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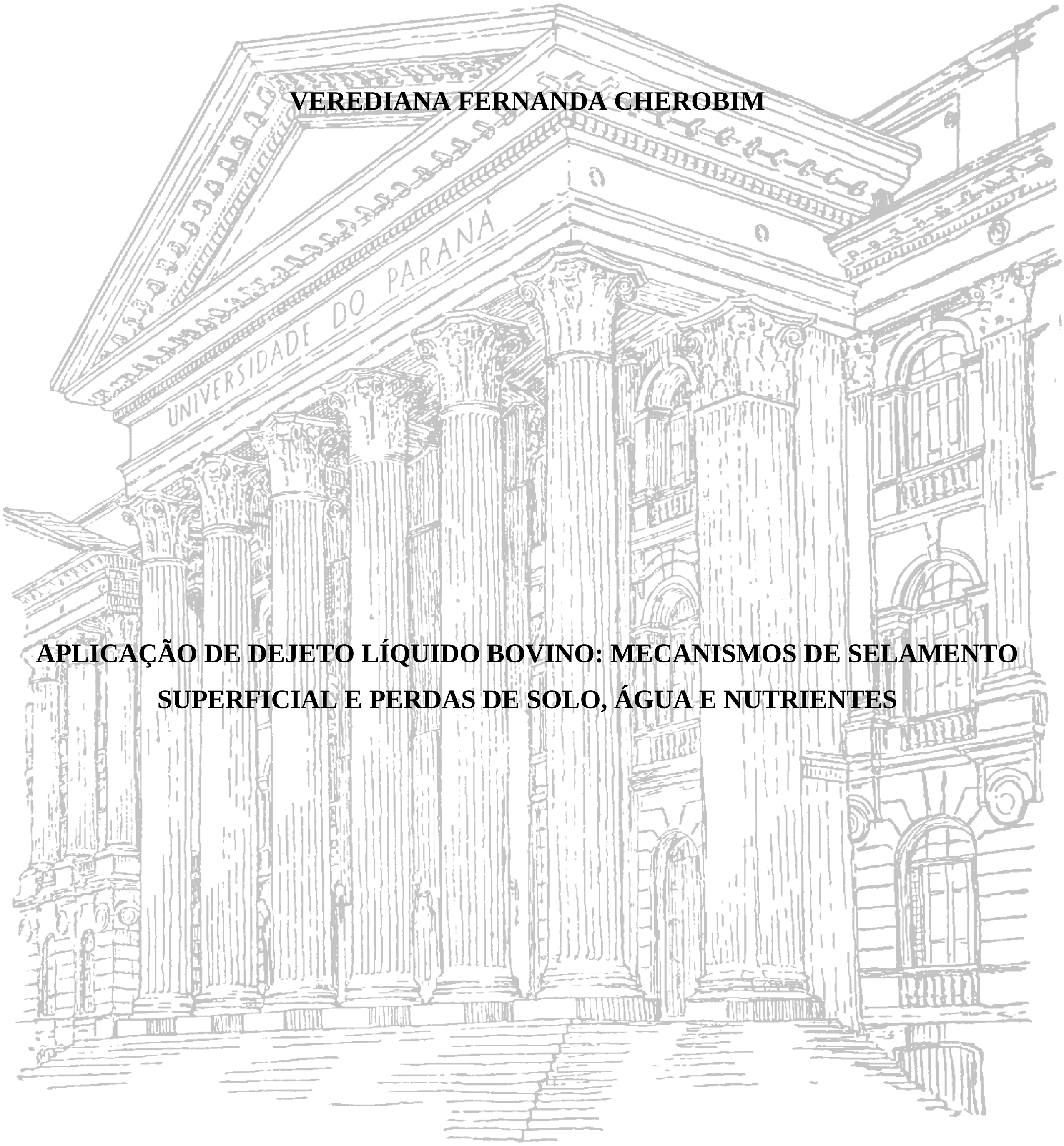

VEREDIANA FERNANDA CHEROBIM

APLICAÇÃO DE DEJETO LÍQUIDO BOVINO: MECANISMOS DE SELAMENTO SUPERFICIAL E PERDAS DE SOLO, ÁGUA E NUTRIENTES

CURITIBA

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Tese apresentada ao Programa de Pós-Graduação em Ciência do Solo, Área de Concentração Solo e Ambiente, do Setor de Ciências Agrárias, Universidade Federal do Paraná, como requisito parcial para à obtenção do título de Doutor em Ciência do Solo.

Orientadora: Profa. Dra. Nerilde Favaretto
Co-orientador: Prof. Dr. Vander de Freitas Melo

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PARECER

A Banca Examinadora designada para avaliar a defesa da Tese de Doutorado de **Verediana Fernanda Cherobin** intitulada: **"Aplicação de dejeto líquido de bovino: mecanismo de selamento superficial e perdas de água, solo e nutrientes ",** do Programa de Pós-Graduação em Ciência do Solo do Setor de Ciências Agrárias da Universidade Federal do Paraná, após análise do texto e arguição do candidato, emitem parecer pela **"APROVAÇÃO"** da referida Tese. O candidato atende assim um dos requisitos para a obtenção do título de **Doutor em Ciência do Solo - Área de Concentração Solo e Ambiente.**

Secretaria do Programa de Pós-Graduação em Ciência do Solo, em Curitiba, 14 de abril de 2017.

Prof. Dra. Nerilde Favaretto, Presidente

Prof. Dr. Luiz Fernando Pires, I°. Examinador

Dr. Gabriel Barth, II°. Examinador

Prof. Dr. Vander de Freitas Melo, III°. Examinador

Prof. Dr. Jeferson Dieckow, IV°. Examinador

Programa de Pós-Graduação em Ciência do Solo – SCA – UFPR
Rua dos Funcionários, 1540 - Bairro Cabral
80035-050 - Curitiba - PR - Fone/Fax: (41) 3350-5648
pgcisolo@ufpr.br | www.pgcisolo.agrarias.ufpr.br

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“O conhecimento da natureza é o caminho para a admiração do Criador.”

Justus Von Liebig

"Em algum lugar, alguma coisa incrível está esperando para ser descoberta.”

Carl Sagan

SUMÁRIO

APLICAÇÃO DE DEJETO LÍQUIDO BOVINO: MECANISMOS DE SELAMENTO SUPERFICIAL E PERDAS DE SOLO, ÁGUA E NUTRIENTES

Autor: M. Sc. Verediana Fernanda Cherobim
Orientador: Profª. Drª. Nerilde Favaretto
Co-orientador: Prof. Dr. Vander de Freitas Melo

RESUMO GERAL

A aplicação de dejeto líquido animal em áreas agrícolas promove melhorias na qualidade do solo, no entanto, o manejo inadequado desse dejeto pode potencializar problemas ambientais. A aplicação de dejeto líquido modifica a superfície do solo através do processo de selamento superficial o qual promove diminuição na infiltração de água e consequentemente aumento nas perdas de solo, água e nutrientes. O objetivo geral deste estudo foi avaliar a influência da aplicação do dejeto líquido bovino (DLB) nos mecanismos de selamento superficial e consequentemente nas perdas de água, solo e nutrientes via escoamento superficial. No intuito de atingir esse objetivo, o estudo foi dividido em três partes, aqui apresentado como capítulos. No primeiro capítulo foram avaliadas as perdas de água, solo e nutrientes com aplicação em superfície de dejeto líquido bovino. Um experimento com chuva simulada foi conduzido em amostras indeformadas, coletadas em área de plantio convencional e plantio direto, com simulação de chuvas nas amostras sem aplicação de dejeto e nos intervalos de 24 horas e 7 dias após a aplicação do DLB. As maiores perdas de água, solo e nutrientes ocorreram quando a chuva simulada foi realizada no intervalo de 24 horas após aplicação do DLB, independente do sistema de preparo. O intervalo de 7 dias entre a aplicação de dejeto e o evento de chuva simulada reduziu as perdas de solo, P particulado e N particulado em ambos os sistemas de preparo. No segundo capítulo foi avaliado a aplicação de dejeto líquido bovino, em sistema de plantio direto, influenciando a condutividade hidráulica do solo através dos mecanismos de selamento superficial. Para tal, um experimento de condutividade hidráulica saturada foi conduzido em solos textura argilosa e franco-argilo arenosa, e os tratamentos foram compostos de dois teores de sólidos totais (0 e 9,4 %); duas doses de DLB (30 e 60 m^3 ha^{-1}); e duas condições de cobertura do solo (0 e 5 Mg ha^{-1} de palhada de aveia). A condutividade hidráulica foi determinada antes da aplicação de DLB e nos intervalos de 24 horas e 7 dias após aplicação do dejeto líquido. A aplicação de dejeto líquido bovino em superfície promoveu selamento superficial do solo e o mecanismo físico (entupimento dos poros pelos sólidos totais) foi o principal agente, contribuindo com cerca de 93 %. O selamento superficial representado pelo Índice de selamento (IS) foi maior no intervalo de 24 horas para todos os tratamentos avaliados, para ambos os solos (argiloso e franco-argilo arenoso). No terceiro capítulo, foram avaliados os mecanismos de selamento superficial do solo pela técnica de tomografia computada. O estudo incluiu dois solos (argiloso e franco-argilo arenoso) e aplicação de DLB com 4,3 % sólidos totais para determinar o efeito do mecanismo físico mais químico e a aplicação de DLB com 0 % de sólidos totais para determinar o mecanismo químico. Análise de imagens obtidas pelo método de tomografia de raio-X foram realizadas antes da aplicação de DLB e nos intervalos de 24 horas e 7 dias após a aplicação do dejeto líquido. A porosidade volumétrica foi quantificada milímetro por milímetro e a mudança de porosidade promovida pela aplicação do DLB foi calculada pela diferença entre antes e após a aplicação do dejeto líquido. A aplicação do DLB promoveu o selamento superficial modificando a porosidade do solo nos primeiros milímetros de profundidade, independente do solo, influenciado principalmente pelo entupimento dos poros. O decréscimo na porosidade foi maior pelo mecanismo físico no intervalo de 24 horas após a aplicação do dejeto líquido.

Palavras-chave: plantio direto, adubo orgânico, qualidade da água, entupimento de poros, dispersão de argila, infiltração, porosidade do solo, microtomografia.

LIQUID DAIRY MANURE APPLICATION: MECHANISMS OF SOIL SURFACE SEALING AND LOSSES OF WATER, SEDIMENT AND NUTRIENTS

Author: M. Sc. Verediana Fernanda Cherobim
Advisor: Prof[a]. Dr[a]. Nerilde Favaretto
Co-Advisor: Prof. Dr. Vander de Freitas Melo

GENERAL ABSTRACT

Liquid animal manure applied in agricultural areas improves soil quality; however, the inadequate management of this manure may potentiate environmental problems. The liquid manure application modifies the soil surface through the surface sealing process, which promotes water infiltration decrease and consequently increases in soil, water and nutrients losses. The general objective of this study was to evaluate the influence of liquid dairy manure (LDM) application in the surface sealing mechanisms and consequently the losses of water, soil, and nutrients through of runoff. In order to achieve this goal, the study was divided into three parts, presented here as chapters. In the first chapter, the losses of water, soil and nutrients with application, on surface, of liquid dairy manure were evaluated. A simulated rainfall experiment was conducted in undisturbed samples, collected in conventional tillage and no-till, with rainfall simulation in the samples without manure application and at intervals of 24 hours and 7 days after LDM application. Highest water, soil and nutrients losses occurred when the simulated rainfall was performed in the interval of 24 hours after LDM application, regardless of the tillage system. The interval of 7 days between manure application and simulated rainfall event reduced the losses of soil, particulate P, and particulate N, in both tillage systems. In the second chapter, the liquid dairy manure application was evaluated in a no-till system, influencing the soil saturated hydraulic conductivity through the surface sealing mechanisms. For this purpose, a saturated hydraulic conductivity experiment was conducted on clayey and sandy clay loam soils, and the treatments were composed of two total solids contents (0 and 9.4 %); two LDM dose (30 and 60 m^3 ha^{-1}); and two soil cover (0 and 5 Mg ha^{-1} of oat straw). Saturated hydraulic conductivity was determined before LDM application and in the intervals of 24 hours and 7 days after LDM application. The liquid dairy manure application, on surface, promoted soil sealing and the physical mechanism (clogging of pores by total solids) was the main agent, accounting for around 93 %. The surface sealing represented by sealing index (SI) was higher in the interval of 24 hours for all evaluated treatments, for both soils (clayey and sandy clay loam). In the third chapter, the soil surface sealing mechanisms by the computerized tomography technique were evaluated. The study included two soils (clayey and sandy clay loam) and LDM application with 4.3 % total solids to determine the effect of physical plus chemical mechanism and LDM application with 0 % of total solids to determine the chemical mechanism. Analysis of images obtained by the X-ray tomography method was performed before LDM application, and in the intervals 24 hours and 7 days after the liquid manure application. The volumetric porosity was quantified millimeter by millimeter, and the change of porosity promoted by LDM application was calculated by the difference between before and after liquid manure application. LDM application promoted the surface sealing modifying the soil porosity in the first millimeters of depth, independent of the soil, mainly influenced by pore clogging. The porosity decrease was greater by the physical mechanism in the interval of 24 hours after liquid manure application.

Key-words: no-till, organic fertilizer, water quality, clogging of pore, clay dispersion, infiltration, soil porosity, microtomography.

INTRODUÇÃO GERAL

A utilização de dejeto líquido animal como fertilizante agrícola é uma solução simples e barata para destinação e reciclagem desse resíduo em áreas agrícolas. Além de ser fonte alternativa e efetiva de nutrientes para as plantas promove melhorias nas propriedades químicas, físicas e biológicas do solo (Adeli et al., 2008; Kheyrodin, 2011). No entanto, o manejo inadequado do dejeto, tais como taxas excessivas, método e tempo de aplicação, promove efeitos ambientais negativos (Allen e Mallarino, 2008; Fares et al., 2008; Kaiser et al., 2009) e representa uma importante fonte difusa de poluição da água (Lord, 1996).

O dejeto líquido aplicado na superfície do solo é extremamente vulnerável a perdas via escoamento superficial principalmente quando a precipitação ocorre pouco tempo após a aplicação (Tabbara, 2003; Mori et al., 2009). A aplicação de dejeto líquido animal modifica a superfície do solo promovendo o selamento superficial, que resulta na diminuição da infiltração de água e consequentemente aumento nas perdas de solo, água e nutrientes, principalmente P e N (Cherobim et al., 2017; Mori et al., 2009). O processo de selamento superficial pela aplicação de dejeto líquido pode ocorrer por mecanismos físicos (entupimento dos poros pelo resíduo), químicos (dispersão de coloides) e biológicos (Barrington et al., 1987; Cihan et al., 2006).

A aplicação de dejeto líquido na superfície do solo, em curto prazo, altera a condutividade hidráulica superficial, a qual reduz a capacidade de infiltração, porém em longo prazo, de modo geral, o dejeto promove melhoria na condutividade hidráulica e na capacidade de infiltração. A alteração das características hidrológicas, em curto prazo, ocorre principalmente pela presença de partículas no dejeto que promovem o entupimento dos poros (Edwards e Daniel, 1993). No entanto, após o tempo viável para tornar o dejeto líquido seco, a condutividade hidráulica pode retornar a sua capacidade próximo a inicial (Chang et al., 1974; Edwards e Daniel, 1993).

O selamento superficial afeta principalmente a porosidade, sendo que técnicas não destrutivas, como a tomografia computada, são necessárias para aprofundar os estudos sobre o processo e mecanismos que afetam a porosidade solo. A tomografia computada (TC) tem sido amplamente utilizada em estudos sobre a porosidade do solo, pois permite a medição dos atributos, obtendo imagens de amostras de solo em duas ou três dimensões, independentemente da forma e geometria de amostra (Beraldo et al., 2014; Pires et al., 2011).

Além disso, a tomografia computadorizada permite investigar as características dos poros a qualquer momento dentro da mesma amostra de solo (Mokwa e Nielsen, 2006). Técnicas avançadas de processamento de imagem proporcionam a oportunidade de representar o objeto em três dimensões e quantificar o volume de poros (Taina et al., 2008).

Nesse contexto, o presente estudo teve como objetivo geral avaliar o efeito da aplicação de dejeto líquido bovino em superfície no processo de selamento superficial e sua influência nas perdas de solo, água e nutrientes.

O presente trabalho foi estruturado e encontra-se subdividido em três capítulos:

Capítulo 1 – Tillage system and time post-liquid dairy manure: effects on runoff, sediment and nutrients losses;

Capítulo 2 – Soil surface sealing by application of liquid dairy manure affecting hydraulic conductivity;

Capítulo 3 – Soil surface sealing promoted by liquid dairy manure application analyzed by x-ray computed tomography.

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CHAPTER 1 - TILLAGE SYSTEM AND TIME POST-LIQUID DAIRY MANURE: EFFECTS ON RUNOFF, SEDIMENT AND NUTRIENTS LOSSES[1]

Abstract

Liquid manure applied in agricultural lands improves soil quality. However, incorrect management of manure may cause environmental problems due to sediments and nutrients losses associated to runoff. The aims of this work were to: (i) evaluate the time effect of post-liquid dairy manure (LDM) application on runoff, sediment and nutrient losses; (ii) compare the effect of conventional tillage and no-till systems on runoff, sediment and nutrients losses after LDM application. A rainfall simulation experiment was conducted on intact soil blocks collected from fields that had been under conventional tillage and no-till systems. Rainfall was applied 24 hours or 7 days after LDM application. Conventional tillage without manure application resulted on higher runoff, sediment and nutrient losses (mainly the particulate fraction) than no-till without manure. The greatest runoff, sediment and nutrients losses occurred in the treatments where simulated rainfall was performed 24 hours after LDM application independent of the tillage system. An interval of 7 days between manure application and the rainfall event reduced sediment, particulate P, and particulate N losses in both conventional and no-till systems. In practical terms, we would recommend a minimum of 7 days between LDM application and rainfall-runoff event to provide agronomic benefits minimizing the potential risk of water pollution.

Key words: Phosphorus, Nitrogen, No-till, rainfall simulation

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1.1. Introduction

Liquid manures are commonly used in agricultural soils as effective sources of plant nutrients, as well as their potential to improve the chemical, physical, and biological properties (Adeli et al., 2008; Fares et al., 2008; Kheyrodin, 2011). However, inappropriate management of manure, such as application methods, excessive rates and timing of application may cause negative effects on water quality (Allen and Mallarino, 2008; Kaiser et al., 2009; Lord, 1996).

Manure applied on soil surface is extremely vulnerable to nutrient losses as surface runoff into ditches and streams, especially when rainfall occurs shortly after application (Allen and Mallarino, 2008; Mori et al., 2009; Tabbara, 2003).

Phosphorus and nitrogen are essential for plant growth, but their application in agricultural fields should be carefully managed, because improper management may result in surface and subsurface water pollution (Casalí et al., 2008; Kato et al., 2009; Wang et al., 2016). Manure application without incorporating into the soil promotes stratification of P within the topsoil with high concentration of P at the soil surface and low potential for P sorption to the soil (Schwab et al., 2006; Sharpley, 2003). In no-till soils, the build-up of nutrients at the surface increases the potential for P and N loading to runoff water, especially in dissolved forms (Sharpley, 2003; Smith et al., 2007).

The transport of nutrients from soil to water may be as soluble or adsorbed to soil particles (mineral and/or organic). Phosphorus transport is mainly associated to surface runoff and nitrogen to leaching (Hatch et al., 2002; Leinweber., 2002; Sharpley et al., 1987). For NO_3-N, due to the low retention capacity in most soils, leaching is the main process involved in transporting of this ion from soil to water (Eghball and Gilley, 1999). However, precipitation events soon after the application of fertilizers (mineral or organic) can promotes losses of NO_3-N in surface runoff (Bertol et al., 2005; Hatch et al., 2002), although its losses are generally small. On the other hand, nitrogen as NH_4-N and particulate N may represent significant losses via surface runoff (Hooda et al., 2000).

Due to the high sorption capacity, particulate P (P bounded to the sediment), generally, dominates P loss by surface runoff on conventional agricultural systems (Kleinman et al., 2011; Verbree et al., 2010). Therefore, controlling the sediment loss as been considered as an effective way to reduce the nutrients loss. Management practices such as conservation tillage systems are effective in reducing soil erosion, and consequently, nutrient losses adsorbed to the sediment (particulate form) and Total N and Total P in surface runoff (Bortolozo et al., 2015; Ramos et al., 2014; Sharpley et al., 2013; Sharpley and Wang, 2014).

The interval between manure application and the rainfall-runoff event have been shown to be an important factor affecting losses of water, sediment and nutrients. In a field experiment with no-tillage, liquid manure applied on soil surface reduced water infiltration 24 hours after application (Cherobim et al., 2015). The lower infiltration and consequently higher runoff was possible due to the surface sealing as a result of clogging of pores (Barrington et al., 1987; Culley and Phillips, 1982). Studies show that when a rainfall event occur immediately after manure application, the P and N concentrations in runoff are greater than when the first rainfall occur in few days after application (Allen and Mallarino, 2008; Schroeder et al., 2004; Smith et al., 2007; Tabbara, 2003). Extending the timing between a rainfall-runoff event and manure application can significantly reduce the risk of excessive runoff nutrients concentration (Hanrahan et al., 2009). In this study, we are particularly interested in how the timing of the rainfall event affects sediment and nutrient runoff after surface application of liquid manure under different tillage systems.

A laboratory rainfall simulation experiment with undisturbed soil sample was designed to: (i) evaluate the interval time effect after application of liquid dairy manure (LDM) on the water, sediment and nutrient losses; and (ii) compare the effect of LDM application in conventional tillage and no-till systems on water, sediment and nutrients losses. This study will provide recommendations of management practices on LDM that offer agronomic benefits with minimal potential risk of water pollution.

1.2. Material and Methods

1.2.1 Experimental site and treatments

This study was performed in the USDA-ARS-National Soil Erosion Research Laboratory at West Lafayette, Indiana. Undisturbed soil samples were collected from the 0-0.1 m layer in conventional tillage (CT) and no-till (NT) fields at the Throckmorton Purdue Agricultural Center (TPAC) in Lafayette, Indiana. The study soil was an Alfisol Miami silt loam (USDA-Soil Survey Staff, 1999). A detailed description of chemical and physical soil characteristics is shown in Table 1. The soil samples were collected in September/October

2014, using metal boxes with the dimension of 0.45 x 0.30 x 0.10 m. The crop residues present on the soil surface were not removed, however the amount of crop residue was minimal.

Table 1. Soil characterization

Tillage system	Depth	Physical properties: Sand	Silt	Clay	MWD	ρ_s	Chemical properties: Ca^{+2}	Mg^{+2}	K^+	P Mehlich	NO_3-N	pH	OC
	m	g kg^{-1}			mm	g cm^{-3}	mg kg^{-1}						g kg^{-1}
CT	0-0.05	440	420	140	0.13	1.33	1522	302	296	140	19	6.4	14.5
CT	0.05-0.10	460	380	160	0.14	1.44	1572	317	218	80	22	6.5	12.8
NT	0-0.05	440	480	80	0.50	1.21	1974	300	422	122	5	6.8	23.8
NT	0.05-0.10	400	460	140	0.46	1.29	1670	321	265	94	6	5.9	13.9

CT: Conventional Tillage; NT: No-till; MWD: Mean Weight Diameter (wet); ρ_s: bulk density; NO_3-N: Nitrate Nitrogen; OC: Organic Carbon

The experiment consisted of six treatments with three replicates: two tillage systems (CT and NT), two intervals between manure application and rainfall simulation, i.e., 24 h and 7 days, and the control (CT and NT without DLM application). The liquid dairy manure (Table 2) at dosage of 60 m^3 ha^{-1} was manually applied on the soil surface and the rainfall simulation was performed 24 hours (24h) and seven days (7days) post-manure application.

The treatments were defined as: CT control and NT control (no manure added), CT 24h and NT 24h (rainfall simulation 24 hours after LDM application), CT 7days and NT 7days (rainfall simulation 7 days after LDM application).

Table 2. Liquid dairy manure (LDM) characterization

	pH	Total dry solids	TKN	NH_4-N	TP	K	Ca	Mg	Na
		%	mg L^{-1}						
LDM	7.5	3.5	2180	1430	360	1270	1300	603	596

TKN: Total Kjeldahl Nitrogen; NH_4-N: Ammonium Nitrogen; TP: Total Phosphorus; K: Potassium; Ca: Calcium; Mg: Magnesium; Na: Sodium.

1.2.2 Simulated rainfall and runoff samplings

Simulated rainfall was applied using deionized water at an intensity of 50 mm h^{-1} for 60 minutes. The soil sample was set to 10 % slope. Prior to each simulation, a pre-wetting low intensity rain of 12 mm h^{-1} was applied for one hour and the soil samples were equilibrated for 24 hours. This procedure minimized the differences between the antecedent soil water s among the treatments and resulted in all the soil samples near their field capacity before the 50 mm h^{-1} runoff-generating rainstorm. The time between rainfall and runoff start was around 3 minutes for all treatments (with or without liquid manure application).

During the 60 minute rainfall event, samples were collected every 5 minutes after runoff initiation. The runoff sample for sediment data was taken in a tared one-liter bottle for two minutes. Immediately after the sediment sample collection, additional runoff samples were taken for soluble and total nutrient analyses. Sediment runoff samples were weighed and then dried at 105° C. Runoff amounts and sediment concentrations were determined gravimetrically. For nutrient analyses, a sample of 60 mL was collected for total digestion (unfiltered samples), while a sample of 20 mL was filtered using 0.45 µm syringe filters to analysis soluble nutrients. Filtered and unfiltered samples were acidified with concentrated sulfuric acid to pH<2 and were frozen to further chemical analysis.

To determine nutrient concentrations in the runoff samples, colorimetric analyses were conducted on a Thermo Scientific KoneLab 20 water chemistry auto-analyzer. Dissolved reactive phosphorus (DRP), nitrate (NO_3-N) and ammonium (NH_4-N) were analyzed with EPA method 365.2, EPA method 353.1 and EPA method 350.1, respectively (U.S. EPA, 1979). Unfiltered water samples were digested with mercuric sulfate and then analyzed total Kjeldahl nitrogen (TKN) and total phosphorus (TP) with test method based on EPA method 351.2 rev 2 (O'Dell, 1993) and EPA method 365.4 (U.S. EPA, 1979). Particulate phosphorus (PP) was obtained by subtracting DRP from TP and particulate nitrogen (PN) was obtained by subtracting NH_4-N from TKN. Total nitrogen (TN) was calculated by the sum between TKN and NO_3-N.

1.2.3 Statistical analysis

Analysis of variance and Tukey's test ($P<0.05$) for mean comparisons procedures and Pearson correlation analyses ($p<0.05$) were performed using the STATISTICA 10 software (StatSoft, 2011).

1.3. Results and Discussion

1.3.1 Runoff rate and sediment loss

Figure 1 shows the runoff and sediment discharge during the 60-minute simulated rainfall. The runoff rate during the simulated rainfall had similar behavior for CT control, CT 24h and NT 24h treatments. The runoff rate was lower in the beginning of the rain and after 5 min, it remained constant (Fig. 1A). This probably was due to surface sealing and clogging of pores from the LDM application (Barrington et al., 1987; Culley and Phillips, 1982) in the CT 24h and NT 24 treatments; or by the raindrop splash (Bradford and Huang, 1994) in the CT treatments. For NT control, NT 7days and CT 7days, the runoff increased gradually (Fig. 1A). For NT control treatment, lesser runoff than CT control can be explained by the higher soil aggregation and stability (Table 1), which promoted greater infiltration. For treatment CT 7days, the dried manure possibly provided soil surface protection against raindrop impact (Barthès et al., 1999), and therefore, increased water infiltration. The lower runoff rate in the NT 7 days probably occurred due to the greater soil aggregation (Table 1) as the protection against raindrop impact by the crust formed with the dried liquid manure (Barthès et al., 1999).

(a) (b)

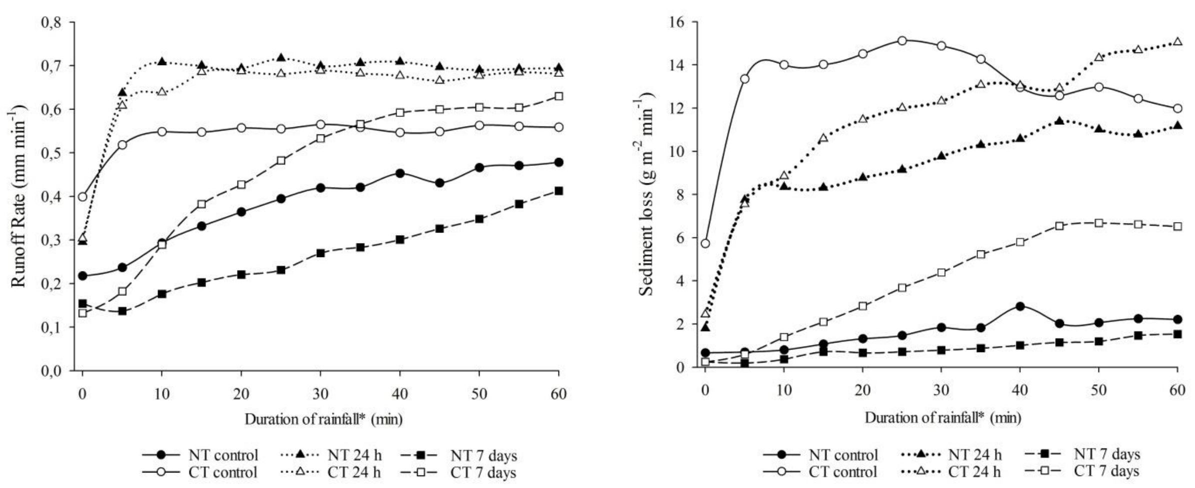

Fig 1. Runoff rate (a) and sediment loss (b) under a single rainfall (~50 mm h^{-1}) for 1 hour in conventional tillage (CT) and no-till (NT) and time post-manure application (24h and 7days).

The total runoff for the 60 min rain interval was higher for the CT 24h and NT 24h treatments (~42 mm h^{-1}) and lower for the NT 7days (~17 mm h^{-1}). Comparing the control and manured treatments, we observed that for conventional tillage the runoff increased 20 % in CT 24h and reduced 14 % in CT 7days, while for no-till the runoff rate increased 72 % in NT 24h and reduced 32 % in NT 7days (Table 3). Time interval between LDM application and rainfall event resulted in a significant effect on cumulative runoff loss. The treatment of 7 days after LDM application compared to 24 hour treatment reduced runoff loss on average 26 % and 60 % to conventional tillage and no-till, respectively. This runoff reduction in 7 days after LDM application reinforces the idea of the dried manure promoting soil surface protection against raindrop impact (Barthès et al., 1999), influencing on soil water infiltration. Cherobim et al. (2015) in a study with no-till system, noted that the LDM application on the soil surface influenced the water infiltration mainly in the first five days, after that the infiltration rate was not different among treatments.

Table 3. Cumulative losses of runoff and sediment for different tillage system and time post-manure application.

	CT Control	CT 24 h	CT 7 days	NT Control	NT 24 h	NT 7 days
Runoff (mm)[a]	35 ab*	42 a	30 b	25 bc	43 a	17 c
Sediment (g m^{-2})[a]	844.5 a	741.7 a	262.9 bc	105.3 c	595.7 ab	54.7 c

[a] Means followed by the same letter are not significantly different by Tukey's test ($P < 0.05$).

CT: Conventional tillage; NT: No-till; Control: treatment without LDM application; 24-h: treatment with LDM and simulated rainfall 24 hours after LDM application; 7-days: treatment with LDM and simulated rainfall 7 days after LDM application.

The sediment loss during the rainfall event (Fig. 1B) followed the runoff loss pattern (Fig. 1A). Three treatments, i.e., CT control, CT 24h and NT 24h showed significantly greater sediment losses during the 1-hr rain, with the CT control treatment showing the greatest loss in the first few minutes. In conventional tillage, the higher losses occurred due the soil disaggregation (Meijer et al., 2013) that facilitated the particles transport through the runoff.

Regarding the cumulative sediment loss, CT control, NT 24h and CT 24h showed greater losses and these losses were not statistically different, while NT control and NT 7days showed less sediment losses (Table 3). Comparing CT treatments, a delay of 7 days after the manure application before the rain event caused a significant reduction in the sediment loss (~850 and ~263 g m^{-2} h^{-1}, respectively) around 70 %. This result reinforces the idea of the possible action of the manure on soil protection against disaggregation by rain drop, especially for conventional tillage.

When comparing tillage systems, our results clearly demonstrate that CT caused higher sediment loss than the NT system, reinforcing that tillage is the major factor driving the sediment loss in the runoff process (Beniston et al., 2015). The conservative tillage system, such as no-till, improves soil stabilization, water infiltration and water holding capacity (Cruse and Herndl, 2009; Sharpley and Wang, 2014), increases soil organic matter in the topsoil (Lal, 2003) and decreases the export of sediment in runoff water (Tiessen et al., 2010).

1.3.2 Nutrients loss

Phosphorus

The losses of different phosphorus fractions are presented in Figures 2A, C, E, and these losses are directly associated with their concentrations (Figures 2B, D, F). The results for TP and PP in the conventional tillage were similar. Treatment CT 24h showed high TP and PP losses in the first 30 minutes, then decreasing gradually. These losses are related to the concentrations of P bound to sediments. Losses of DRP the treatments CT 24h and NT 24h were also high in the beginning, and decreasing gradually (Fig. 2E). This phenomenon was caused by the high concentration of soluble P present in the LDM that results in greater P losses mainly in the first minutes of runoff. For other treatments, the losses of all forms of P were mostly constant during the rainfall event (Fig. 2A, B).

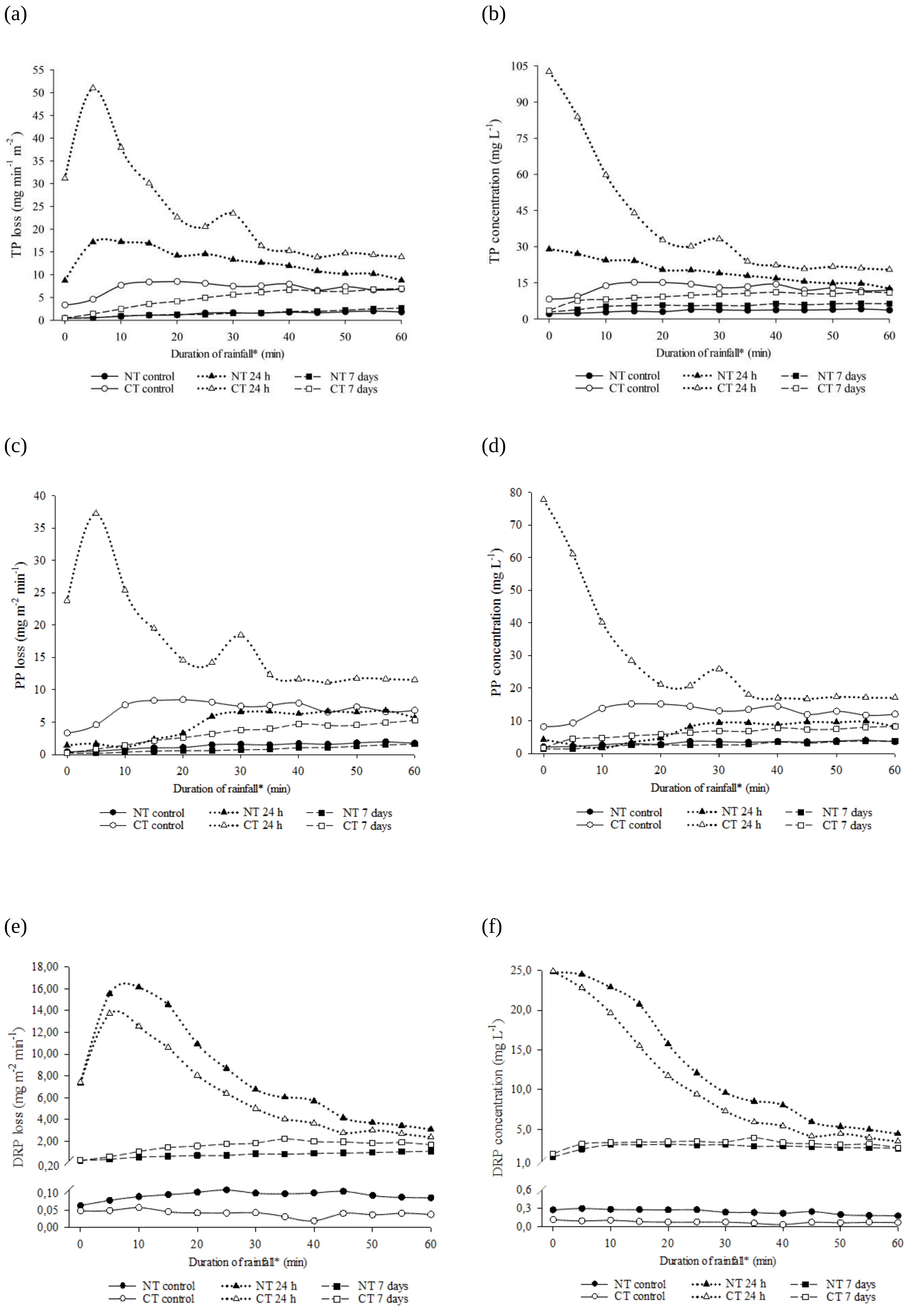

Fig 2. Total P (a, b), Particulate P (c, d), and DRP (e, f) under a single rainfall (~50 mm h^{-1}) for 1 hour in conventional tillage (CT) and no-till (NT) and time post-manure application (24 h and 7 days).

For cumulative P losses from the 1-h rain event, the total P was the highest in CT 24h (1527 mg m^{-2}), followed by NT 24h (834 mg m^{-2}). The high TP loss in the CT 24h is due to high PP loss. For CT 24h, the TP loss was 336 % greater than that from the CT control, whereas TP loss from NT 24h was 916 % greater as compared to NT control. Seven days after the manure application, TP from the CT 7days decreased by 80 % as compared to the TP loss from CT 24h, while NT 7days decreased 88 % as compared to NT 24h (Table 4). Comparing the control treatments in the partition of the P fractions, , the percentage of TP as DRP was higher in the no-till than in the conventional tillage (i.e., 7.3 % vs. 0.8 %), while PP showed the inverse proportion (Table 5). However, in terms of cumulative losses, the conventional tillage lost 45 % less to DRP and 180 % more to PP, when compared to the no-till treatment (Table 4).

Table 4. Cumulative loss and average concentration of dissolved reactive P (DRP), particulate P (PP), total P (TP), soluble NH_4–N, soluble NO_3–N, particulate N (PN), and total N (TN) in runoff for different tillage system and time post-manure application.

	DRP	PP	TP	NH_4-N	NO_3-N	PN	TN
	Loss (mg m^{-2})[a]						
CT Control	2.71 d	453.4 b	456.1 c	1.54 d	4.91 b	1279 b	1285 b
CT 24 h	410.9 a	1116 a	1527 a	558.1 a	16.4 ab	3374 a	3948 a
CT 7 days	100.2 b	209.7 b	309.9 c	71.3 b	22.9 ab	1214 b	1308 b
NT Control	6.09 d	85.3 c	91.4 d	1.73 d	6.27 b	230.2 c	238.2 c
NT 24 h	530.2 a	303.4 b	833.7 b	482.7 a	17.1 ab	3194 a	3694 a
NT 7 days	48.8 c	51.2 c	99.3 d	18.5 c	50.8 a	210.2 c	279.5 c
	Concentration (mg L^{-1})[a]						
CT Control	0.08 d	12.7 b	12.8 c	0.04 d	0.15 c	36.2 c	36.4 bc
CT 24 h	10.7 a	29.1 a	39.8 a	13.6 a	0.42 bc	86.6 a	100.6 a
CT 7 days	3.22 b	6.21 c	9.43 c	2.35 b	0.83 b	36.5 c	39.7 b
NT Control	0.25 c	3.19 d	3.44 d	0.07 d	0.31 bc	8.62 d	9.18 d
NT 24 h	12.9 a	6.87 c	19.8 b	11.6 a	0.42 bc	79.9 ab	92.0 a
NT 7 days	2.79 b	2.74 d	5.53 d	1.12 c	3.71 a	11.6 d	16.4 cd

[a] Means followed by the same letter in the column are not significantly different by Tukey's test ($P < 0.05$).

CT: Conventional tillage; NT: No-till; Control: treatment without LDM application; 24-h: treatment with LDM and simulated rainfall 24 hours after LDM application; 7-days: treatment with LDM and simulated rainfall 7 days after LDM application.

Table 5. Percentage of the total P (TP) as dissolved reactive P (DRP) and particulate P (PP) and of the total N (TN) as ammonium (NH_4–N), nitrate (NO_3–N) and particulate N (PN) for the treatments calculated using the average concentration in runoff for different tillage system and time post-manure application.

	CT Control	CT 24 h	CT 7 days	NT Control	NT 24 h	NT 7 days
	% of TP as DRP and PP					
DRP	0.8	26.9	34.1	7.3	65.0	50.5
PP	99.2	73.1	65.9	92.7	35.0	49.5
	% of TN as NH_4–N, NO_3-N and PN					
NH_4-N	0.1	13.5	5.9	0.8	12.6	6.8
NO_3-N	0.4	0.4	2.1	3.4	0.5	22.5
PN	99.5	86.1	91.9	95.8	86.9	70.6

CT: Conventional tillage; NT: No-till; Control: treatment without LDM application; 24-h: treatment with LDM and simulated rainfall 24 hours after LDM application; 7-days: treatment with LDM and simulated rainfall 7 days after LDM application.

The loss of particulate P was higher in 24h after manure application in both tillage systems. This occurred probably because the liquid manure recently applied in the surface had light organic matter that floated and was transported in the runoff (McDowell and Sharpley, 2002). After 7 days, the drying and crusting of manure decreased the availability of light organic matter to runoff and decreased the PP loss (Kleinman and Sharpley, 2003; Vadas et al., 2007). Due the lower aggregate stability, the CT treatment had greater loss of organic materials from LDM plus soil particles than those from the NT treatment.

The absence of a significant difference in total P loss between NT control and NT 7days and between CT control and CT 7days can be related to sediment loss, soil-bound P, and desorption of P. Johnson et al. (2011), working with dairy manure slurry in a no-till system and applying simulated rainfall 72 hours post application, did not find differences in total P loss when compared control treatment and treatment with slurry applied in the soil surface.

In our study, the highest DRP loss occurred in the treatments with rainfall simulation 24 hours following LDM application, in both no-till and conventional tillage system (Table 4). Johnson et al. (2011) also observed highest DRP loss in manured treatments when compared to control treatment (no manure). In the treatments with 7 days post LDM application, the DRP loss decreased, however the loss remained greater that control treatments in both systems, demonstrating similar tends are those observed by Vadas et al. (2007). Time interval between rainfall event and LDM application had a significant effect on

DRP concentration and loss (Table 4). A rainfall event occurring 7 days after liquid manure application reduced DRP concentration and loss on average 70 % and 76 % to conventional tillage, and 78 % and 91 % to no-till, respectively.

The time interval between manure application and runoff event has an essential role in the P losses. Avoiding manure application before a forecasted rainfall event is very important to minimize P losses (Schroeder et al., 2004; Allen and Mallarino, 2008). Moreover, it is worth emphasizing that the applied manures can contribute as dissolved P in runoff for a long time after they are applied on soil (Vadas et al., 2007).

Nitrogen

The losses of total N, particulate N, NO_3-N, and NH_4-N are shown in Figures 3A, C, E and G, respectively, with the concentration data following similar trends as the mass loss (Figures 3B, D, F, H). Total N, particulate N and NH_4-N had the same behavior, showing greatest losses occurred from the 24h treatment of both CT and NT systems, mainly during the first few minutes of the applied rainfall. The NO_3-N loss from the NT 7days treatment show highest losses among all treatments during the one hour rainfall event, but the amounts were very small. The CT and NT control treatments behaved similarly, showing lowest losses among all treatments independent of N-fractions. For total N, the treatment of 7 days after LDM application reduced the loss in both tillage systems. This occurred mainly due to the decreased concentration of particulate N in relation to 24h post-application treatment.

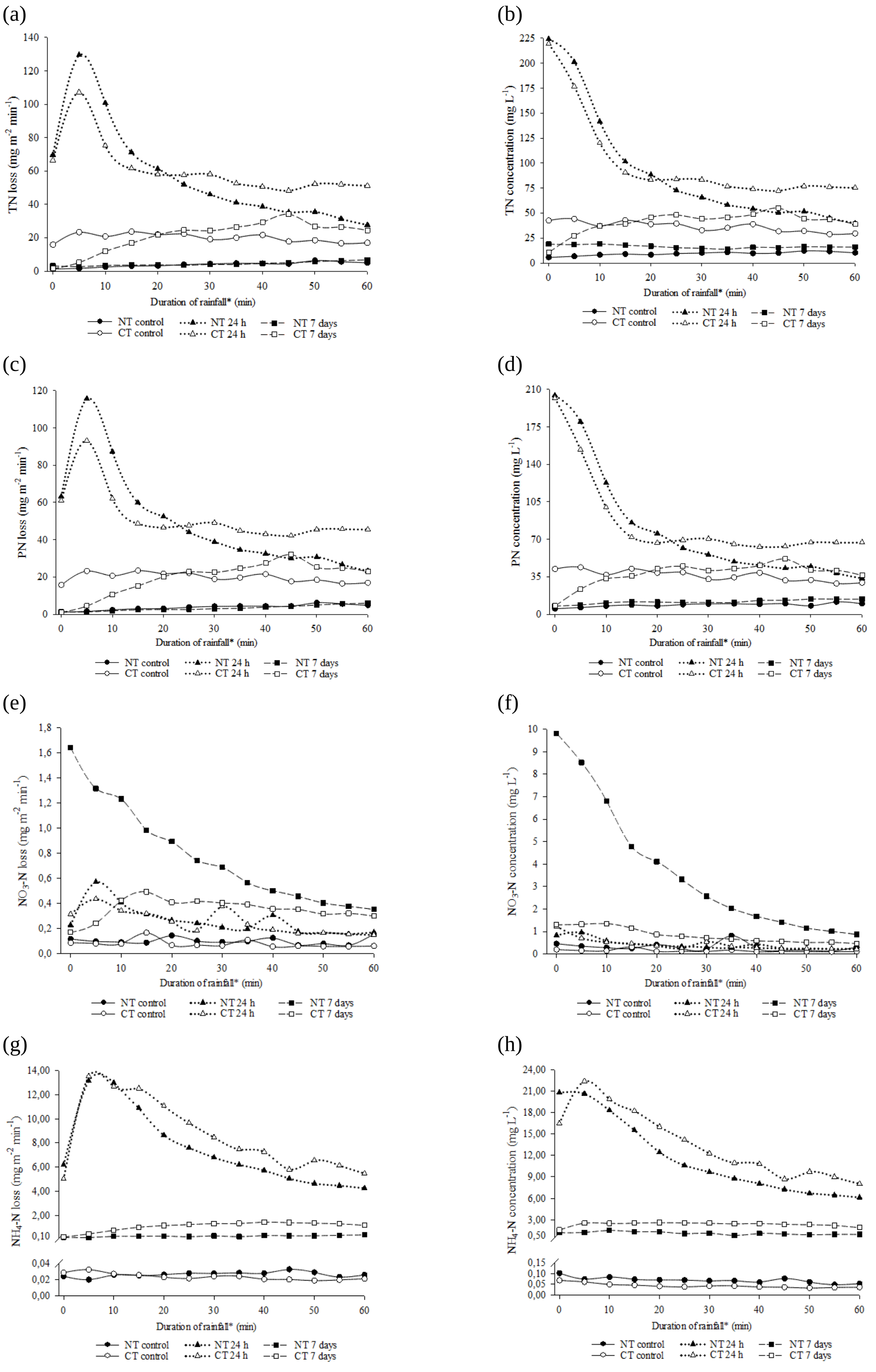

Fig 3. Total N (a, b), Particulate N (c, d), NO_3-N (e, f), and NH_4-N (g, h), under a single rainfall (~50 mm h^{-1}) for 1 hour in conventional tillage (CT) and no-till (NT) and time post-manure application (24 h and 7 days).

For cumulative nitrogen losses (Table 4), the total N (TN) and particulate N (PN) losses were higher in the NT 24h and CT 24h treatments. The cumulative losses of TN and PN for NT control and NT 7days were significantly lower than others treatments. Increasing time between LDM application and rainfall event decreased the loss of NH_4-N, PN and TN, corroborating the results by Smith et al. (2007). Comparing cumulative loss of NH_4-N in 24h versus 7days treatments, the loss was decreased 87 % in CT and 96 % in NT treatments.

The cumulative loss for nitrate was higher in LDM treatments when compared to control treatments. In contrast to NT, PN and NH_4-N concentrations, NO_3-N concentrations (Table 4) increased as time increased. The cumulative loss of NO_3-N was higher in 7 days after LDM application, this probably occurred by the nitrification process (nitrifying bacteria). It is common for greater biological activities in no-till soils than in conventional tilled soils, which can explain the greater losses in no-till system (Table 4). Sharpley and Wang (2014) showed that conservative tillage caused an increase in nitrate and soluble P losses.

Among all the treatments, the biggest fraction of N concentration was as particulate N (> 70 %). In the control treatments, the particulate fraction was even higher, i.e., 99.5 and 95.8 % in CT and NT, respectively (Table 5). It is common to have a strong correlation between the loss of particulate nutrients and sediment loss (Kleinman et al., 2011; Vadas et al., 2004). In our experiment, the PN concentration was positively correlated to sediment loss ($r = 0.73$).

1.4. Conclusions

Runoff, sediment and nutrient losses (mainly the particulate fraction) were affected by tillage systems. Without the manure application, conventional tillage resulted in higher losses than those from no-till system. The greatest fractions of nutrient losses were found in the particulate fraction, indicating erosion as the primary process associated with nutrient loss.

The time post liquid dairy manure affected runoff, sediment and nutrients losses (except nitrate-N). In our research, the 24 hours post-manure application resulted in higher losses in conventional and no-till systems. Seven days after manure application, the losses were significantly decreased.

This information is important in managing and planning manure applications in order to minimize the nitrogen and phosphorus losses, mainly for those in the particulate fractions (sediment-associated). Therefore, in practical terms, we would recommend using weather forecast in making decisions on when to apply liquid dairy manure provide agronomic benefits and avoid risk of water pollution.

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CHAPTER 2 - SOIL SURFACE SEALING BY LIQUID DAIRY MANURE AFFECTING SATURATED HYDRAULIC CONDUCTIVITY

Abstract

The liquid manure applied on soil surface alters hydraulic conductivity by surface sealing. In this study we are interested to: (i) evaluate the mechanisms (chemical and physical) of surface sealing process acting in sandy clay loam and clayey soils under no-till and liquid manure application (LDM); (ii) evaluate the effect of total solids content of liquid dairy manure (LDM) on surface sealing; (iii) evaluate the effect of soil cover (straw) on surface sealing by LDM application; and (iv) evaluate the effect of time after LDM application on surface sealing. The experimental design was completely randomized, with five replicates. The treatments were composed of two total solids content of LDM (0 % and 9.4 %); two doses of LDM (30 and 60 m^3 ha^{-1}); two soil cover (0 and 5 Mg ha^{-1} of oat straw). The saturated hydraulic conductivity (K_{sat}) was determined before and 24 hours and 7 days after LDM application. The liquid dairy manure application on soil surface promoted the surface sealing in both soils and around 93 % of sealing surface was due to physical mechanism and around 7 % to chemical mechanism. The application of LDM with 9.4 % TS (total solids) promoted greater sealing index (greater surface sealing) compared to LDM with 0 % TS, mainly in the interval of 24 hours after LDM application. The 60 m^3 ha^{-1} LDM dose resulted in greater sealing index. The soil cover with 5 Mg ha^{-1} of straw resulted the lower sealing index (lower surface sealing) than soil with 0 Mg ha^{-1} of straw. The sealing index was greater in the interval of 24 hours for all treatments evaluated in both, clayey soil and sandy clay loam soil.

Key-words: no-till, organic fertilization, soil cover, soil crusting, clay dispersion

2.1. Introduction

Surface hydraulic conductivity and infiltration capacity of the soil are important factors determining the amount of runoff resulting from a rainfall and are greatly affected by surface sealing. The surface sealing is characterized by the presence of a thin layer of high density and low porosity (Hillel, 1980; Sumner and Stewart, 1992) and it occurs usually after heavy rainfall events (Badorreck et al., 2013; Jakab, 2013). However, the application of liquid manure also promotes surface sealing, influencing the water infiltration and contributing to the occurrence of soil, water and nutrients losses (Smith et al., 2007; Mori et al., 2009; Cherobim et al., 2017).

The surface sealing with application of liquid manure can occur by physical, chemical and biological mechanisms, which are influenced by the soil texture as well as the composition of the animal slurry (Culley and Phillips, 1986; Cihan et al., 2006). The physical mechanism is the main agent of the soil surface sealing occurring through of the pore clogging by particulate material present in the liquid manure (Barrington et al., 1987; Chang et al., 1974; deTar, 1979; Rowsell et al., 1985). The total solids content that constitutes the animal slurry has a great influence in this kind of mechanism. Usually, the contribution of the chemical mechanism in surface sealing is negligible and depends mainly of soil texture, manure pH, and concentration of dispersant elements present in the manure (Barrington et al., 1987). The dispersed particles move through the soil profile clogging the pore spaces and causing surface sealing (Irvine and Reid, 2001).

The interval between manure application and rainfall event affects the surface sealing and consequently the water infiltration process. In the short-term (less than four days after liquid manure application) the hydrologic characteristics was affected by surface sealing promoted by fine manure particles (Edwards and Daniel, 1993). However, in long-term (greater than four days after the liquid manure application), it is possible to recover the soil hydraulic conductivity close to initial probably due to time available to dry the liquid manure (Chang et al., 1974; Edwards and Daniel, 1993; de Vries, 1972).

Little research has been published regarding surface sealing characteristics in soils under liquid manure application. So, in this study, we are interested to understand the physical and chemical mechanisms of soil surface sealing by application of liquid dairy manure (LDM) under no-till affecting the hydraulic conductivity of sandy clay loam and clayey soils.

A laboratory with saturated hydraulic conductivity experiment was designed to: (i) understand the contribution of the physical and chemical mechanism of surface sealing by LDM application; (ii) evaluate the effect of total solids content of LDM on surface sealing; (iii) evaluate the effect of soil cover (straw) on surface sealing by LDM application; (iv) evaluate the effect of time after LDM application on surface sealing.

2.2. Material and Methods

2.2.1. Soil characterization

The soil samples were taken from two experimental fields, in Castro (24°51’50”S and 49°56’25”W) and Ponta Grossa (25°00’35”S, 50°09’16”W). These fields had been cultivated under crop rotation (soybean-maize-oat-wheat) and managed with no-till system for more than 20 years. The soils (Table 1) are classified as Oxisol in the US Soil Taxonomy (Soil Survey Staff, 1999), corresponding to Brazilian Soil Taxonomy (Embrapa, 2013) as brown Latosol (Castro) with clayey texture and Red-Yellow Latosol (Ponta Grossa) with sandy clay loam texture.

Table 1. Physical and chemicals properties of the investigated soils at depth of 0-0.20 m.

	Physical properties							
	Clay	Silt	Sand	MWD	ρ_s	Mic	Mac	K_s
	—— g kg^{-1} ——			mm	g cm^{-3}	—— % ——		mm h^{-1}
Sandy clay loam	228	33	739	1.33	1.50	28	15	47.0
Clayey	597	217	186	2.09	1.19	46	9	23.3
	Chemical properties							
	pH	Al^{3+}	H+Al	Ca^{2+}	Mg^{2+}	P	K	C
	$CaCl_2$	——— $cmol_c$ dm^{-3} ———				—— mg dm^{-3} ——		g dm^{-3}
Sandy clay loam	5.1	0	3.5	3.7	0.7	19.0	0.2	13.2
Clayey	5.7	0	3.9	6.5	4.3	5.8	0.3	21.8

MWD: Mean Weight Diameter (wet); ρ_s: bulk density; Mac: macroporosity; Mic: microporosity; K_s: saturated hydraulic conductivity.

Source: Adapted from Mori et al. (2009) and Cherobim et al. (2015).

2.2.2 Experimental design and treatments

Undisturbed soil samples were collected with a cylinder (Ø=4.9 cm) from the 0-5.3 cm upper layer, in soils described previously. The study consisted of two trials (clayey soil and sandy clay loam soil), being the experimental design and treatments the same to both soils.

The experimental design was completely randomized, with five replicates. The treatments were: two total solids content of LDM (0 and 9.4 %); two doses of LDM (30 and 60 m^3 ha^{-1}); two soil cover (0 and 5 Mg ha^{-1} of oat straw), arranged in factorial scheme 2x2x2, totaling 8 treatments. The saturated hydraulic conductivity (K_{sat}) was determined before LDM application, 24 hours and 7 days after LDM application. Each soil cylinder consisted of a single sample which was analyzed before and after LDM application. The treatments with application of liquid dairy manure with 9.4 % total solids (Table 2) was performed to determine physical plus chemical mechanism and application of liquid dairy manure with 0 % total solids (filtered by 0.45 µm membrane filter) to determine chemical mechanism. The difference between than resulted the physical mechanism.

The saturated hydraulic conductivity was measured using the method of falling head permeameter (Klute and Dirksen, 1986).

Sealing index was defined to study the soil surface sealing promoted by liquid dairy manure application (greater SI means greater effect of surface sealing). Sealing index (SI) was calculated as:

$$SI = K_{sat} \text{ before LDM application} - K_{sat} \text{ after LDM application}$$

Table 2. Liquid dairy manure (LDM) characterization, on wet basis.

	pH	Total dry solids	TN	TP	K	Ca	Mg	Na
		%	g L^{-1}					
LDM	7.5	9.4	4.2	2.6	4.5	2.3	1.1	0.6

TN: Total Nitrogen; TP: Total Phosphorus.

2.2.3 Statistical analysis

Variance analysis and Tukey test was performed in order to assess the statistical differences ($P < 0.05$) on sealing index (K_{sat} before LDM – K_{sat} after LDM application) considering total solids content (0 and 9.4 %), LDM dose (30 and 60 m^3 ha^{-1}) and, soil cover (0 and 5 Mg ha^{-1}). The analysis procedures were performed using the STATISTICA 10 software (StatSoft, 2011). Due the high variability, the data were submitted to logarithmic transformations for adequate statistical analyze.

2.3. Results and Discussion

Analyzing the interactions in the clayey soil (Table 3), the greater sealing index was found with LDM 9.4 % TS and no presence of straw, in the interval of 24 hours after LDM application. So, in practical terms, no soil cover (straw) linked with LDM application with high total solids content and rainfall 24 hours of LDM application results the worst condition to surface sealing and hydraulic conductivity on clayey soils.

Table 3. Sealing index of clayey soil influenced by double interaction between total solids (TS) content, LDM dose, and soil cover (straw) in 24 hours and 7 days after LDM application.

	LDM Dose		Straw	
	30 m^3 ha^{-1}	60 m^3 ha^{-1}	No	5 Mg ha^{-1}
TS content	------------------*24 hours after LDM application* ------------------			
0 %	ns	ns	0.85 bA	0.65 bA
9.4 %	ns	ns	17.1 aA	4.71 aB
LDM Dose				
30 m^3 ha^{-1}	ns	ns	ns	ns
60 m^3 ha^{-1}	ns	ns	ns	ns
TS content	------------------*7 days after LDM application* ------------------			
0 %	ns	ns	ns	ns
9.4 %	ns	ns	ns	ns
LDM Dose	ns	ns	ns	ns
30 m^3 ha^{-1}	ns	ns	ns	ns
60 m^3 ha^{-1}	ns	ns	ns	ns

Means followed by the same letters do not differ statistically by Tukey test at 5 % probability. Upper case letter compare the double interaction horizontally, and lower case letter compare them vertically. ns = no significant by Tukey test at 5 % probability

In the sandy clay loam soil (Table 4), in 24 hours after LDM application, the sealing index was greater in the 60 m^3 ha^{-1} LDM with LDM 9.4 % TS and 0 Mg ha^{-1} straw. The interaction between LDM dose and TS content shows that the LDM dose influences the hydraulic conductivity independent of TS content, that is, the higher the liquid manure dose, higher the surface sealing and lower the hydraulic conductivity. However, the effect of surface sealing in 30 and 60 m^3 ha^{-1} LDM was greater with LDM 9.4 % TS, indicating the greater effect of total solids content on surface sealing.

The sealing index in 24 hours after LDM application was greater with LDM 9.4 % TS application under no presence of straw (Table 4). Comparing the soil cover, 5 Mg ha^{-1} of oat straw decreased the sealing index around 81 % in relation to no presence of straw. The same situation was presented in the clayey soil for the interaction between TS content and soil cover (straw), indicating the greater effect of soil cover on controlling surface sealing by short-term LDM application.

In the interval of 7 days after LDM application, the interaction between TS content and LDM dose showed greater sealing index with 60 m^3 ha^{-1} LDM 9.4 % TS (Table 4). However, comparing the LDM application intervals, the sealing index for interaction between LDM dose and TS was much higher in 24 hours than 7 days after LDM application, showing that the interval of LDM application is very important for minimize the surface sealing.

Table 4. Sealing index of sandy clay loam soil influenced by double interaction between total solids (TS) content, LDM dose, and soil cover (straw) in 24 hours and 7 days after LDM application.

Treatment	Dose		Straw	
	30 m^3 ha^{-1}	60 m^3 ha^{-1}	No	5 Mg ha^{-1}
TS content	------------------*24 hours after LDM application* ------------------			
0 %	0.30 bB	0.48 bA	0.45 bA	0.33 bA
9.4 %	2.77 aB	7.93 aA	9.16 aA	1.53 aB
LDM Dose				
30 m^3 ha^{-1}	ns	ns	ns	ns
60 m^3 ha^{-1}	ns	ns	ns	ns
TS content	------------------*7 days after LDM application* ------------------			
0 %	0.50 bA	0.47 bA	ns	ns
9.4 %	0.82 aB	1.59 aA	ns	ns
LDM Dose				
30 m^3 ha^{-1}	ns	ns	ns	ns
60 m^3 ha^{-1}	ns	ns	ns	ns

Means followed by the same letters do not differ statistically by Tukey test at 5 % probability. Upper case letter compare the double interaction horizontally, and lower case letter compare them vertically. ns= no significant by Tukey test at 5 % probability.

The total solids content (TS) of LDM plays an important role in the surface sealing process because it defines the contribution of each mechanism acting in the sealing. In our study, we are supposing that LDM with 9.4 % TS defines the physical plus chemical mechanism while the LDM with 0 % TS defines the chemical mechanism (no clogging of pores will occur by manure solid particles in this condition).

For the interval of 24 hours after LDM application, in both soils, greater sealing index, which means greater surface sealing, was found with application of LDM with 9.4 % TS compared to 0 % TS (Fig 1a, b). Comparing the total solid content (0 and 9.4 %), the application of LDM with 0 % TS resulted in a sealing index smaller, around 93 %, to both clayey soil and sandy clay loam soil. So, considering that LDM 0 % TS reflects only the chemical mechanism and that LDM 9.4 % TS reflects physical plus chemical mechanism, we can conclude that around 7 % of the surface sealing was due to chemical mechanism and 93 % to physical mechanism. The surface sealing which resulted on lower hydraulic conductivity occurred mainly by physical mechanism through of clogging of pores due the fine particulate material present in the liquid manure (Maulé et al., 2000; Mostaghimi et al., 1989; Roberts and Clanton, 2000; Rowsell et al., 1985). The chemical mechanism contribution on surface sealing was not significantly, but the sealing promoted by this mechanism was due, possible, by effects of pH increase and CTC increase by organic compounds, and due the presence of dispersant elements (Na and K; Table 2), which enabled the clay dispersion (Barrington et al., 1987).

For the interval of 7 days after LDM application, the sealing index also was significantly major in LDM 9.4 % TS than LDM 0 % TS, around 40 % to clayey soil and 60 % to sandy clay loam soil. However, comparing the intervals after LDM application, the sealing index (surface sealing) with application of LDM 9.4 % was strongly greater in the interval of 24 hours than the interval of 7 days (91 % major in clayey soil and 77 % in sandy clay loam soil). The surface sealing decrease in the interval of 7 days after LDM application can be explained by process of drying of the liquid dairy manure few days after-application, which allows recover the hydraulic conductivity close to initial (Chang et al., 1974; Edwards and Daniel, 1993; de Vries, 1972). This explains the smaller sealing index, which means lower surface sealing, in the interval of 7 days when compared to 24 hours after LDM application (Fig 1a, c).

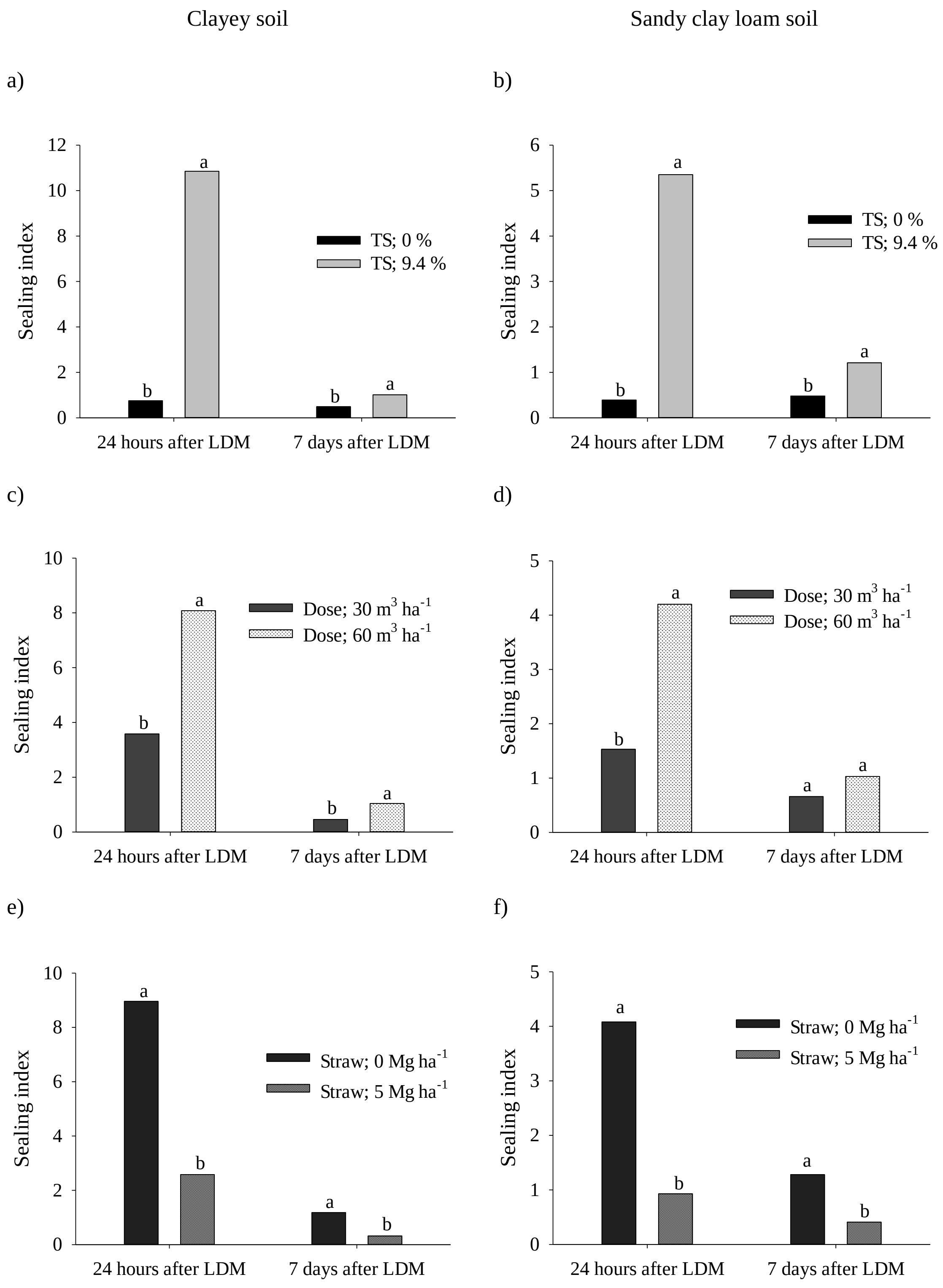

Fig 1. Sealing index (K_{sat} before LDM – K_{sat} after LDM application), showing effects of total solids (TS), LDM dose, and soil cover (straw) in surface sealing mechanisms with 24 hours and 7 days after LDM application, on clayey soil (a, c, and e) and sandy clay loam soil (b, d, and f).

The LDM dose data (Fig 1c, d) shows greater surface sealing (greater sealing index) with application of 60 m^3 ha^{-1} LDM in the interval of 24 hours after LDM application in both soils. The decrease in sealing index with 30 m^3 ha^{-1} LDM, when compared to 60 m^3 ha^{-1}, was around 55 % to clayey soil and 63 % to sandy clay loam soil. The dose effect in the interval of 7 days after LDM application was smaller in relation to interval of 24 hours, showing the importance of the adequate interval in the manure application. Study with crescent LDM doses and water infiltration showed that the increase of LDM dose applied on soil surface affected the hydraulic conductivity decreasing the water infiltration, mainly short time (1 day) after manure application (Cherobim et al., 2015).

The soil cover (straw), in both interval of application (24 hours and 7 days), shows that sealing index was influenced by the presence of straw in clayey soil and sandy clay loam soil (Fig 1e, f). The greater sealing index values (greater surface sealing) occurred in the interval of 24 hours after LDM application in the 0 Mg ha^{-1} of straw. Comparing the presence or not of straw in soil surface (0 and 5 Mg ha^{-1}), the 5 Mg ha^{-1} of straw decreased the sealing index values around 70 % to clayey soil and 81 % to sandy clay loam soil, showing a positive effect of the straw on decreasing surface sealing, mainly in sandy clay loam soil. In the interval of 7 days after LDM application, sealing index values were greater in 0 Mg ha^{-1} than 5 Mg ha^{-1} of straw. The presence of straw on soil surface is pretty important due the protection of soil surface against to erosion process (Donjadeea and Tingsanchalib, 2016), and, in the case of liquid manure application, the straw presence avoids the direct contact of manure with the pores of soil, and consequently avoid the surface sealing and the decrease in hydraulic conductivity.

Comparing the soils, the clayey soil was more affected by the LDM application than sandy clay loam soil, mainly in the interval of 24 hours after application (Fig 1). For total solids content, the sealing index was around 50 % greater to both TS content (0 and 9.4 % TS); for the LDM dose the sealing index increased 58 % to LDM 30 m^3 ha^{-1} and 48 % to LDM 60 m^3 ha^{-1}; while for soil cover, the increase in sealing index was 46 % to 0 Mg ha^{-1} of straw and 65 % to 5 Mg ha^{-1} of straw. The difference in sealing index values between the soils indicates that in the clayey soil the surface sealing by LDM application was greater than sandy clay loam soil.

2.4. Conclusions

The liquid dairy manure application on soil surface promotes the surface sealing. The physical mechanism was the main mechanism acting on surface sealing in clayey and sandy clay loam soils. The clayey soil was more susceptible to surface sealing by LDM application. The worst condition for surface sealing was interval of 24 hours after LDM application, higher total solids content (9.4 % TS), higher dose (60 m^3 ha^{-1}) and lower soil cover (0 Mg ha^{-1} of straw).

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CHAPTER 3 - SOIL SURFACE SEALING PROMOTED BY LIQUID DAIRY MANURE APPLICATION ANALYZED BY X-RAY COMPUTED TOMOGRAPHY

Abstract

Liquid manure application on soil surface promotes surface sealing affecting the soil porosity, mainly shortly after application. The purpose of this research was: (i) to evaluate the surface sealing process in soil with clayey texture and sandy clay loam texture under long term no-till system and liquid dairy manure (LDM) application; (ii) to assess the contribution of the physical and chemical mechanisms in the process of soil surface sealing. The treatments included application of liquid dairy manure with 4.3 % total solids to determine physical plus chemical mechanism and application of liquid dairy manure with 0 % total solids (filtered by 0.45 µm membrane filter) to determine chemical mechanism. Image analysis obtained by X-ray microtomography method was performed before LDM application and 24 hours and 7 days post LDM application. The porosity was quantified millimeter by millimeter and the porosity changed by LDM application was calculated by the difference before and after liquid manure application. LDM application promoted soil surface sealing modifying the soil porosity in the first depth millimeters, independent of the soil texture. The soil sealing surface by LDM application was influenced mainly by the clogging of pores. The decrease porosity was greater in the physical plus chemical mechanism treatment and interval of 24 hours post-application.

Key-words: no-till, soil porosity, clogging pores, clay dispersion, microtomography, Oxisol

3.1. Introduction

The use of liquid animal manure as an agricultural fertilizer is a simple and cheap solution to dispose and recycle this residue on agricultural land. The application of liquid animal manure on soil surface is beneficial because it improves chemical, physical and biological soil attributes (Fares et al., 2008; Kheyrodin and Antoun, 2011; Mellek et al., 2010; Van Eekeren et al., 2009), and consequently increases crop productivity (Bandyopadhyay et al., 2010). However, inappropriate management of liquid manure, such as application of high doses and short interval between the manure application and the rainfall occurrence, can increases the runoff and nutrients losses (Allen and Mallarino, 2008; Cherobim et al., 2017; Mori et al., 2009).

There are evidences that, in short term, the application of liquid animal manure in agricultural lands may affects soil properties by the soil surface sealing process, modifying its capacity to water infiltration (Cherobim et al., 2017; Cherobim et al., 2015). Usually, the soil surface sealing is characterized by the presence of a thin layer of high density and low porosity that occurs after heavy rainfall events (Augeard et al., 2007; Assouline, 2004; Hillel, 1980). Indeed, soil surface sealing has been linked with physical, chemical and biological mechanisms due to accumulation of liquid manure in lagoons and earthen manure storage facilities (Cihan et al., 2006; Culley and Phillips, 1986). Those mechanisms are influenced by the soil texture as well as the composition of the animal manure.

Among the sealing mechanisms, the physical is the main mechanism of the soil surface sealing occurring through of the clogging of pore by suspended organic particles present and by the high viscosity of the liquid manure (Barrington et al., 1987; DeTar, 1979). Usually, the contribution of the chemical mechanism in surface sealing is negligible and depends mainly of the type of soil texture, soil pH, and amount of dispersant elements present in the manure (Barrington et al., 1987).

Few studies were found about the process of soil surface sealing mechanisms affected by liquid manure in manure storages (Barrington et al., 1987; Culley and Phillips, 1986), however there is no research studying the process and mechanisms in agricultural areas.

The soil surface sealing affects mainly surface porosity, so no-destructive techniques, such computed tomography, are necessary for a investigate study about this process and the mechanisms that affect the pore of soil.

Computed tomography (CT) have been largely used in studies about soil porosity, since is a no-destructive and no-invasive technique that allows measuring of soil attributes, obtaining images of soil samples in two or three dimensions, independent of the shape and geometry of sample (Beraldo et al., 2014; Pires et al., 2011; Pires et al., 2010). Besides that, the CT allows to investigate of pores characteristics any time within the same soil sample (Mokwa and Nielsen, 2006) and advanced techniques of image processing provides the opportunity to represent the object in three dimensions and to quantify the pore volume (Taina et al., 2008).

Due the need of more detailed study in relation to soil surface sealing mechanisms by liquid manure application and their implications, mainly in short term and no-till, the purpose of this research was: (i) evaluate the surface sealing process in soil with clayey texture and sandy clay loam texture under no-till system and liquid dairy manure application, using X-ray computed tomography (analyze of pores) and (ii) determine the contribution of the physical and chemical mechanisms in the process of soil surface sealing.

3.2. Material and Methods

3.2.1. Soil samples

The soil samples were taken from two experimental fields, in Castro (24°51’50”S and 49°56’25”W) and Ponta Grossa (25°00’35”S, 50°09’16”W) municipalities, Brazil, in which land has been cultivated under crop rotation (soybean-maize-oat-wheat) and managed with no-till system for more than 20 years. The soils were classified as Oxisol in the US Soil Taxonomy (Soil Survey Staff, 1999), corresponding to Brazilian Soil Taxonomy (Embrapa, 2013) as Brown Latosol (Castro) with clayey texture and, Red-Yellow Latosol (Ponta Grossa) with sandy clay loam texture. More information of chemical and physical soil characteristics is shown in Table 1.

Table 1. Physical and chemicals properties of the soils investigate, at depth of 0-0.20 m

	Physical properties							
	Clay	Silt	Sand	MWD	ρ_s	Mic	Mac	K_s
	g kg^{-1}			mm	g cm^{-3}	%		mm h^{-1}
Sandy clay loam	228	33	739	1.33	1.50	28	15	47.0
Clayey	597	217	186	2.09	1.19	46	9	23.3
	Chemical properties							
	pH	Al^{3+}	H+Al	Ca^{2+}	Mg^{2+}	P	K	C
	$CaCl_2$	cmol$_c$ dm^{-3}				mg dm^{-3}		g dm^{-3}
Sandy clay loam	5.1	0	3.5	3.7	0.7	19.0	0.2	13.2
Clayey	5.7	0	3.9	6.5	4.3	5.8	0.3	21.8

MWD: Mean Weight Diameter (wet); ρ_s: bulk density; Mac: macroporosity; Mic: microporosity; K_s: saturated hydraulic conductivity.

Source: Adapted from Mori et al. (2009) and Cherobim et al. (2015).

Previously to sampling, surface crop residues were removed. Two undisturbed soil samples were collected for each soil (clayey and sandy clay loam soil) with a cylinder (Ø=4.9 cm) from the 0-2 cm upper layer. Liquid dairy manure (Table 2) was applied, only once, in each soil sample. The LDM application was on surface, by dripping, at dosage of 60 m^3 ha^{-1}. Sealing surface study included application of liquid dairy manure with 4.3 % total solids to determine physical plus chemical mechanism and application of liquid dairy manure with 0 % total solids (free TS; filtered by 0.45 µm membrane filter) to determine chemical mechanism.

The analyses on soil surface sealing were made on two samples for each soil type, being a single sample for physical plus chemical mechanism and other single sample for chemical mechanism. The experiment consisted of different analyzes intervals: control (before LDM application), 24 hours post LDM application and 7 days post LDM application. To investigate the mechanisms of surface sealing, computed tomography analyses were performed, on each soil sample, before liquid dairy manure application and after 24 hours and 7 days post LDM application.

Table 2. Liquid dairy manure (LDM) characterization, on wet basis.

	pH	Total dry solids	TN	TP	K	Ca	Mg	Na
		%	g L^{-1}					
LDM	7.6	4.3	2.3	0.3	1.8	1.6	0.5	0.3

TN: Total Nitrogen; TP: Total Phosphorus.

3.2.2 X-ray computed tomography

Tomography images of soil samples were obtained using a X-ray microtomograph, Model 1172 of Skyscan, composed of a cone beam source operating at source voltage and current of 100 kV and 90 µA, respectively. The detector configuration (camera of 11 MP with 2x2 binning, creating 1336 x 3872 pixel radiograms) and the distances between source–object–camera were adjusted to produce images with a pixel size of 12.89 µm. The rotation step was 0.4◦ over 360◦ and scan duration was around 3 hours and 15 minutes.

The acquisition of tomographic images (cross-sections) was performed in two stages. The first one was the acquisition of images in various angular projections of the sample along a rotation of 360º with very accurate rotational steps, and the second one consisted in the reconstruction of images of cross-sections from the images of the angled projections through the Feldkamp cone-beam volumetric reconstruction algorithm. All images in this work were obtained with a resolution of 12.89 µm.

After obtaining the reconstructed density data from micro CT, images were processed for further analysis. First the images were filtered to reduce noise and then segmented to pores, solid, and manure phases, which enabled quantitative investigations of the pores. In segmentation, grey-scale histograms were used to select manually the threshold grey-scale values (50-255). Segmentation is an essential step, as it may considerably affect the subsequent analyses.

The images were reconstituted into micro-CT sections with the software NRecon (Liu, 2010) and processed with the SkyScan softwares CTAnalyser - CTAn (Kharitonov, 2003) and CTVox (Boons, 2010). Each sample was dissected into ten layers of 1 mm, considering the top of soil sample as the first layer. Changes in soil surface were based on volumetric soil porosity observed before and 24 hours and 7 days after the samples received liquid dairy manure application. Relative percentage of porosity was calculated considering the treatment control (no LDM application) as 100 % of pores.

3.3. Results and Discussion

3.3.1 Physical plus chemical mechanism of surface sealing (application of LDM with 4.3 % total solids)

Previous studies have evidenced that animal liquid manure application on soil surface of agricultural fields decreases the water infiltration and increases the runoff (Cherobim et al., 2017; Cherobim et al., 2015; Roberts and Clanton, 2000), but the mechanisms that influences the soil surface sealing were not fully elucidated. In this study, we measured volumetric soil porosity in each 1 mm layer up to 10 mm trying to understand the mechanisms that govern soil surface sealing after liquid manure application.

Figure 1 illustrates the first millimeter to the treatments control, 24 hours and 7 days after application of liquid dairy manure (LDM) with 4.3 % total solids to clayey soil (Fig 1a) and sandy clay loam soil (Fig 1b). For example, in the clayey soil (Fig 1a), the total volume of first millimeter of sample was 1931.19 mm^3, being that pore volume was of 1282.85 mm^3 (66.4 %) to control, 953.99 mm^3 (49.3 %) to 24 hours post LDM application, and 1227.56 mm^3 (63.5 %) to 7 days post LDM application treatment. The pore volume occupied by LDM in the treatment of 24 hours was 330.86 mm^3 (26 %), while in the treatment of 7 days was 55.29 mm^3 (4.3 %). To sandy clay loam soil (Fig 1b) the pore volume filled by LDM was similar to clayey soil, about 25 % in treatment of 24 hours and 7.4 % in treatment of 7 days post LDM application.

These results indicated that the application of LDM caused soil surface sealing, clogging pores by fine particles and modifying the soil porosity in the first depth millimeters, independent of the soil texture. The greater clogging of pores occurred in the treatment of 24 hours post LDM application. In the interval of 7 days post application had a decrease in clogging of pores, showing the importance of the interval between LDM application and rainfall event to minimize the sealing surface and avoid issues of soil water infiltration.

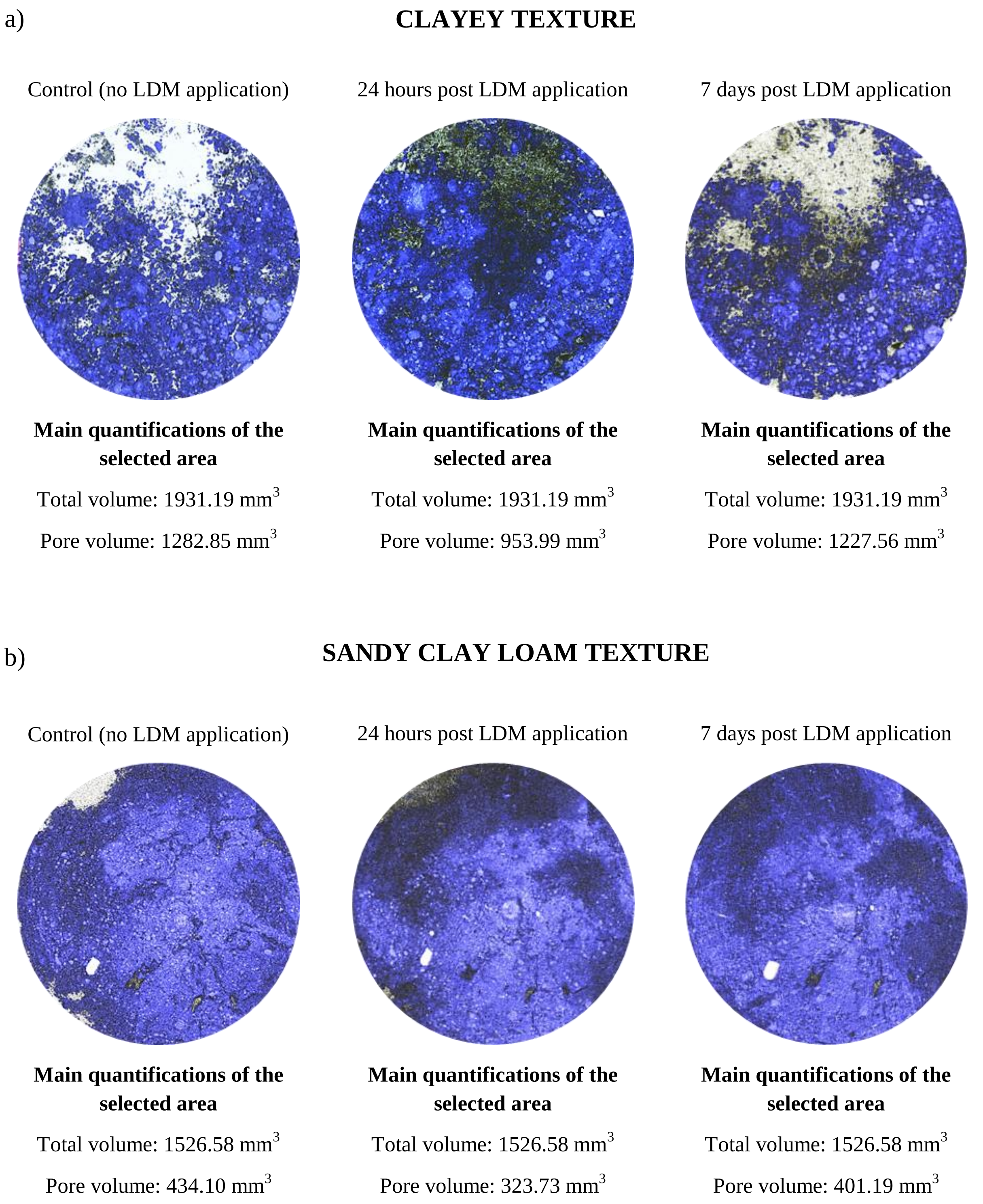


Fig 1. Example of 3D images of first millimeter of clayey soil (a) and sandy clay loam soil (b) samples analyzing the physical plus chemical mechanism (LDM application with 4.3 % total solids).

Analyzing the soil surface sealing from application of LDM with 4.3 % total solids, which compass the physical plus chemical mechanism (Fig. 2), we observed that the change of porosity was stronger in the interval of 24 hours post LDM application, mainly in the first two millimeters in both soils. The decrease in porosity when compared the control and 24 hours treatments was around 25 % and 20 % in the first and second millimeter, respectively. In the depth of 3 to 5 millimeters the decrease in porosity was around 11 %, while that in the depths below this decrease was lower 5 % in relation to control treatment. The change of porosity was influenced by the total solids (4.3 %; Table 2) present in LDM that promoted clogging of surface pores. In the soil surface sealing, the physical mechanism is the main factor on the sealing process, occurring through of the clogging of pore by suspended organic particles present and by the high viscosity of the liquid manure (Barrington et al., 1987; DeTar, 1979).

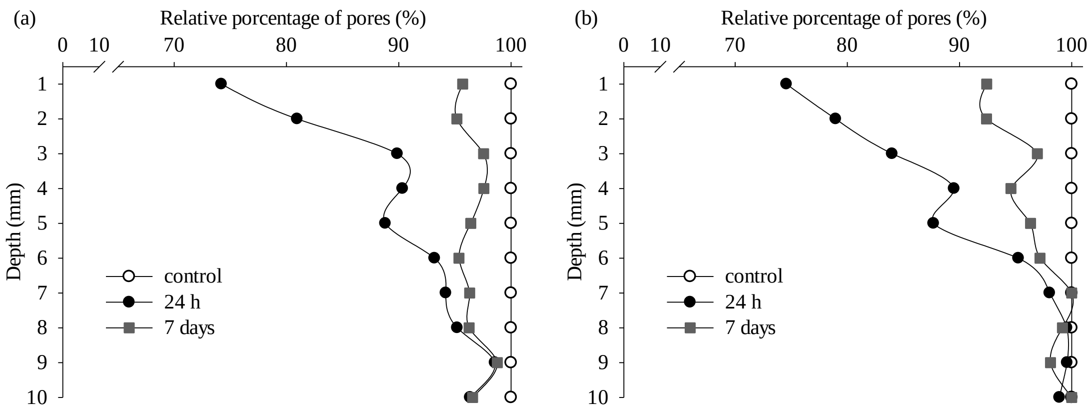


Fig. 2: Change in porosity by physical plus chemical mechanism in clayey soil (a) and sandy clay loam soil (b) with liquid dairy manure application (4.3 % total solids). Percentage relative being the porosity in control treatment considered as 100 %.

The treatment of 7 days post LDM application had a decrease lower 7 % in all the depth analyzed in relation to control treatment, in both soil textures. Comparing the manured treatments, the porosity in 7 days post application was greater than porosity in 24 hours, mainly in first two millimeters (Fig. 2). The recover in porosity (values close to control) with 7 days post manure application can be explained mainly by drying process. The liquid dairy manure dries after few days allowing the recovery of the porosity and consequently the recovery of the hydraulic conductivity (Chang et al., 1974; Edwards and Daniel, 1993). Also, the recovery can be affected by the biological activity that promotes degradation of volatile solids (more biodegradable than other solids) present in total solid content of the liquid manure (Zhang and Westerman, 1997). The interval of manure application influences the water infiltration, being that 7 days post LDM application resulted in a decreasing in soil surface sealing and consequently greater infiltration when compared to interval of 24 hours post-application.

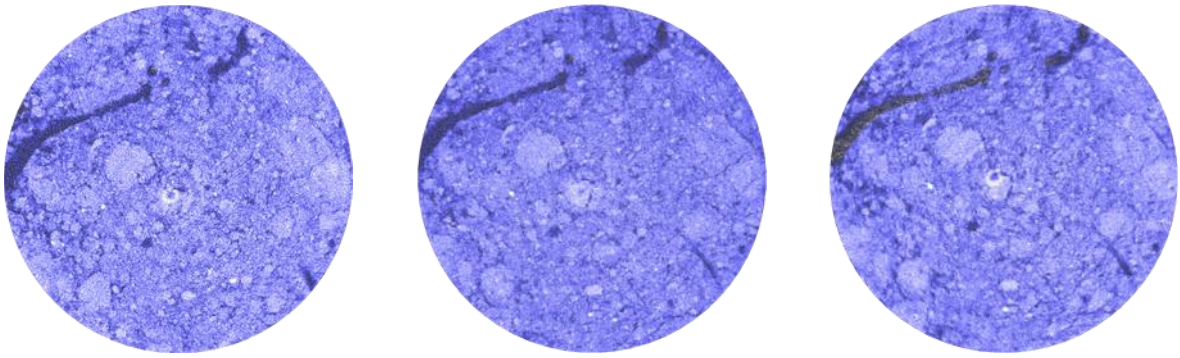
3.3.2 Chemical mechanism of surface sealing (application of LDM with 0 % total solids)

Figure 3 illustrates the first millimeter to the treatments control, 24 hours and 7 days post liquid dairy manure 0 % total solids application to clayey soil (Fig 1a) and sandy clay loam soil (Fig 1b). In the clayey soil (Fig 1a), the total volume of first millimeter of sample was 1605.48 mm^3, being that pore volume was of 23.79 % to control, 22.57 % to 24 hours post LDM application, and 22.96 % to 7 days post LDM application treatment. In sandy clay loam soil (Fig 1b) the pore volume was of 18.47 %, 17.64 %, and 17.53 % to control, 24 hours and 7 days post LDM application, respectively. The change of soil porosity with LDM 0 % solids application was similar in both soils. The decrease of porosity in manured treatments in relation to control treatment was around 5.1 % in 24 hours and 3.5 % in 7 days post LDM application to clayey soil, and 4.5 % and 5.1 % to sandy clay loam soil.

Analyzing only the chemical mechanism (LDM application 0 % total solids), the decrease in the porosity in clayey soil (Fig. 4a) was just in the first three millimeters and was lower than 5 % in both treatments, 24 hours and 7 days after application of LDM. In the other depths, not occurred modification in the soil porosity when compared to control treatment. In the sandy clay loam soil (Fig. 4b) the change of porosity by chemical mechanism was observed in all depths. The decrease of porosity occurred in 24 hours and 7 days after LDM application and was lower than 6 %.

a) **CLAYEY TEXTURE**

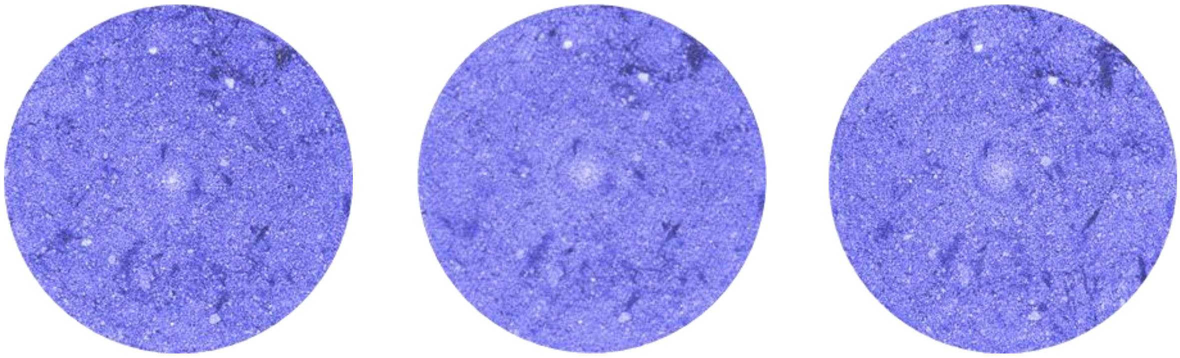
Control (no LDM application)	24 hours post LDM application	7 days post LDM application



Main quantifications of the selected area	**Main quantifications of the selected area**	**Main quantifications of the selected area**
Total volume: 1605.48 mm^3	Total volume: 1605.48 mm^3	Total volume: 1605.48 mm^3
Pore volume: 381.93 mm^3	Pore volume: 362.42 mm^3	Pore volume: 368.59 mm^3

b) **SANDY CLAY LOAM TEXTURE**

Control (no LDM application)	24 hours post LDM application	7 days post LDM application



Main quantifications of the selected area	**Main quantifications of the selected area**	**Main quantifications of the selected area**
Total volume: 1360.44 mm^3	Total volume: 1360.44 mm^3	Total volume: 1360.44 mm^3
Pore volume: 252.02 mm^3	Pore volume: 240.73 mm^3	Pore volume: 239.24 mm^3

Fig 3. Example of 3D images of first millimeter of clayey soil (a) and sandy clay loam soil (b) samples analyzing the chemical mechanism (LDM application with 0 % total solids).

The change of soil surface porosity when was applied LDM 0 % total solids occurs due the high manure pH and the presence soluble dispersant elements in the manure (Na and K; Table 2), that can cause clay dispersion contributing to surface sealing (Barrington et al., 1987). The Na^+ and K^+, due its low valence, promote a distension of the diffuse double layer of the ions adsorbed at the negative electrical charges (CTC) of the soil colloids, which promotes a move away from adjacent clay particles and humic compounds. As a consequence, the soil colloids remain dispersed and may move through the soil clogging the pore spaces and promoting surface sealing (Irvine and Reid, 2001).

In addition to the dispersing elements, the manures (non-humified organic matter) have a large amount of carboxyls per atom of carbon (17.2-22.7 ($R\text{-}COO^-$) COOH/mmol$_{(-)}$ g^{-1} C) (Ohno et al., 2007). So, application of manure to the soil increase the superficial negative charge, increasing the clay dispersion and reducing the aggregation of soil (Benites and Mendonça, 1998; Tavares Filho et al., 2010).

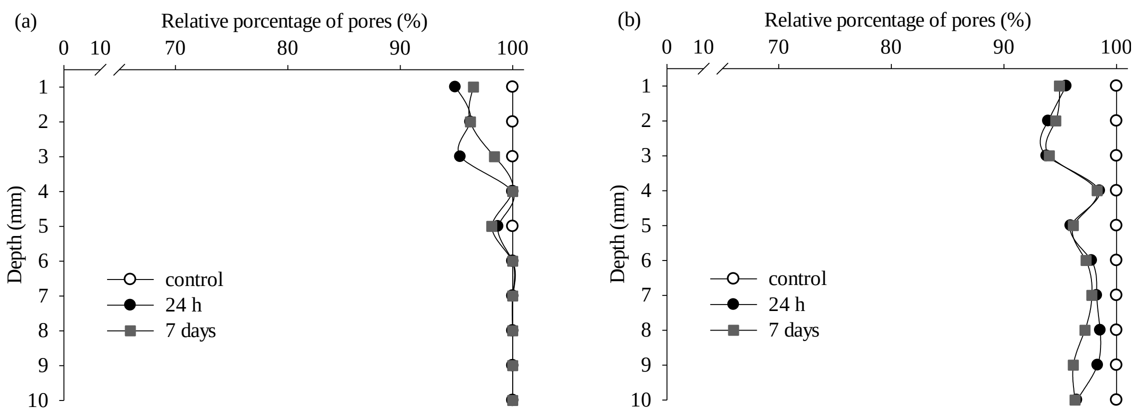


Fig. 4: Change in porosity by chemical mechanism in soil of clayey texture (a) and sandy clay loam texture (b) with liquid dairy manure application (0 % total solids). Percentage relative being the porosity in control treatment considered as 100 %.

Barbosa et al. (2015), performing a study with aggregation and clay dispersion of an Oxisol treated with swine manure, found that manure application resulted in dynamic modifications of the dispersible clay contents and aggregation processes. They observed that in 0 day after manure application had an increase the dispersible clay content, being the maximum dispersion was 15 days after application; between 15 and 30 days after application occurred flocculation and restructuring of the soil.

Although observed, the change in soil porosity when was applied LDM 0 % total solids was small, so the isolated effect of the chemical mechanism (clay dispersion) is not strong enough to cause a potential soil surface sealing. However, the action of the chemical mechanism in the sealing is important and depends of the type of soil , the soil pH, and the dispersant elements content in manure and also.

So, in our study, the change of porosity surface by chemical mechanism (clay dispersion) was pretty smaller when compared to physical mechanism (clogging pores). Therefore, the decrease in the soil porosity by LDM application on soil surface showed that process of soil sealing surface was influenced mainly by the clogging of pores.

3.4. Conclusions

The application of liquid dairy manure promoted soil surface sealing. The surface sealing was stronger in the first millimeters and in interval of 24 hours post LDM application, in both soil textures evaluated. The physical mechanism was the mainly factor of sealing surface due the clogging of pores. Soil surface sealing by chemical mechanism due clay dispersion was present, but was smaller than physical mechanism. Computed tomography (CT) technique was effective to evaluate the porosity change and soil sealing surface promoted by liquid dairy manure application.

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CONCLUSÕES FINAIS

A aplicação de dejeto líquido bovino na superfície do solo em curto prazo promove o processo de selamento superficial, principalmente logo após aplicação. O selamento superficial do solo influencia diretamente na infiltração da água e resulta em maior escoamento superficial e consequentemente, maiores perdas de água solo e nutrientes.

No processo de selamento superficial, o mecanismo físico é o principal agente selante, pois promove o entupimento dos poros devido aos sólidos totais presentes no dejeto líquido bovino, dificultando a entrada de água no solo. A ação do mecanismo químico no processo de selamento superficial é muito inferior comparado ao mecanismo físico, sendo dependente principalmente do teor de agentes dispersantes presentes no dejeto. O selamento superficial do solo é fortemente influenciado pelo intervalo de aplicação do dejeto líquido, bem como pela dose aplicada, teor de sólidos totais presentes no dejeto e cobertura do solo.

Sendo assim, práticas de manejo adequadas do dejeto líquido bovino, tais como taxa de aplicação, intervalo entre aplicação e ocorrência de precipitação, bem como práticas conservacionistas do solo são extremamente importantes para minimizar o selamento superficial do solo e evitar possíveis riscos de poluição dos corpos hídricos.

Como conclusão final, verificamos a necessidade de realizar mais pesquisas em relação ao processo e mecanismos de selamento superficial do solo pela aplicação de dejeto líquido animal. Sugerimos realizar trabalhos a campo a fim de estudar o selamento superficial, bem como estudos relacionados a composição do dejeto e sua relação direto com o solo, principalmente a curto prazo.

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