SHORT AND LONG-TERM EFFECTS OF TILLAGE SYSTEMS AND NUTRIENT SOURCES ON SOIL PHYSICAL PROPERTIES OF A SOUTHERN BRAZILIAN HAPLUDOX[1]

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SUMMARY

Soil tillage promotes changes in soil structure. The magnitude of the changes varies with the nature of the soil, tillage system and soil water content and decreases over time after tillage. The objective of this study was to evaluate short-term (one year period) and long-term (nine year period) effects of soil tillage and nutrient sources on some physical properties of a very clayey Hapludox. Five tillage systems were evaluated: no-till (NT), chisel plow + one secondary disking (CP), primary + two (secondary) diskings (CT), CT with burning of crop residues (CTb), and CT with removal of crop residues from the field (CTr), in combination with five nutrient sources: control without nutrient application (C); mineral fertilizers, according to technical recommendations for each crop (MF); 5 Mg ha^{-1} yr^{-1} of poultry litter (wetmatter) (PL); 60 m^3 ha^{-1} yr^{-1} of cattle slurry (CS) and; 40 m^3 ha^{-1} yr^{-1} of swine slurry (SS). Bulk density (BD), total porosity (TP), and parameters related to the water retention curve (macroporosity, mesoporosity and microporosity) were determined after nine years and at five sampling dates during the tenth year of the experiment. Soil physical properties were tillage and time-dependent. Tilled treatments increased total porosity and macroporosity, and reduced bulk density in the surface layer (0.00–0.05 m), but this effect decreased over time after tillage operations due to natural soil reconsolidation, since no external stress was applied in this period. Changes in pore size distribution were more pronounced in larger and medium pore diameter classes. The bulk density was greatest in intermediate layers in all tillage treatments (0.05–0.10 and 0.12–0.17 m) and decreased down to

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the deepest layer (0.27–0.32 m), indicating a more compacted layer around 0.05–0.20 m. Nutrient sources did not significantly affect soil physical and hydraulic properties studied.

Index terms: bulk density, pore size distribution, manure.

RESUMO: *PROPRIEDADES FÍSICAS DE UM NITOSSOLO VERMELHO APÓS CURTO E LONGO PRAZO DE APLICAÇÃO DE SISTEMAS DE PREPARO E DE FONTES DE NUTRIENTES*

O preparo do solo promove alterações na sua estrutura. A magnitude das mudanças varia com a natureza do solo, o método de preparo e o teor de água no solo e reduz com o tempo após a operação. O objetivo deste estudo foi avaliar efeitos de curto (período de um ano) e longo prazo (após nove anos) da aplicação de tratamentos de preparo do solo e de fontes de nutrientes sobre algumas propriedades físicas em um Nitossolo muito argiloso. Os sistemas de preparo estudados foram plantio direto (NT), preparo com escarificador + uma gradagem (CP), preparo com uma aração + duas gradagens (CT), CT com os resíduos queimados (CTb) e CT com os resíduos retirados (CTr). Esses sistemas foram associados com cinco fontes de nutrientes: testemunha, sem aplicação de nutrientes (T); adubação mineral, de acordo com a recomendação para cada cultura (MF); 5 Mg ha^{-1} ano^{-1} de matéria úmida de cama de aviário (PL); 60 m^3 ha^{-1} ano^{-1} de dejeto líquido de bovinos (CM); e 40 m^3 ha^{-1} ano^{-1} de dejeto líquido de suínos (SM). Densidade do solo (BD), porosidade total (TP) e parâmetros derivados da curva de retenção de água (macroporosidade, porosidade de armazenamento e porosidade residual) foram determinados depois de 9 anos e em cinco épocas de amostragem durante o décimo ano de experimentação. Propriedades físicas e hidráulicas do solo foram dependentes do preparo e da época de amostragem. O preparo aumentou a porosidade total e a macroporosidade e reduziu a densidade do solo na camada superficial (0,00–0,05 m), porém esse efeito diminuiu com o tempo após as operações de preparo, devido à reconsolidação natural do solo, uma vez que nenhum estresse externo foi aplicado nesse período. Alterações na porosidade do solo foram mais pronunciadas nas classes de macro e mesoporos. Todos os tratamentos de preparo apresentaram maior densidade do solo nas camadas intermediárias (0,05–0,10 e 0,12–0,17 m) e reduziram na camada mais profunda (0,27–0,32 m), indicando a presença de uma camada com maior estado de compactação entre aproximadamente 0,05 e 0,20 m de profundidade. As fontes de nutrientes não afetaram significativamente as propriedades físicas estudadas.

Termos de indexação: densidade do solo, distribuição de tamanho de poros, dejetos animais.

INTRODUCTION

Soil physical properties which directly affect plant growth and yield (e.g. temperature, mechanical resistance, water and oxygen availability) are determined by internal soil properties, conditions above soil surface, as well as by the soil-crop-atmosphere relationship (Forsythe, 1967). Of the four factors, water is the dominant controlling factor and the other three are affected by water content (Letey, 1985). The same author pointed out that soil texture, bulk density, pore size distribution, clay content as well as mineralogy, hydraulic conductivity, thermal conductivity, air permeability, and penetration resistance are related to physical growth factors, and most of them are influenced by soil management and tillage.

Soil tillage is the major agricultural practice affecting soil physical properties because it promotes changes in soil structure and porosity, which in turn affect soil hydraulic properties and the processes of water infiltration, runoff and storage, soil temperature, and chemical transport (Ahuja et al., 1998). According to these authors, soil tillage generally decreases soil bulk density and increases soil porosity by loosening the soil. These changes are greater after the primary tillage (e.g. moldboard or chisel plow), but moderate after secondary tillage (e.g. disking). The magnitude of the changes varies with the soil type, tillage method, and soil water content. The changes in these properties are not permanent and tend to revert asymptotically over time to values close to those of soil before tillage, due to natural reconsolidation during wetting and drying cycles, to slaking and dispersion of soil aggregates enhanced by the raindrop impact on the soil surface, and to external stress application through traffic and/or trampling (Ahuja et al., 1988).

In general, no-till topsoil layer has significant greater bulk density (Fernandes et al., 1983; Derpsch et al., 1991; Hubbard et al., 1994; Stone & Silveira, 2001; Bertol et al., 2004), lower saturated hydraulic conductivity (Hubbard et al., 1994), and greater water storage than the same layer in minimum and conventional tillage treatments (Sidiras et al., 1983; Bragagnolo & Mielniczuk, 1990; Salton & Mielniczuk, 1995). The arrangement of soil particles in the bulk soil must be such that at least 10 per cent of the soil volume is contained in pores of over 50 μm (fissures and transmission pores, e.g. macropores), to allow excess water to drain freely through the soil profile. These pores must also run from the surface to a depth far enough below the surface to allow adequate root growth in an aerobic environment (Greenland, 1979). According to this author, it is desirable also that at least 10 per cent of the soil volume is filled with pores which store water usable by plant, of the order of 0.5 to 50 μm equivalent pore diameter (storage pores). Pores with diameter ≤ 0.5 μm, called residual plus bonding pores, are filled with water in a tension range not easily available to crops that are mainly related to intrinsic soil properties (e.g. clay content, type of clay mineral and stable organic matter content). A pore diameter of ≤ 0.2 μm was defined as the class of residual pores, that are filled with water at the permanent wilting point (1.5 MPa tension).

The changes in pore size distribution due to tillage can be determined using the soil-water content-suction relationship, known as soil water retention curve. Based on the literature and empirical analysis of the available data on soil water retention curve, Ahuja et al. (1998) pointed out that: (a) under field conditions tillage did not significantly change the air-entry value of the soil tension; (b) tillage increased the absolute slope value of the log-log relationship bellow the air-entry value; and (c) the changes due to tillage in the retention curve occurred only in the large pore-size range, approximately between the tension of air-entry and 10 times this value. The pore size distribution is reflected in the shape of log-normal soil-water content-tension curve; the higher the volume of larger pores, the greater is the slope of the water retention curves below air-entry value. According to Dexter (2004), the slope of the water retention curve at the inflection point can be used as an index of soil physical quality (called S index) which is intended to be easily and unambiguously measurable using standard laboratory equipments. The value of S is indicative of the extent to which the soil porosity is concentrated into a narrow range of pore sizes and, in most soils, larger values of S are consistent with the presence of a better-defined structural porosity.

Several studies were carried out to determine soil tillage effect on physical and hydrological properties, but most of them showed only basic attributes (bulk density, total porosity, macro and microporosity) at a given sampling time. The objective of this study was to determine some physical attributes after 9 years (long-term effect) of applying soil tillage and nutrient source treatments, as well as the seasonal changes during a 12 month period (short-term effect).

MATERIAL AND METHODS

This study was conducted using samples collected in a field experiment, performed nine years prior to this analysis, at the Epagri Experimental Station of Campos Novos, Santa Catarina, Brazil (27 ° 24 ' S, 51 ° 13 ' W, 970 m.a.s.l.), on a Typic Hapludox, a Nitossolo Vermelho in Brazilian classification (Embrapa, 2005), with 705 g kg^{-1} clay, 32 g kg^{-1} organic matter, and 92 % base saturation in the Ap horizon. Before the experiment installation, the field had been used for crop production for over twenty years under conventional tillage system (e.g. primary disking plow plus two secondary diskings).

The main treatments were a combination of residue management and soil tillage, namely: no-till (NT); chisel plow + 1 secondary disking (CP); primary + 2 secondary diskings (CT); CT with burned crop residues (CTb) and; CT with crop residue removal from the field (CTr). The chiseling and primary disking mobilized the soil down to, respectively, a depth of 0.25 and 0.15 m. A direct drilling machine was used to sow the cover crops in autumn and the cash crops in spring. A tractor with approximately 4.0 Mg and four-wheel drive was used to perform the primary tillage operations (e.g. primary disking and chisel plow) and a tractor with approximately 2.9 Mg and two–wheel drive was used to perform the secondary tillage operations (e.g. secondary disking) and sowing. Only soybean was harvested with a combine harvester (mass of about 10 Mg).

Nutrient source treatments consisted of: control, without nutrient application (C); mineral fertilizers according to technical recommendations for each crop (CFSRS/SC, 1995) (MF); 5 Mg ha^{-1} yr^{-1} poultry "litter" (PL); 60 m^3 ha^{-1} yr^{-1} cattle slurry (CS) and; 40 m^3 ha^{-1} yr^{-1} swine slurry (SS). The tillage treatments were established annually, in 6 m wide and 30 m long stripes transversely to the slope, before sowing of the spring/summer cash crops. Nutrient source treatments were applied before secondary disking, in bands 6 m wide and 30 m long, transversely to soil tillage systems (slope direction), within each block, in a 5 x 5 factorial design, with 25 treatment combinations and three replications, applied in subdivided random blocks.

Undisturbed soil cores were sampled in all plots at the end of the ninth year, six months after applying the last tillage (in the layers 0.00–0.05, 0.05–0.10, 0.12–0.17, and 0.27–0.32 m), using stainless steel rings (0.05 m high, diameter of 0.062 m). Cores were also sampled in the layers 0.025–0.075 and 0.125–0.175 m before tillage operations, and 1, 60, 120, and 240 days after sowing during the tenth year of the experiment, with mineral fertilizer combinations with all tillage systems. Cores were sampled in crop interrows, avoiding areas with recent machinery traffic.

Bulk density (BD) was determined by the relation between soil dry-mass and total core volume, and parameters related to soil porosity were determined in undisturbed and disturbed samples, based on the soil water retention curve.

The water retention curves for low tension were derived from undisturbed samples. Soil cores were prepared by removing soil excess on either end, fixing filter paper with rubber bands on the bottom and saturated overnight by capillarity. After saturation, soil cores were submitted consecutively to tensions of 0.2, 0.7, 1.2, 2.2, 6 and 10 kPa, respectively for 6, 12, 24, 24, 48 and 48 h on a tension table. The core mass plus filter paper and rubber band were measured after saturation and tensions. Water retention at tensions of 100, 300 and 1.500 kPa was determined with Richards´ apparatus, using disturbed air-dried soil samples and passed through a sieve with 2 mm mesh. The gravimetric moisture values determined at these tensions were multiplied by respective bulk density to compute volumetric moisture.

Total porosity (TP) and microporosity (pores < 0.2 μm diameter) values were derived directly from the water retention curve and correspond, respectively, to volumetric water content at saturation and at a tension of 1.500 kPa. Macroporosity (pores > 50 μm diameter) and mesoporosity (pores 50–0.2 μm diameter, responsible for water storage at a tension range readily available to crops) correspond, respectively, to the difference in volumetric water content between TP and 6 kPa, and between 6 and 1.500 kPa. The equivalent pore diameters were determined according to the capillary theory and calculated by the equation:

$$D = (4\ \sigma \cos \phi)/\psi \qquad (1.2)$$

where D represents the equivalent pore diameter (μm), σ the surface tension of water (72.7 kPa at 20 °C), ϕ the contact angle between liquid and solid (= 0º for soil-water contact), and ψ the tension (kPa).

The van Genuchten equation (van Genuchten, 1980) was adjusted to the mean values of volumetric water content and respective tension for each layer within each treatment, using RETC software (U.S. Salinity Laboratory, 1999):

$$\Theta = \Theta_r + \frac{(\Theta_s - \Theta_r)}{[1 + (\alpha\psi)^n]^m} \qquad (1)$$

where Θ represents the volumetric water content at a given tension ($m^3\ m^{-3}$), Θ_r the residual volumetric water content ($m^3\ m^{-3}$), Θ_s the saturated volumetric water content ($m^3\ m^{-3}$), ψ the tension (kPa), and α, n and m the coefficients.

ANOVA test was run for quantifying variances among tillage systems, nutrient sources, layers, sampling dates, and interactions among them. Mean differences were compared using the Tukey test ($p < 0.05$).

RESULTS AND DISCUSSION

Long-term effect

The analysis of variance showed statistical differences for soil layer and interaction between layer and soil tillage with regard to all soil physical parameters at the end of the ninth year of soil tillage and nutrient treatments. There were no differences among soil tillage, nutrient sources, and interaction between nutrient sources and soil tillage or layer. The coefficient of variation was below 10 % for most parameters, except for macroporosity, which is affected by the higher variability usually found in larger pores (Souza et al., 2001). In view of the interaction between layers and soil tillage, the Tukey test was performed comparing means for soil tillage within each layer on the one and comparing means for soil layer within each soil tillage system on the other hand (Table 1).

Statistical significance in bulk density among tillage systems was observed only in the 0.12–0.17 m layer (Table 1); the effect of soil tillage on this parameter was small at the end of the ninth year. In this layer, no-till (NT) and chisel plow (CP) treatments resulted in lower bulk density then conventional tillage treatments. The small differences among tillage treatments in the upper layers (0.00–0.05 and 0.05–0.10 m) are probably due to the time after tillage (wetting and drying cycles) and soil disturbance caused by the direct drilling machine used to sow the winter cover crops 15 days before soil sampling, which loosens the soil. The double disk system of the direct drilling machine penetrated the soil down to a depth of 0.07–0.08 m and, although sampling was performed in the interrow area, the distance between two rows (0.17 m) was too small to avoid soil disturbance, particularly in the surface layer (0.00–0.05 m). These results are in disagreement with most previous studies (Fernandes at al., 1983; Derpsch et al., 1991; Hubbard et al., 1994; Stone & Silveira, 2001; Bertol et al., 2004), whereas similar results were found by Vieira & Klein (2007), Abreu et al. (2003) and Albuquerque et al. (1995), and can be explained by the seasonal variability of bulk density, once soil cores were sampled six months after tillage treatments. In samples collected one year later in the same experiment, although before cover crop seeding, Veiga et al. (2007) found greater bulk density in NT than in CP and CT at depths of 0.05 and 0.15 m. However, these authors stated that this higher compaction was not restrictive to root growth, as indicated by values of penetration resistance.

The greatest bulk density was observed in the 0.05–0.10 m layer in all soil tillage systems, followed by 0.12–0.17 m (Table 1). Bulk density was lower in the top (0.00–0.05 m) and lowest (0.27–0.32 m) layers, and similar in both. Thus, the layer with highest compaction was observed at the same depth and similar magnitude in all soil tillage treatments at that sampling time. The bulk density values in this layer are close to limiting values for root growth and water/gas flux through the soil, based on the relation between restrictive bulk density and clay content found by Reinert et al. (2006). Considering soil tillage systems, total porosity showed the same trend as bulk density. In the 0.12–0.17 m layer, total porosity was highest in CP and NT systems.

Differences in macroporosity were found after nine years of applying tillage treatments in the 0.12–0.17 m layer, where macroporosity was lowest for CT treatments (Table 1). For each treatment, differences were only observed in the upper layer, compared to the others. Macroporosiy was lower than 0.10 $m^3 m^{-3}$ in the 0.05–0.10 m and 0.27–0.32 m layers in NT and CP treatments, and below 0.05 m in conventional tillage (CT) treatments, with restrictive values to internal water and gas flux (Greenland, 1979). The smaller volume of larger pores at 0.12–0.17 m under conventional tillage as compared to no-till and chisel plow is due to the plow pan layer, with greater bulk density and smaller porosity.

Differences in mesoporosity (pores 50–0.2 μm diameter) were observed in the first and third layers sampled after nine years of tillage system application, with highest value in NT in the 0.00–0.05 m layer and in CTr in 0.12–0.17 m. The values of mesoporosity were higher than 0.10 $m^3 m^{-3}$ in all tillage systems, considered by Greenland (1979) as desirable for water storage and supply, once this pore class is related to water retention in a tension range available to the crops. At that sampling date, water storage capacity in NT treatment was greater considering all sampled layers. The increasing mesoporosity down to the profile in tilled treatments can not be explained by changes in bulk density, but rather by different standards of pore size distribution (Figure 1). Microporosity (pores < 0.2 μm diameter plus water films) on the other hand, was closely related to bulk

Table 1. Physical properties determined in four layers after nine years of applying five soil tillage systems (averaged across five nutrient sources)

Layer	Soil tillage system				
	NT	CP	CT	CTb	CTr
m	Bulk density– BD (Mg m^{-3})				
0.00–0.05	1.10 aB	1.09 aB	1.03 aB	1.07 aB	1.08 aB
0.05–0.10	1.28 aA	1.27 aA	1.30 aA	1.27 aA	1.29 aA
0.12–0.17	1.19 bAB	1.20 bAB	1.26 aA	1.24 abA	1.23 abA
0.27–0.32	1.11 aB	1.11 aB	1.10 aAB	1.09 aB	1.10 aB
	Total porosity– TP ($m^3 m^{-3}$)				
0.00–0.05	0.601 aA	0.589 aA	0.610 aA	0.585 aA	0.586 aA
0.05–0.10	0.527 aB	0.541 aA	0.528 aB	0.535 aB	0.526 aB
0.12–0.17	0.560 abAB	0.575 aA	0.542 bB	0.538 bB	0.554 abAB
0.27–0.32	0.540 aB	0.550 aA	0.544 aAB	0.549 aB	0.544 aAB
	Macroporosity – Mac ($m^3 m^{-3}$)				
0.00–0.05	0.149 aA	0.186 aA	0.225 aA	0.203 aA	0.198 aA
0.05–0.10	0.075 aB	0.068 aB	0.054 aB	0.063 aB	0.057 aB
0.12–0.17	0.104 abAB	0.124 aAB	0.069 bcB	0.055 cB	0.064 bcB
0.27–0.32	0.074 aB	0.071 aB	0.074 aB	0.079 aB	0.069 aB
	Mesoporosity – Mes ($m^3 m^{-3}$)				
0.00–0.05	0.209 aA	0.163 bA	0.160 bA	0.143 bB	0.147 bB
0.05–0.10	0.164 aA	0.183 aA	0.178 aA	0.179 aAB	0.174 aAB
0.12–0.17	0.166 bA	0.157 bA	0.165 bA	0.172 abAB	0.186 aAB
0.27–0.32	0.201 aA	0.207 aA	0.200 aA	0.198 aA	0.204 aA
	Microporosity– Mic ($m^3 m^{-3}$)				
0.00–0.05	0.243 aB	0.239 aC	0.239 aC	0.239 aC	0.241 aC
0.05–0.10	0.287 aA	0.290 aAB	0.294 aAB	0.294 aAB	0.295 aAB
0.12–0.17	0.290 aA	0.294 aA	0.312 aA	0.312 aA	0.304 aA
0.27–0.32	0. 265 aAB	0.272 aB	0.272 aB	0.272 aB	0.271 aBC

NT: no-till; CP: chisel plow; CT: conventional tillage; CTb: CT with burned crop residues; and CTr: CT with removal of crop residues. Means followed by the same lower case letter in a given row and capital letter in a given column are not statistically different (Tukey, $p < 0.05$).

density, (with a correlation coefficient of 0.84***), because of the degree of packing of the soil particles.

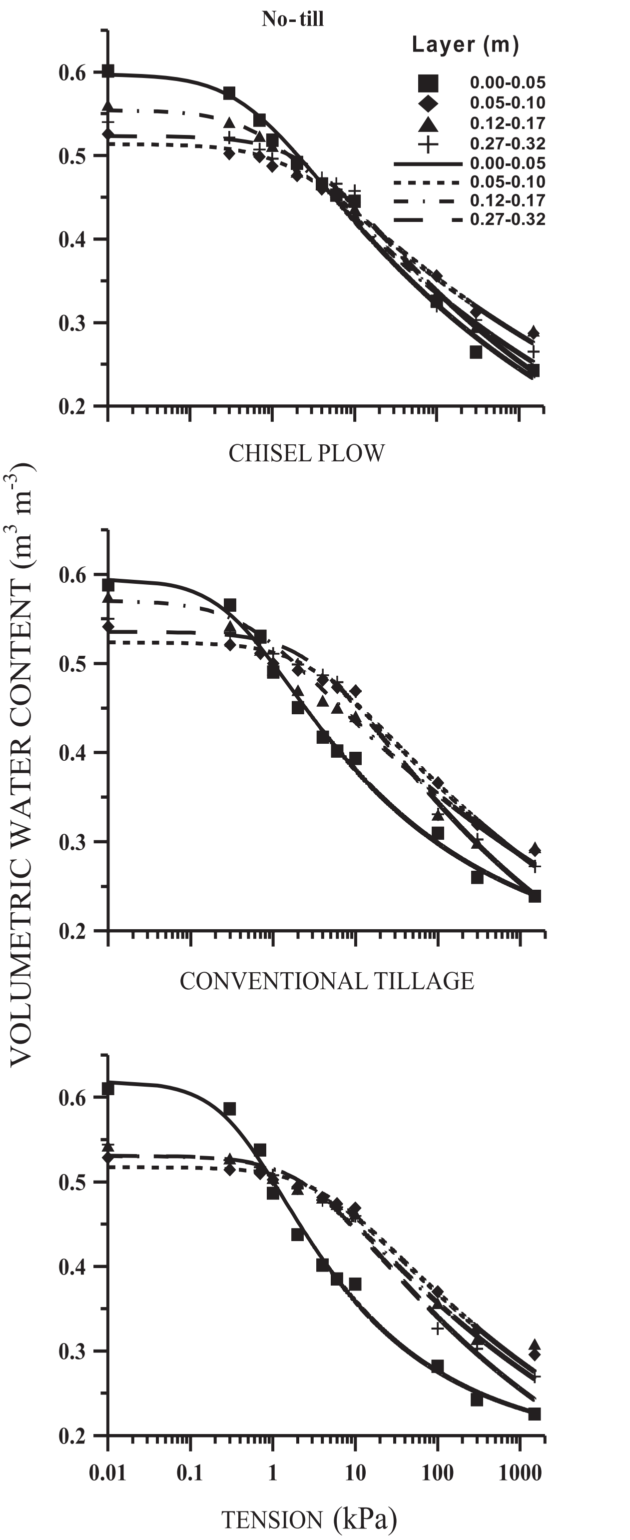

Figure 1. Soil water retention curves in four layers, after nine years of no-till, chisel plow and conventional tillage systems (averaged across nutrient sources).

Measured points of water retention curves and van Genuchten adjustments for three soil tillage systems and four layers are shown in figure 1. Air-entry values were lowest in the 0.00–0.05 m and highest in the 0.05–0.10 m layer because of higher macropore volume in the former and lower in the latter layer. The pore size distribution in the four layers in NT and CP followed the same trend/pathern. In CT the differentiation in the pore size distribution in the surface layer was higher than in the others. In tilled treatments, water retention in the upper layer was greater than in deeper layers until 1 kPa tension, while in NT it happened from around 5 kPa.

At a tension of 10 kPa, water storage in the upper layer was around 0.10, 0.07 and 0.02 m^3 m^{-3} lower than in the deeper layers, respectively, in the CT, CP and NT systems. This suggests that, the looser the soil, the lower is the water holding capacity in a tension range available to crops.

Short-term effect

Statistical significance was found for all soil parameters among sampling dates, soil tillage, soil layer, interaction between soil tillage and layer, and, for some parameters, interaction between layer and sampling dates. In order to use uniform criteria, the Tukey test was performed for all parameters comparing soil tillage and sampling dates within each layer (Tables 2 and 3).

A trend of bulk density increase was observed between sowing and the time immediately before plowing in both layers, mainly because of the reduced total porosity in tilled treatments (Table 2). This change was due to natural soil settlement caused by wetting and drying cycles and surface breakdown of soil aggregates promoted by raindrop impact on soil surface without protection (Ahuja et al., 1998), even without external stress application during the sampling period. Considering the five sampling dates (Table 3), bulk density in the upper layer was higher in the no-till than in the other tillage systems (0.025–0.075 m), as found in other studies when samples were collected only once in different tillage systems (Fernandes at al., 1983; Derpsch et al., 1991; Hubbard et al., 1994; Stone & Silveira, 2001; Bertol et al., 2004).

Pore size distribution changed seasonally, mainly in the upper layer (Table 2 and Figure 2). Differences among tillage systems in total porosity were only observed immediately after sowing and were highest in CP, intermediate in CT and lowest in the NT system. In the 0.025–0.075 m layer, considering the five sampling dates, total porosity was lowest in the no-till system. Total porosity decreased significantly from the first to the last sampling dates in both layers, following the asymptotic trend to reach the same porosity as before tillage, as described by Ahuja et al. (1998). It means that no long-term effect of soil tillage operations in loosening up the soil is expected, even if

Table 2. Physical properties determined in two layers at five sampling dates in the tenth year (averaged across tillage systems)

Layer(cm) and Sampling date (DAS)	Physical properties				
	BD	TP	Mac	Mes	Mic
0.025–0.075 m	Mg m^{-3}		m^3 m^{-3}		
1	1.05 BC	0.661 A	0.202 A	0.225 A	0.234 B
60	1.00 C	0.601 B	0.231 A	0.149 B	0.221 B
120	1.04 BC	0.579 B	0.220 A	0.127 C	0.232 B
240	1.09 B	0.590 B	0.185 A	0.164 B	0.241 B
360	1.18 A	0.534 C	0.120 B	0.152 B	0.263 A
0.125–0.175 m					
1	1.15 B	0.608 A	0.119 AB	0.205 A	0.284 B
60	1.18 B	0.555 B	0.127 AB	0.038 C	0.290 B
120	1.17 B	0.550 B	0.140 A	0.123 C D	0.288 B
240	1.20 B	0.562 B	0.087 B	0.180 B	0.296 B
360	1.30 A	0.512 C	0.083 B	0.119 B	0.318 A
CV (%)	6.9	5.2	33.3	6.9	7.3

DAS: days after sowing; BD: bulk density; TP: total porosity; Mac: macroporosity; Mes: mesoporosity; Mic: microposority. Means followed by the same letters in a given column for each layer are not statistically different (Tukey, $p < 0.05$).

Table 3. Physical and hydraulic properties determined in two layers of five tillage systems (averaged across sampling dates in the tenth year)

Layer(cm) and tillage system	Physical properties				
	BD	TP	Mac	Mes	Mic
0.025–0.075 m	Mg m^{-3}		m^3 m^{-3}		
No-till	1.16 A	0.568 B	0.123 B	0.188 A	0.256 A
Chisel plow	1.02 B	0.602 A	0.215 A	0.164 B	0.224 AB
Conventional tillage	1.08 AB	0.592 AB	0.191 A	0.162 B	0.239 AB
CT + residue burned	1.03 B	0.601 A	0.226 A	0.142 B	0.233 B
CT + residue removed	1.07 B	0.593 AB	0.205 A	0.150 B	0.238 B
0.125–0.175 m					
No-till	1.21 A	0.554 A	0.117 A	0.147 AB	0.291 A
Chisel plow	1.19 A	0.568 A	0.133 A	0.139 B	0.296 A
Conventional tillage	1.22 A	0.551 A	0.101 A	0.150 AB	0.300 A
CT + residue burned	1.18 A	0.555 A	0.110 A	0.153 AB	0.292 A
CT + residue removed	1.20 A	0.559 A	0.095 A	0.167 A	0.297 A
CV (%)	6.9	5.2	33.3	6.9	7.3

BD: bulk density; TP: total porosity; Mac: macroporosity; Mes: mesoposority; Mic: microporosity. Means followed by the same letter at a given column for each layer are not statistically different (Tukey, $p < 0.05$).

no external stress is applied to the soil surface. The reduction in total porosity was mainly due to decreases in macroporosity, especially in CP treatment.

In the NT system, the macropore volume was lowest immediately after sowing, greatest 60 to 240 days thereafter and intermediate prior to the following sowing. In the CP system larger pores tended to decrease over time after plowing, which did not result in a higher volume of mesopores. For this tillage system, the lowest volume of larger pores was found only 360 days after plowing and sowing operations (immediately before subsequent annual tillage). The higher macroporosity in the CP system resulted in higher saturated hydraulic conductivity and lower volumetric water retention along the corn cycle (Veiga, 2005), which can contribute, respectively, to greater fertilizer and pesticide leaching or to lower water availability to crops.

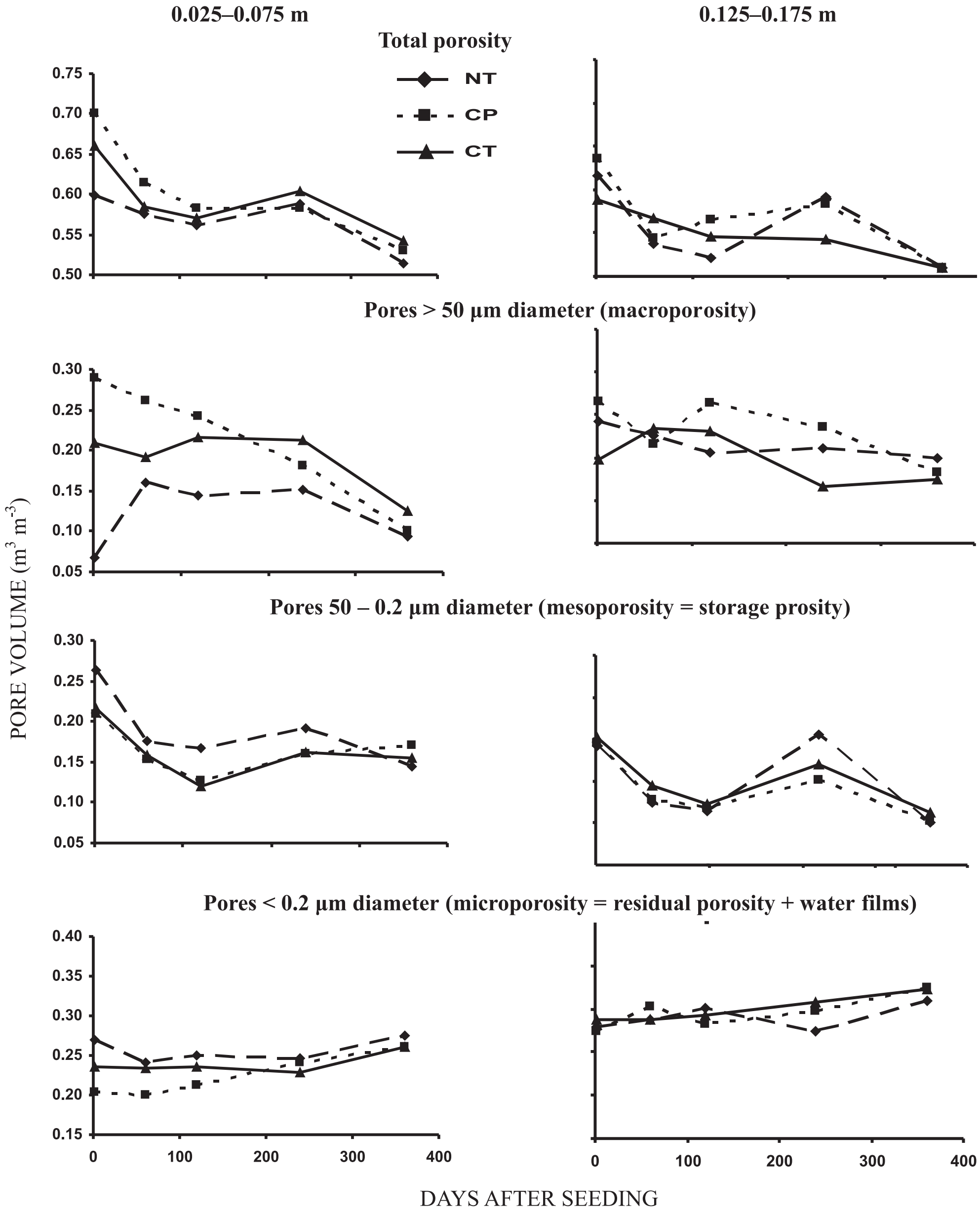

Figure 2. Changes in pore size distribution during the tenth year of no-till (NT), chisel plow (CP), and conventional tillage (CT) systems.

Mesoporosity decreased over time after sowing and followed the same trend in all tillage systems, but seems to be susceptible to the environmental conditions at sampling time (mainly soil water content), as indicated by results obtained 240 days after sowing in the 0.125–0.175 m layer. The greatest volume of mesoporosity was found in NT system immediately after sowing operations, but differences decreased over time. In other words, the NT system has a greater water storage capacity in a tension range which is available to crops in this layer during the cash crop cycle. A steady tendency to increase was observed for microporosity with increasing sampling dates after sowing, which is related to increases in bulk density. Since this porosity is mainly affected by intrinsic soil properties, the variation in volumetric water content at this crop-available tension is related to seasonal variation in bulk density.

CONCLUSIONS

Tilled treatments increased total porosity and macroporosity, and reduced bulk density in the surface layer, but this effect decreased over time after tillage operations due to natural soil reconsolidation, without external stress application. Changes in pore size distribution were more pronounced in larger and medium pore diameter classes. In all tillage treatments bulk density was greatest in the intermediate layers (0.05–0.10 and 0.12–0.17 m) and decreased downwards (0.27–0.32 m), indicating the presence of higher compaction in the layer 0.05–0.20 m. Nutrient source treatments did not affect soil physical and hydraulic properties.

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