografia Física do Paraná*. 2 ed. Rio de Janeiro, pp. 175–189.
- Malavolta, E., 2006. *Manual de nutrição mineral de plantas*. Ceres, Piracicaba, Brazil, p. 638.
- Mekaku, T., Uehara, G., 1972. Anion adsorption in ferruginous tropical soils. *Soil Sci. Soc. Am. Proc.* 36, 296–300.
- Muzilli, O., 1983. Influência do sistema de plantio direto, comparado ao convencional sobre a fertilidade da camada arável do solo. *R. Bras. Ci. Solo* 7, 95–102.
- Negassa, W., Dultz, S., Schlichting, A., Leinweber, P., 2008. Influence of specific organic compounds on phosphorus sorption and distribution in a tropical soil. *Soil Sci.* 173, 587–601.
- Nelson, D.W., Sommers, L.E., 1982. Total carbon, organic carbon and organic matter. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), *Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties*, 9. Agron, pp. 539–579.
- Oades, J.M., 1984. Soil organic matter and structural stability: mechanisms and implications for management. *Plant Soil* 76, 319–337.
- Oades, J.M., Gillman, G.P., Uehara, G., Hue, N.V., van Noordwijk, M., Robertson, G.P., Wada, K., 1989. Interactions of soil organic matter and variable-charges clays. In: Coleman, D.C., Oades, J.M., Uehara, G. (Eds.), *Dynamics of Soil Organic Matter in Tropical Ecosystems*. University of Hawaii at Manoa, Nifital project, pp. 69–95.
- Pavan, M.A., Bingham, F.T., Pratt, P.F., 1985. Chemical and mineralogical characteristics of selected acid soils of the State of Paraná, Brazil. *Turrialba* 35, 131–139.
- Pierre, W.H., Banwart, W.L., 1973. Excess-base and excess-base/nitrogen ratio of various crop species and plant parts. *Agron. J.* 65, 91–96.
- Potter, K.N., Torbert, H.A., Jones, O.R., Matocha, J.E., Morrison Jr., J.E.P.W.U., 1998. Distribution and amount of soil organic C in long-term management systems in Texas. *Soil Tillage Res.* 47, 309–321.
- Raij, B.Van., 1969. Capotential acidityidade de troca de cations de frações orgânicas e minerais de solos. *Bragantia* 28, 85–112.
- Raij, B.Van., Quaggio, J.A., 1983. Métodos de análises de solo para fins de fertilidade. Instituto Agronômico, Campinas, p. 31.
- Resck, D.V.S., 1998. Agricultural intensification systems and their imponential acidity on soil and water quality in the Cerrados of Brazil. In: Lal, R. (Ed.), *Soil Quality and Agricultural Sustainability*. Ann Arbor Press, Chelsea, MI, pp. 288–300.
- Sá, J.C.M., 1999. Manejo da fertilidade do solo no sistema plantio direto. In: Siqueira, J.O., Moreira, F.M.S., Lopes, A.S., Guilherme, L.R.G., Faquin, V., Furtini Neto, A.E., Carvalho, J.G. (Eds.), *Soil Fertility, Soil Biology, and Plant Nutrition Interrelationships*. Soc. Bras. Ci. Solo. UFLA, Lavras, MG, Brazil, pp. 267–320.
- Sá, J.C.M., Lal, R., 2008. Stratification ratio of soil organic matter pools as an indicator of carbon sequestration in a tillage chronosequence on a Brazilian Oxisol. *Soil Tillage Res.* DOI 10.1016/j.still.2008.09.003 (on line).
- Sá, J.C.M., Cerri, C.C., Dick, W.A., Lal, R., Vesnke-Filho, S.P., Piccolo, M.C., Feigl, B.E., 2001. Organic matter dynamics and carbon sequestration rates for a tillage chronosequence in a Brazilian Oxisol. *Soil Sci. Soc. Am. J.* 65, 1486–1499.
- Sanchez, P.A., 1976. Clay mineralogy and ion exchange process. In: *Properties and Management of Soils in the Tropics*, A Wiley-Interscience Publication, New York, pp. 135–161.
- Sas Institute, 1990. *SAS/STAT User's Guide*. Statistics. Version 6, 4 ed. SAS Inst., Cary, NC.
- Séguy, L., Bouzinac, S., Husson, O., 2006. Direct-Seeded tropical soil systems with permanent soil cover: learning from Brazilian experience. In: Uphoff, N., et al. (Eds.), *Biological Approaches to Sustainable Soil Systems*. Taylor and Francis Group, CRC Press Publ., Boca Raton, FL, pp. 323–342.
- Shear, G.M., Moschler, W.W., 1969. Continuous corn by the no-tillage an conventional tillage methods: a six year comparison. *Agron. J.* 61, 524–526.
- Sidiras, N., Pavan, M.A., 1985. Influencia do sistema de manejo no seu nível de fertilidade. *Rev. Bras. Ci. Solo* 9, 249–254.
- Silva, J.E., Lemanski, J., Resck, D.V.S., 1994. Perdas de matéria orgânica e suas relações com a capotential acidityidade de troca catiônica em solos da região de cerrados do oeste baiano. *R. Bras. Ci. Solo* 18, 541–547.

- Triplett Jr., G.B., Van Jr., Doren, 1969. Nitrogen, phosphorus, and potassium fertilization on no-tillage maize. *Agron. J.* 61, 637–639.
- Uehara, G., 1995. Management of isoelectric soils of humid tropics. In: Lal, R., Kimble, J., Levine, E., Stewart, B.A. (Eds.), *Soil Management and Greenhouse Effect*. CRC/Lewis Publishers, Boca Raton, FL, pp. 271–278.
- Uehara, G., Keng, J., 1975. Management implications of soil mineralogy in Latin America. In: Bornemiza, E., Alvarado, A. (Eds.), *Soil Management in Tropical America*. North Carolina State University, Raleigh, pp. 351–362.
- Whitbread, A., Blair, G., Konboon, Y., Lefroy, R., Naklang, K., 2003. Managing crop residues, fertilizers and leaf litters to improve soil C, nutrient balances, and the grain yield of rice and wheat cropping systems in Thailand and Australia. *Agric. Ecosyst. Environ.* 100, 251–263.