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Dairy liquid manure and no-tillage: Physical and hydraulic properties and carbon stocks in a Cambisol of Southern Brazil

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ABSTRACT

Application of liquid manure is often related to risks of nutrient losses by runoff and thus to the deleterious effects on water quality; but scarce is the information about the beneficial effects of liquid manure on soil physical conditions and its contribution in reducing runoff and nutrient losses in long-term, especially in no-tillage (NT) soils in tropics and subtropics. This study assessed the contributions of dairy liquid manure (DLM) on structural and hydraulic quality and on total organic carbon (TOC) stocks of a sandy clay loam Cambisol under NT, in Southern Brazil. The DLM was applied during 2 years, at rates of 0, 60, 120 and 180 m^3 ha^{-1} $year^{-1}$ (DLM-0, DLM-60, DLM-120 and DLM-180, respectively). In the 0–5 cm layer, the application of DLM-180 decreased soil bulk density (1.32 to 1.17 Mg m^{-3}), increased macroporosity (0.24 to 0.32 m^3 m^{-3}), increased mean weight diameter of water-stable aggregates (1.59 to 1.94 mm), increased the larger macroaggregates (>4.00 mm), decreased the microaggregates (<0.25 mm) and increased nearly five times the saturated hydraulic conductivity (54 to 246 mm h^{-1}), compared to unamended soil. Similar but smaller trends for those properties were observed in 5–10 cm, while no alterations occurred in 10–20 cm layer. Application of DLM increased the soil water sorptivity from 2.78 mm $min^{-0.5}$, in unamended soil, to 10.34 mm $min^{-0.5}$, in DLM-180-amended, and so the respective infiltration rate from 164 to 241 mm h^{-1}. The total annual C addition (crops plus manure) increased almost linearly from 5.5 to 10.5 Mg ha^{-1} with increments in DLM rate, but increments in TOC stocks in the whole 0–20 cm layer were observed only between unamended (stock of 23.4 Mg C ha^{-1}) and amended soils (average stock of 26.5 Mg C ha^{-1}), and not among amended soils. In general, findings of structural and hydraulic improvements support the possibility of DLM application to diminish runoff and associated nutrient losses in coarse-textured NT soils in long-term, contributing thus to mitigation of water eutrophication problems. Additionally, the tendency for increments in TOC stocks due to DLM application might indicate a potential of this management practice into promoting C sequestration.

1. Introduction

The application of liquid manure in croplands as a nutrient source or as a disposal strategy in areas of intensive livestock production has risen great concern on the potential of phosphorus (P) and nitrogen (N) losses by runoff and the subsequent water quality degradation by eutrophication (Eghball and Gilley, 1999; Sharpley et al., 1994). This concern is particularly true for no-tillage (NT) soils where manure is placed directly on surface, is not incorporated, and thus may be a risk of P and N losses (Allen and Mallarino, 2008). High runoff nutrients concentration in conservation tillage has also been a concern even without manure application (Barbosa et al., 2009; Bertol et al., 2007a,b). In a study conducted by Bertol et al. (2007a) in Southern Brazil, NT management showed higher P, potassium (K) and organic carbon in runoff sediments than in conventional tillage. Studies have shown that much of the runoff P and N losses occur at rainfall events shortly after the application of manure, because of soil sealing caused by the accommodation of liquid manure particles on soil surface (Bundy et al., 2001; Mori et al., 2009; Smith et al., 2001). Thus, manure should not be applied when there is a probability of rainfall events with occurrence of runoff within days of application (Mori et al., 2009; Wortmann and Shapiro, 2008). Ceretta et al. (2005) observed a direct relation between swine liquid manure rate and the amount of P and N losses in a subtropical Acrisol subjected to NT in an experiment with natural rainfall. However, Silveira (2009) in a long-term experiment with natural rainfall conducted in the same area of the present study,

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showed that increasing the application rate of dairy liquid manure from 0 to 180 $m^3 ha^{-1} year^{-1}$ has in fact reduced P and N losses in runoff, suggesting that some improvements in physical and hydraulic properties of the soil might have occurred due to manure application in NT.

The "Campos Gerais" region of Paraná State in Southern Brazil is considered as one of the country's pioneer regions to adopt NT, but it is also one of the greatest dairy producers and so of manure, that must be properly displaced. Most of the generated liquid manure is applied in NT croplands and contributes to reduce costs on synthetic fertilizers, but potentially represents a risk of P and N losses.

Several studies have shown the beneficial effects of animal manure on soil structural quality, by reducing bulk density, increasing macroporosity, water infiltration rate, saturated hydraulic conductivity and others (Aoyama et al., 1999; Bhattacharyya et al., 2007; Fares et al., 2008; Hati et al., 2007; Mikha and Rice, 2004). However, most of this information was obtained under conventional tillage systems mainly in temperate soils, with manure being incorporated into the 17- to 20-cm depth of the plow layer. The important questions now are how, when, and which rate to apply the manure on NT soils to improve structural quality and at the same time to decrease potential hazards of P and N losses by runoff. In the long-turn, it is possible that liquid manure application increases the water infiltration rates and reduces the water, P and N losses in runoff (Bundy et al., 2001; Smith et al., 2001), but the water infiltration following liquid manure application at short-term can be reduced and increase nutrient losses (Mori et al., 2009; Gilley et al., 2007). Cattle manure application in NT soils improved macroaggregation and aggregate-protected C and N in a temperate silt loam soil (Mikha and Rice, 2004), but in one of the few studies conducted in subtropical conditions of Southern Brazil the application of cattle manure for 9 years did not affect aggregate stability of a NT Nitisol, nor other physical properties like bulk density, macro and microporosity (Veiga et al., 2008).

The information related to liquid manure application effects on soil structural and hydraulic properties that regulate runoff rates in NT soils of tropics and subtropics are too scarce, despite the high rainfall erosivity indices and increases in NT area in those regions. The objective of this study was to assess the contributions of dairy liquid manure application to improve structural and hydraulic quality and organic carbon stocks of a subtropical Cambisol subjected to NT.

2. Materials and methods

2.1. Experimental area

This study was based on a field experiment located in the research station of ABC Foundation for Agricultural Assistance and Technical Divulgation, near the town of Ponta Grossa, Campos Gerais region, Parana State, Brazil (25°00′35″S, 50°09′16″W, 890 m altitude). The soil is classified as Haplic Cambisol (FAO-WRB), with sandy clay loam texture in the 0–20 cm layer (739 $g kg^{-1}$ of sand; 33 $g kg^{-1}$ of silt and 228 $g kg^{-1}$ of clay) and sandstone as a parent material. The regional climate is subtropical with mild summers, classified as Cfb (Köppen). The annual average temperature and rainfall are between 17 and 18 °C and 1400 and 1600 mm, respectively, without dry season (Caviglione et al., 2000).

The experiment was installed in November 2005, in a 15% slope area managed under NT system for more than 10 years, with a rotation system involving wheat (*Triticum aestivum* L.) and black oat (*Avena strigosa* Schreb.) in winter and soybean (*Glycine max* (L.) Merr.) and maize (*Zea mays* L.) in summer. After each harvesting and before each planting operation, spontaneous vegetation was desiccated with glyphosate herbicide. The only soil mobilization occurs in a very narrow strip of 5–6 cm wide where seeds are placed by a no-till adapted planter. The soil disturbance depth varied from about 3 cm in wheat to 5 cm in maize sowing. More than 90% of soil surface remain covered with crop residues. The treatments consisted of four annual rates of dairy liquid manure (DLM): 0, 60, 120 and 180 $m^3 ha^{-1}$, hereafter referred as DLM-0, DLM-60, DLM-120 and DLM-180, respectively. The experiment was set on a randomized complete block design, with four replications, and plots were 3.5-m wide and 9.0-m long. Each annual DLM rate was split in two applications: (i) half before sowing of winter crop and (ii) half before sowing of summer crop. The DLM was brought from a dairy farm near the experiment and was applied with a watering can without sieve.

The cropping sequence, the dry matter concentration of applied DLM and crop yields since the beginning of the experiment until soil sampling are given in Table 1.

2.2. Soil sampling

Soil samples were collected in September 2007, almost 2 years after the beginning of the experiment, at two points per plot, in three of the four replications. A trench 20-cm wide, 40-cm long and 20-cm deep, transversal to the lines of wheat crop, was opened at each sampling point. Two types of samples were collected from the wall of the trench, in the 0–5, 5–10 and 10–20 cm layers: (i) undisturbed soil cores in cylinders of 5.6-cm diameter and 3.1-cm height introduced vertically until the middle of the layer; and (ii) undisturbed soil blocks of 10 cm × 10 cm wide and thickness equivalent to that of the layer, collected with spatula. The samples were carefully packed to avoid breakdown during transport to the laboratory. A third type of sample was collected with dutch auger in the 20–40 cm layer, at the bottom of the trench.

2.3. Macroporosity, microporosity, bulk density and saturated hydraulic conductivity

The soil extending beyond each end of the cylinder containing the core sample was trimmed, to make sure the soil volume was the same of the cylinder. Samples were saturated (12 h), submitted to a tension of 6 kPa (24 h) to drain macropore water in a simple apparatus of tension table proposed by Leamer and Shaw (1941) and then weighed. Microporosity was considered as equivalent to the volume of water contained in the sample at the end of the 24-h period of 6 kPa tension. Macroporosity was calculated from the difference between total porosity and microporosity. Total porosity was calculated from bulk and particle densities (Danielson and Sutherland, 1986). Particle density was measured according to Blake and Hartge (1986) and since variability was very low, it was considered the average value of 2.60 $Mg m^{-3}$ to obtain total porosity. Soil bulk density was determined after drying samples at 105 °C.

A constant hydraulic head of 2 cm was imposed on soil cores and the flux of water passing through the sample was measured at the end of each hour, during 8- or 9-h period when constancy in the flux was achieved (Klute and Dirksen, 1986). The conductivity was calculated using Darcy's equation and the average flux of water of the last two or three constant measurements.

2.4. Aggregate size distribution and mean weight diameter

The undisturbed soil blocks at field moisture content were manually and gently broken apart into aggregates to pass in 8-mm-mesh sieve. Afterwards, aggregates were air dried at room temperature and a 50-g sample was capillary wetted in a filter paper funnel for 12 h. These aggregates were carefully transferred

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Table 1
Cropping sequence, dairy liquid manure (DLM) dry matter at each application and crop yields.

Year	Crop	DLM rate[a] ($m^{-3}\,ha^{-1}\,year^{-1}$)	DLM dry matter ($kg\,m^{-3}$)	Crop yield[b] ($Mg\,ha^{-1}$)
2005/06 (summer)	Soybean	0	16.0	2.44
		60	16.0	2.51
		120	16.0	2.69
		180	16.0	2.33
2006 (winter)	Black oat	0	86.4	2.16
		60	86.4	2.63
		120	86.4	2.81
		180	86.4	3.39
2006/07 (summer)	Maize	0	68.4	9.86
		60	68.4	11.15
		120	68.4	11.86
		180	68.4	10.16
2007 (winter)	Wheat	0	110.2	n.d.[c]
		60	110.2	n.d.
		120	110.2	n.d.
		180	110.2	n.d.

[a] Half of the rate was applied before summer and half before winter cropping.
[b] Grain yield for soybean and maize and aboveground dry matter for black oat.
[c] Not determined. The wheat harvesting was after the soil sampling, and so it is not considered as C addition.

to the top sieve of a set of five sieves (4-, 2-, 1-, 0.50- and 0.25-mm mesh) that were submitted to 36 oscillations per minute, amplitude of 25 mm, during 15 min in a Yoder's wet sieving apparatus (Carpenedo and Mielniczuk, 1990; Kemper and Rosenau, 1986). Aggregates retained on each sieve were carefully transferred to aluminum pans, dried at 50 °C and weighed to determine the size distribution and to calculate wet mean weight diameter (MWD) (Carpenedo and Mielniczuk, 1990; Kemper and Rosenau, 1986).

2.5. Water infiltration

Double-cylinder infiltrometers were concentrically placed at two points per plot and driven 5 cm into the soil. The diameters were 20 and 40 cm for the inner and outer cylinder, respectively. A constant hydraulic head of 5 cm was maintained in the inner cylinder. Water was automatically supplied by a PVC reservoir (diameter of 10 cm and 150-cm height) vertically disposed above the inner cylinder. This reservoir had a visible graduated scale that allowed the measurement of water consumption (i.e., infiltration). Measurements were carried out during 120 min, and infiltration rates were determined at the end of 5, 10, 15, 20, 30, 45, 60, 75, 90, 105 and 120 min. A hydraulic head of 5 cm was manually maintained in the outer cylinder. The procedure here adopted was an adaptation from Bouwer (1986).

The measured infiltration data obtained in the field were fitted in the cumulative infiltration function of the Philip's model (Philip, 1957):

$$I = St^{0.5} + At$$

where I is the cumulative infiltration (mm), S the soil water sorptivity ($mm\,min^{-0.5}$), t the time (min) and A the transmittivity ($mm\,min^{-1}$).

Using parameters of the Philip's model, we calculated the corresponding infiltration rate:

$$I = 0.5S^{-0.5} + A$$

This rate is valid for the early stages of infiltration and thus related to the heavy rains of short duration common in the summer rainy season of the region.

2.6. Total organic carbon

A soil sample of approximately 20 g from each layer was crushed in a mortar until passing a 0.50-mm mesh sieve and total organic carbon (TOC) concentration was determined in a 30-mg aliquot by dry combustion in a Vario EL III analyzer (Elementar Analysensysteme, GmbH, Germany). The TOC stock in each layer was corrected to the equivalent mass of soil (Sisti et al., 2004) and in this case the DLM-0 treatment was the reference. We assumed the bulk density of the 20–40 cm layer was same as that of 10–20 cm layer.

Annual C addition from crops was estimated from detailed historic information about grain yield of soybean and maize and aboveground dry matter yield of black oat (Table 1). The C addition was calculated according to the procedure suggested by Bolinder et al. (2007), with some modifications. It was considered a harvest index of 0.4 for soybean and 0.5 for maize (Bolinder et al., 2007); and to calculate the root residue we considered a shoot-to-root (S/R) ratio of 4.4 for black oat (Pietola and Alakukku, 2005), 5.2 for soybean and 5.6 for maize (Bolinder et al., 2007). The C addition by extra-root material (rhizodeposits) was also calculated, and that was considered as being equivalent to 0.65 times the amount of root residue (Bolinder et al., 2007). It was also assumed that C concentration in the aboveground and root residue and in extra-root material was 400 g kg^{-1}.

The estimate of C addition by DLM was based on its dry matter concentration (Table 1) and on an average C concentration in dry matter of 359 g kg^{-1}(Mori et al., 2009).

2.7. Statistical analysis

Results were submitted to analysis of variance (ANOVA) and the means comparison was obtained by Tukey test ($P < 0.10$).

3. Results and discussion

3.1. Structural properties

The application of DLM-180 decreased soil bulk density in the 0–5 cm layer from 1.32 to 1.17 $Mg\,m^{-3}$, while no alterations occurred after application of DLM-60 and DLM-120 compared to DLM-0 (Fig. 1a). Similar trend was observed in the 5–10 cm layer,

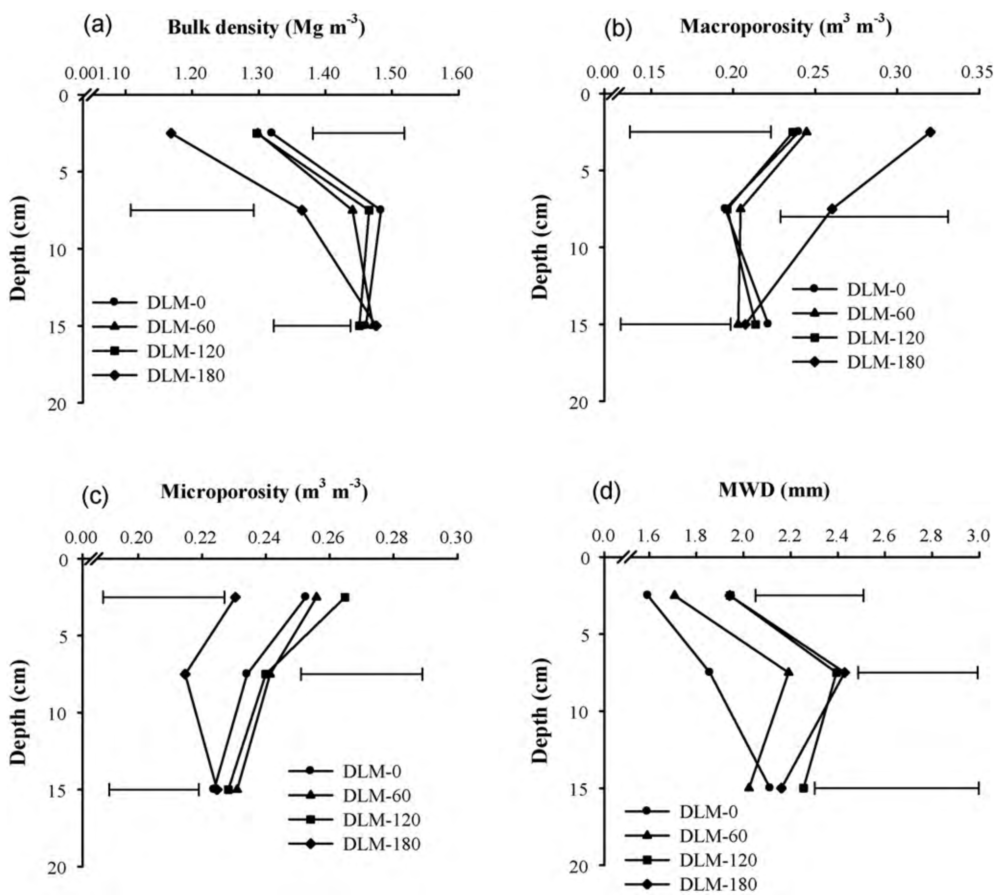

Fig. 1. Soil bulk density (a), macroporosity (b), microporosity (c) and mean weight diameter (MWD) of water-stable aggregates (d) in 0–5, 5–10 and 10–20 cm layers as affected by dairy liquid manure (DLM) application rates: 0 m^{-3} ha^{-1} $year^{-1}$ (DLM-0), 60 m^{-3} ha^{-1} $year^{-1}$ (DLM-60), 120 m^{-3} ha^{-1} $year^{-1}$ (DLM-120) and 180 m^{-3} ha^{-1} $year^{-1}$ (DLM-180). Horizontal bars represent the least significant difference, according to Tukey test ($P < 0.10$).

although the decrease in bulk density promoted by DLM-180 was not significant. Alterations in bulk density were not observed even with the highest application rate of DLM-180 in the 10-20 cm layer. According to variations in bulk density, macroporosity in 0–5 and 5–10 cm layers tended to be greater with application of DLM-180, but remained practically unaltered with application of DLM-60 and DLM-120 (Fig. 1b).

The decrease in bulk density and increase in macroporosity with application of the highest DLM rate could be attributed both to direct and indirect effects. The direct effect is the soil physical conditioning promoted by the particulate organic nature of the solid constituents of DLM (Bulluck et al., 2002; Fares et al., 2008; Haynes and Naidu, 1998), which were possibly incorporated in soil disturbances caused by sowing disks. This effect is supposedly more evident in the top 0–5 cm layer, once DLM was applied directly on soil surface and operation of sowing disk is more intense in this layer. The indirect effect could be an improvement in root density and elongation because of nutrients supply by DLM application. Despite being direct or indirect, several works recognize the positive influence of manure on bulk density and soil porosity (Fares et al., 2008; Zhang et al., 2006). The intriguing result, however, for which no plausible explanation could be found was the almost null effect of DLM-60 and DLM-120 on bulk density and macroporosity, so that effects were evident only to the highest rate of DLM-180, suggesting that only this rate triggered the direct and indirect effects mentioned above.

In all DLM rates, there was a clear trend of increase in bulk density from the 0–5 cm (1.27 Mg m^{-3} in average) to the 5–10 cm layer (1.44 Mg m^{-3} in average) (Fig. 1a), and a decrease in macroporosity from 0.26 to 0.21 m^3 m^{-3} in average (Fig. 1b). These results are related to the supposed larger root concentration and to the most intensive mechanical disturbance caused by disks during planting operations in the 0–5 cm compared to the 5–10 cm layer.

The application of DLM-180 tended to diminish microporosity in the 0–5 and 5–10 cm depth (Fig. 1c). This could be associated with the increase of macroporosity and thus to a consequent depletion of part of microporosity. Other studies, however, have shown increases in micropores (<30 μm) proportion with manure application and so the water storage at field capacity, without changing the macropores proportion (Haynes and Beare, 1996; Schjonning et al., 1994).

Related to aggregation, application of DLM tended to increase the mean weight diameter (MWD) of water-stable aggregates, although not significant in all layers (Fig. 1d). In the upper layer, the unamended MWD of 1.59 mm increased to 1.71 mm after application of DLM-60 and to 1.94 mm (average) with DLM-120 and DLM-180 (Fig. 1d). Similar trend was observed in the 5–10 cm layer, while in the deepest layer there was not a clear difference. Among aggregate size-classes, those that were affected by DLM application were >4.0 and <0.25 mm (Fig. 2a–c). In general, most of the aggregates were bigger than 4 mm and smaller that 0.5 mm. In the 0–5 and 5–10 cm layers, there was a tendency for increase in the proportion of macroaggregates >4 mm with increase in DLM rate, concomitant to a tendency for decrease in the proportion of aggregates in the 0.5–0.25 and <0.25 mm classes. These results make evident the direct role of DLM in acting as binding agent, or its indirect role by stimulating root and hyphae that bind small structural unites (0.5–0.25 and <0.25 mm) into larger ones (>4.0 mm), increasing so the MWD (Fig. 1d).

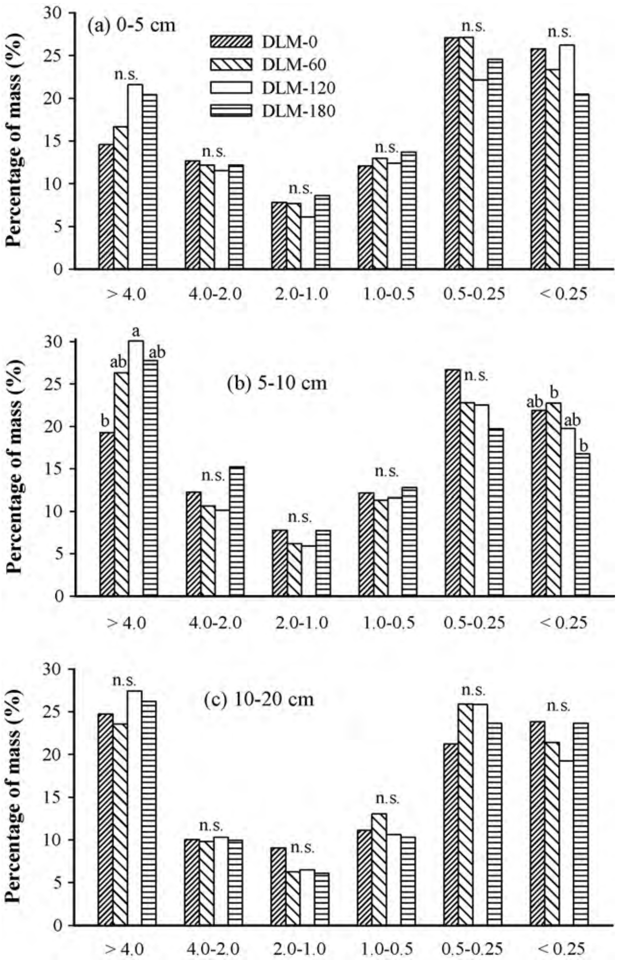

Fig. 2. Aggregates size distribution in 0–5 (a), 5–10 (b) and 10–20 cm layers (c) as affected by dairy liquid manure (DLM) application rates: 0 m^{-3} ha^{-1} $year^{-1}$ (DLM-0), 60 m^{-3} ha^{-1} $year^{-1}$ (DLM-60), 120 m^{-3} ha^{-1} $year^{-1}$ (DLM-120) and 180 m^{-3} ha^{-1} $year^{-1}$ (DLM-180). Letters above bars compare DLM rates within the same aggregates size class, according to Tukey test ($P < 0.10$).

Several studies reporting the beneficial effect of manure application on the amount and size of water-stable aggregates are cited in the review by Haynes and Naidu (1998). The manure as a source of organic matter has a fundamental role in the formation and stabilization of aggregates. This effect was clearly evidenced in NT soils by Mikha and Rice (2004), where application of cattle manure further increased the proportion of macroaggregates (>2.00 mm) and also the macroaggregate-protected carbon. Wortmann and Shapiro (2008) emphasized the role of macro-aggregates in physically protecting phosphorus and thereby reducing its potential loss through runoff. However, the size and proportion of water-stable aggregates decreased by increasing cattle manure rate in the study of Whalen and Chang (2002), and that was attributed to the desaggregation by dispersant agents, specially monovalent cations, as sodium, present in the manure.

3.2. Hydraulic properties

The application of DLM-180 increased saturated hydraulic conductivity five times in the 0–5 cm and almost three times in the 5–10 cm layer compared to the unamended soil (Fig. 3). The two intermediate DLM rates also increased saturated hydraulic conductivity in the top layer, but only DLM-120 increased it significantly. In the 10–20 cm layer, alterations in hydraulic conductivity were comparatively smaller. Although positive alterations caused by DLM application on hydraulic conductivity

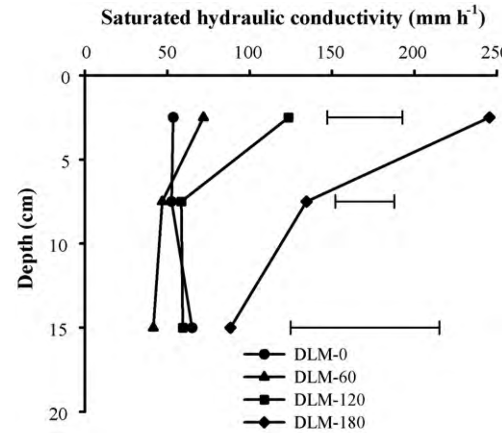

Fig. 3. Saturated hydraulic conductivity in 0–5, 5–10 and 10–20 cm layers as affected by dairy liquid manure (DLM) application rates: 0 m^{-3} ha^{-1} $year^{-1}$ (DLM-0), 60 m^{-3} ha^{-1} $year^{-1}$ (DLM-60), 120 m^{-3} ha^{-1} $year^{-1}$ (DLM-120) and 180 m^{-3} ha^{-1} $year^{-1}$ (DLM-180). Horizontal bars represent the least significant difference, according to Tukey test ($P < 0.10$).

were evident only to the two upper layers, expectations are that in long-term manure application may increase hydraulic conductivity and improve other physical properties in the deeper layers as well. Bhattacharyya et al. (2007) observed increments in hydraulic conductivity up to 45-cm depth after 8 years of farmyard manure application in a silty clay loam soil of India.

Those increments in hydraulic conductivity have actually resulted from increments in macroporosity, since a close and direct relationship between those two properties was observed (Fig. 4). According to the linear adjustment, the hydraulic conductivity would be null in case the macroporosity be inferior to 0.15 m^3 m^{-3}, with obviously negative consequences in terms of increments in runoff. In this case, a reduction in macroporosity would be worst to lower hydraulic conductivity and increase runoff than to lower aeration and oxygen availability to roots, which occur when macroporosity is lower than 0.10 m^3 m^{-3} (Dexter, 1988).

Similarly to the trend observed in saturated hydraulic conductivity, water infiltration rate increased with application of DLM (Fig. 5), as expected due to increments in parameters *S* (sorptivity) and *A* of the Philip's model and the cumulative infiltration in 120 min (Table 2). Although following the same trend, the absolute values of saturated hydraulic conductivity were

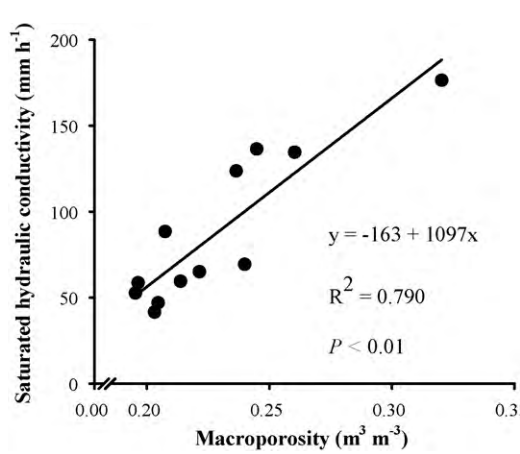

Fig. 4. Relationship between macroporosity and saturated hydraulic conductivity. Data from 0–5, 5–10 and 10–20 cm layers as affected by the four dairy liquid manure rates: 0, 60, 120 and 180 m^{-3} ha^{-1} $year^{-1}$.

Table 2
Water infiltration parameters as obtained by Philip's model and affected by dairy liquid manure (DLM) application rates.

DLM rate[a] ($m^3\ ha^{-1}\ year^{-1}$)	S^b ($mm\ min^{-0.5}$)	A^c ($mm\ min^{-1}$)	R^2	$I_{measured}{}^d$ (mm)	$I_{estimated}{}^e$ (mm)
0	2.78 ± 0.48[f]	2.36 ± 0.33	0.98	311 ± 43	313 ± 35
60	5.14 ± 0.58	3.14 ± 1.72	0.97	421 ± 190	433 ± 200
120	11.18 ± 7.30	3.30 ± 0.66	0.99	526 ± 57	519 ± 45
180	10.34 ± 5.37	3.92 ± 0.87	0.99	583 ± 40	583 ± 57

[a] Half of the rate was applied before summer and half before winter cropping.
[b] Sorptivity.
[c] Parameter A of Philip's model.
[d] Cumulative infiltration in 120 min measured in the field by double-cylinder infiltrometers.
[e] Cumulative infiltration in 120 min estimated by Philip's model.
[f] Number following the ± symbol refers to the standard deviation.

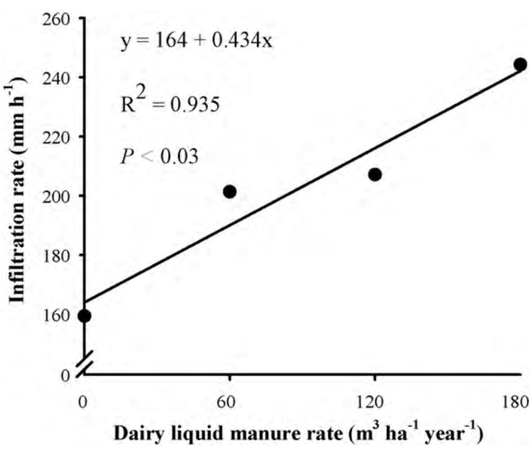

Fig. 5. Water infiltration rate according to Philip's model (parameters in Table 2) as affected by dairy liquid manure (DLM) application rates.

lower than those of infiltration rate possibly due to sample handling, to a smaller hydraulic head (2 cm compared to 5 cm in infiltration test) and to the fact that core samples were not collected in the crop row, which was considered in the infiltration test and supposedly had a contribution to increase infiltration by root channels effects.

Increments in water infiltration rates by increasing rates of cattle manure application were previously reported by Fares et al. (2008), at proportions up to 185% higher compared to the untreated treatment. In our study, increments of 10 mm in the infiltration rate were obtained for each 23 $m^{-3}\ ha^{-1}\ year^{-1}$ increment in DLM rate (Fig. 5), but it is worth mentioning that soil originally had a high water infiltration rate (164 $mm\ h^{-1}$, at DLM-0) because of its sandy clay loam texture.

Findings on increasing saturated hydraulic conductivity (Fig. 3), sorptivity (Table 2) and water infiltration rates (Fig. 5) in this study threw up some evidence about the possibility of DLM application to diminish runoff and P and N losses in this NT soil. In a previous study conducted by Silveira (2009) in the same experiment of the current study, the runoff amount in DLM-180 after natural rainfall was only 1/5 of that recorded in DLM-0 and the same trend was observed for N and P losses. In spite of those results, the application of high rates of DLM like 180 $m^{-3}\ ha^{-1}$ cannot be recommended yet as a general practice to farmers. The study was conducted in a sandy clay loam soil subjected to good management like crop rotation, cover crops and no-tillage, and therefore the found results may not necessarily reflect what would happen in soils with different textural characteristics and subjected to different management conditions, and in a long-term condition. For example, in a study following the application of cattle (60 $m^3\ ha^{-1}\ year^{-1}$) and swine (40 $m^3\ ha^{-1}\ year^{-1}$) liquid manure for 9 years, Veiga et al. (2009, 2008) did not observe improvements in soil physical and hydraulic properties in a clayey Nitisol of Southern Brazil. Likewise, in another clayey soil of this same region, runoff and sediment losses were higher with application of swine liquid manure (60 $m^3\ ha^{-1}\ year^{-1}$) followed by immediate rainfall (Bertol et al., 2007b). But in spite of that, results found in our study opposed to most of the current views that almost always emphasize the hazardous aspects of animal manure application in terms of P and N losses by runoff and deterioration of water quality (Allen and Mallarino, 2008; Smith et al., 2001).

In order to better understand the effects of liquid manure application in terms of P and N losses by runoff, these effects should be separated into short- and long-term effect. The short-term effect is associated with a surface sealing that may occur during the first rainfall event after manure application (Bundy et al., 2001), and the consequent runoff increment because of infiltration reductions. The amount of runoff and nutrient losses, however, depends on the time between manure application and the next rainfall (Gilley et al., 2007), the rainfall intensity (Kleinman et al., 2006) and the manure source and rate (Shigaki et al., 2007). The worst situation would be a high intensity rainfall event immediately after manure application (Mori et al., 2009). The long-term effect is the improvement of soil structural and hydraulic qualities, as observed in the current and in previous studies (Bundy et al., 2001; Smith et al., 2001), with positive effects in reducing losses of water, sediment and nutrients. Bertol et al. (2007a) showed that P and K concentration in runoff decreased exponentially in NT soil following a set of five rainfall events within a 4-month period. The key points are (i) to handle well the short-term effect by applying liquid manure only when rainfall is not forecasted for the next few days, (ii) to recommend manure rate based on the crop nutrients need considering the soil P increments balance to avoid excessive and environmental risky levels, (iii) to define the soil phosphorus environmental threshold to help on manure rate recommendation, and (iv) to asses nitrogen leaching risk, especially in sandy soils.

3.3. Carbon addition and total organic carbon stocks

The total annual C addition increased from 5.5 to 10.5 $Mg\ ha^{-1}$, almost following a linear trend, when DLM application rates increased from 0 to 180 $m^3\ ha^{-1}\ year^{-1}$ (Fig. 6). Most of the total C addition derived from crop residue (at least 60%, in DLM-180), but this crop-C addition did not change so significantly across DLM rates like manure-C addition, since the application of each 60 m^{-3} DLM $ha^{-1}\ year^{-1}$ was equivalent to an addition of 1.51 Mg C $ha^{-1}\ year^{-1}$. Therefore, most of the difference in total C addition was attributed to manure-C application.

In soil, C concentration did not differed among manure rates as well as between amended and unamended soils, but tended to increase with DLM application, being this tendency more evident in top and less in the bottom layers (Fig. 7). However, when C

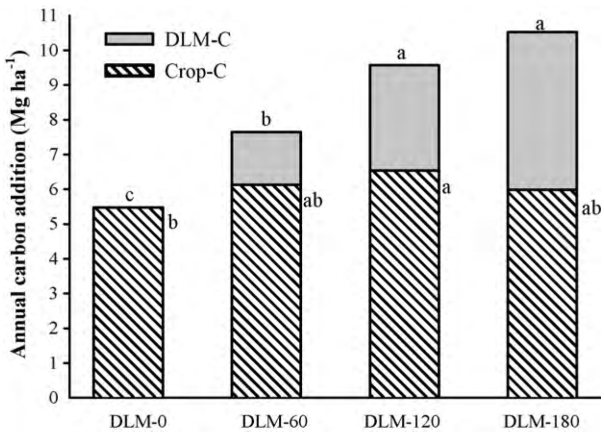

Fig. 6. Annual carbon addition by crop residue (crop-C) and dairy liquid manure (DLM-C) as affected by dairy liquid manure application rates: $0\ m^{-3}\ ha^{-1}\ year^{-1}$ (DLM-0), $60\ m^{-3}\ ha^{-1}\ year^{-1}$ (DLM-60), $120\ m^{-3}\ ha^{-1}\ year^{-1}$ (DLM-120) and $180\ m^{-3}\ ha^{-1}\ year^{-1}$ (DLM-180). Letters above bars compare DLM rates, according to Tukey test ($P < 0.10$).

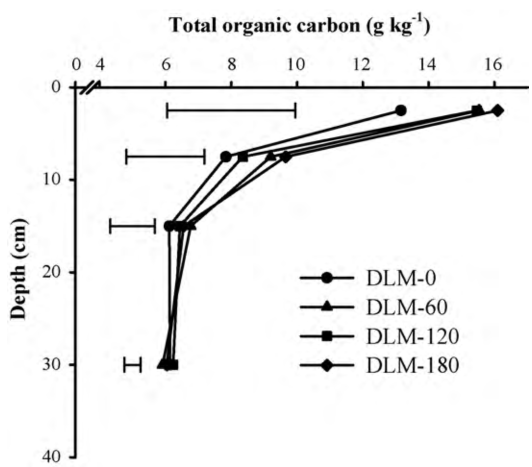

Fig. 7. Soil total organic carbon concentration in 0–5, 5–10, 10–20 and 20–40 cm layers as affected by dairy liquid manure (DLM) application rates: $0\ m^{-3}\ ha^{-1}\ year^{-1}$ (DLM-0), $60\ m^{-3}\ ha^{-1}\ year^{-1}$ (DLM-60), $120\ m^{-3}\ ha^{-1}\ year^{-1}$ (DLM-120) and $180\ m^{-3}\ ha^{-1}\ year^{-1}$ (DLM-180). Horizontal bars represent the least significant difference, according to Tukey test ($P < 0.10$).

stocks were integrated in the whole 0–20 cm layer, difference could be observed only between unamended and amended soil but not among amended soils that received DLM-60, DLM-120 and DLM-180 (Fig. 8). The same trend, although less evident, was observed in the 0–40 cm layer. This is rather intriguing since great differences in the linear increment of C addition due to manure application (Fig. 6) were not reflected in linear changes of TOC stocks (Fig. 8). That might be attributed to the fact that the experiment was only 2 years old, a short period to expect great changes in TOC stocks.

Comparing the average TOC stock in the 0–20 cm layer of amended treatments ($26.5\ Mg\ ha^{-1}$) with TOC stock in DLM-0 ($23.4\ Mg\ ha^{-1}$), the annual C sequestration rate with DLM application during these 2 years was $1.55\ Mg\ C\ ha^{-1}\ year^{-1}$. Thus, besides contributing to the improvement of soil physical conditions, manure application may also contribute to mitigation of climate change; but to make sure about this contribution, a life cycle analysis computing all greenhouse gases emissions associated with the production of each cubic meter of the manure should also be accounted.

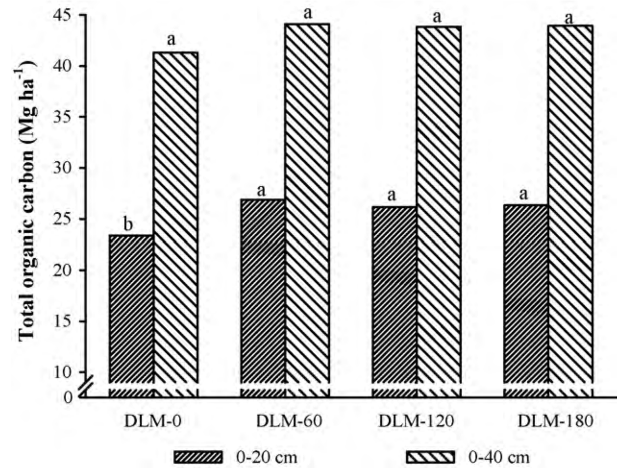

Fig. 8. Soil total organic carbon stocks in the 0–20 and 0–40 cm layers as affected by dairy liquid manure application rates: $0\ m^{-3}\ ha^{-1}\ year^{-1}$ (DLM-0), $60\ m^{-3}\ ha^{-1}\ year^{-1}$ (DLM-60), $120\ m^{-3}\ ha^{-1}\ year^{-1}$ (DLM-120) and $180\ m^{-3}\ ha^{-1}\ year^{-1}$ (DLM-180). Letters above bars compare DLM rates within the same layer, according to Tukey test ($P < 0.10$).

4. Conclusion

The application of DLM in no-tillage soil for 2 years improved the structural quality, by changing physical attributes like bulk density, macroporosity and aggregates mean weight diameter; and also hydraulic attributes by increasing the saturated hydraulic conductivity and water infiltration rate. All these improvements supposedly contribute to reduce runoff potential and to mitigate P and N losses in the long-term in no-tillage soil, opposing the sometimes generalized understandings that liquid manure application contributes to deterioration of water quality. Additionally, the tendency for increments in total organic C stocks due to DLM application might indicate a potential of this management practice into promoting C sequestration and contributing to global warming mitigation, characterizing so a win–win situation. Important to emphasize, however, that the study was conducted in a sandy clay loam soil, and results and conclusions may not be applicable to other textural conditions.

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