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Review

Soil surface sealing by liquid dairy manure affects saturated hydraulic conductivity of Brazilian Oxisols

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ABSTRACT

Liquid manure applied on the soil surface may alter its hydraulic conductivity by surface sealing. In this study, we evaluated the chemical and physical mechanisms of the surface sealing process acting in sandy clay loam and clayey soils after liquid manure application (LDM). Factors affecting surface sealing, such as LDM dosage, total solids content of LDM, straw cover, and time after LDM application, were also studied. The saturated hydraulic conductivity (K_{sat}) was determined before and 24 h and 7 days after LDM application, and the sealing index was calculated. The liquid dairy manure application on the soil surface promoted surface sealing in both soils; around 93% of sealing surface was due to physical mechanisms and around 7% chemical mechanisms. The application of LDM with 9.4% total solids (TS) promoted a greater sealing index (greater surface sealing) compared to LDM with 0% TS, mainly within 24 h of LDM application. Greater surface sealing was also observed with a higher LDM dose (60 m^3 ha^{-1}). Soil cover with 5 Mg ha^{-1} of straw resulted in a lower sealing index (lower surface sealing) than soil with 0 Mg ha^{-1} of straw. Sealing index was greatest at 24 h after LDM application for all treatments (solids content, LDM dose and soil cover) in both soils (clayey and sandy clay loam). The clayey soil was more susceptible to surface sealing after LDM application than the sandy clay loam. In practical terms, application of LDM with a high total solids content to bare soil when followed by rainfall 24 h after LDM application, enhanced susceptibility to surface sealing and, consequently, greater detrimental effect on surface water quality.

1. Introduction

Hydraulic conductivity at the soil surface and infiltration capacity are two factors that determine the amount of runoff resulting from a rainfall event and are greatly affected by surface sealing. Soil surface sealing is characterised by the presence of a thin layer of high density and low porosity (Hillel, 1998; Sumner and Stewart, 1992) and usually occurs after heavy rainfall events (Badorreck et al., 2013; Jakab et al., 2013). However, the application of liquid manure also promotes surface sealing, influencing water infiltration and contributing to the occurrence of soil, water and nutrient losses (Cherobim et al., 2017; Mori et al., 2009; Smith et al., 2007).

Surface sealing with application of liquid manure can involve physical, chemical and biological mechanisms (Culley and Phillips, 1986; Cihan et al., 2006). Physical clogging of pores by the particulate present in the liquid manure is the main mechanism by which soil surface sealing occurs (Chang et al., 1974; deTar, 1979; Rowsell et al., 1985; Barrington et al., 1987). Both the total solid content of the animal slurry and the total load (application dose) influence the above mentioned pore clogging, and thus, infiltration and runoff rates (Cherobim et al., 2015; Mori et al., 2009).

In contrast, the contribution of chemical mechanisms to surface sealing by liquid manure application is negligible and depends mainly on manure pH and concentration of dispersant elements present in the manure (Barrington et al., 1987). On the other hand, a clay dispersion by chemical forces would be a problem in soil with saline-sodic wastewater application (Halliwell et al., 2001; Tillman and Surapaneni, 2002). The dispersed particles move through the soil profile, clogging the pore spaces and causing surface sealing (Irvine and Reid, 2001). The chemical mechanism involved in surface sealing through the clay dispersion can be influenced by factors such as soil texture and mineralogy, pH, aggregates, building agents and soil sodicity (Balks et al., 1998; Shainberg, 1992).

Seal formation on cultivated soil begins with the breakdown of

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surface aggregates and the physical dispersion forces are influenced by the raindrop impact (Bradford and Huang, 1992). Straw mulch is a sustainable management strategy that reduces surface sealing and, consequently, runoff and erosion, since the straw protects the soil surface from the effect of raindrop impact and improves soil stability (Bradford and Huang, 1992; Prosdocimi et al., 2016; Zhang et al., 2014). In a study using rainfall simulation, it was observed that greatest pore clogging at the soil surface occurred with conventional tillage (no soil cover) compared to conservation tillage (Rosa et al., 2013). Soil cover, straw for example, with surface application of liquid manure will act as a protective layer which will retain the manure particles, thus avoiding clogging of pore spaces.

The interval between manure application and a 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 were affected by surface sealing promoted by fine manure particles (Edwards and Daniel, 1993). However, in the long-term (greater than four days after the liquid manure application), soil hydraulic conductivity can return to a value that approximates its initial value, probably due to drying of the liquid manure that partially unclogged the surface pores (Chang et al., 1974; Edwards and Daniel, 1993; de Vries, 1972).

The objective of this study was to clarify the process associated with soil surface sealing after application of liquid dairy manure (LDM) to sandy clay loam and clayey soils under a no-till system. More specifically, our study aimed to ascertain the impact of the following factors on saturated hydraulic conductivity due to surface sealing caused by LDM application: (i) the relative contribution of physical and chemical mechanisms; (ii) the effect of total solids content of LDM; (iii) the effect of soil cover (straw); (iv) the effect of time after LDM application.

2. Material and methods

2.1. Soil characterisation

The soil samples were collected from two experimental fields, one field in Castro (24°51′50"S and 49°56′25"W) and one in Ponta Grossa (25°00′35"S, 50°09′16"W). These fields had been cultivated under crop rotation, involving soybean (*Glycine max*), maize (*Zea mays*), oats (*Avena spp*) and wheat (*Triticum aestivum*), and managed with a no-till system for more than 20 years. The soils (Table 1) were classified as Oxisol according to the US Soil Taxonomy (Soil Survey Staff, 1999), corresponding to the Brazilian Soil Taxonomy (Embrapa, 2013) classification as a Latosol with clayey texture (Castro) and sandy clay loam texture (Ponta Grossa).

Table 1
Physical and chemical properties of the investigated soils at depth of 0-0.20 m.
Source: Adapted from Mori et al. (2009) and Cherobim et al. (2015).

	Physical properties							
	Clay	Silt	Sand	MWD	ρ_s	Mic	Mac	K_s
	– g kg^{-1} –			mm	Mg m^{-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.

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. Experimental design and treatments

Undisturbed soil samples were collected using a cylinder of 49 mm diameter from the 0–53 mm upper layer. The study consisted of two experiments (clayey soil and sandy clay loam soil), with the same experimental design and treatments used for both.

The experimental design was completely randomised, with five replicates. The treatments were: two total solids (TS) contents of LDM (0 and 9.4%); two doses of LDM (30 and 60 m^3 ha^{-1}); two soil covers (0 and 5 Mg ha^{-1} of oat straw), arranged in a 2 × 2 × 2 factorial scheme, with a total of eight treatments. The saturated hydraulic conductivity (K_{sat}) was determined with deionised water before LDM application, and 24 h and 7 days after LDM application. Each soil cylinder consisted of a single sample which was analysed before and after LDM application. The treatment involving application of LDM containing 9.4% TS (Table 2) was performed to determine physical and chemical mechanisms; application of LDM containing 0% TS (filtered using a 0.45-μm membrane filter) was performed to determine chemical mechanisms. The physical mechanism was determined as the difference between the treatment with LDM containing 9.4% TS and the treatment with LDM free of TS.

The saturated hydraulic conductivity was measured using the method of falling head permeameter (Reynolds and Elrick, 2002). Details of the methodology were reported by Cavalieri et al. (2009).

Sealing index (SI) was used to indicate soil surface sealing promoted by LDM application. A higher SI value indicates a greater effect of surface sealing. SI was calculated as:

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

Where SI is the sealing index and Ksat is the saturated hydraulic conductivity.

2.3. Statistical analysis

Preliminary statistical analysis indicated that the data required logarithmic transformation (base10) to achieve the assumption required for ANOVA. ANOVA and Tukey's test ($P < 0.05$) for mean comparison procedures were performed using the STATISTICA 10 software (StatSoft, 2011).

3. Results

With both soil types, at 24 h after LDM application, a higher SI value, indicating greater surface sealing, was found with application of LDM containing 9.4% TS compared to 0% TS (Fig. 1a, b); the SI value with LDM containing 0% TS was around 93% less. Therefore, considering that LDM 0% TS reflects only the chemical mechanism and that LDM 9.4% TS reflects the physical plus chemical mechanisms, it can be concluded that around 7% of the surface sealing was due to the chemical mechanisms and 93% the physical mechanism.

At 7 days after LDM application, the SI value also was significantly greater with LDM 9.4% TS than LDM 0% TS, around 40% in clayey soil and 60% in sandy clay loam soil (Fig. 1a, b). However, comparing the intervals after LDM application, the SI value (surface sealing) with application of LDM 9.4% was much greater after 24 h than after 7 days (91% greater in clayey soil and 77% in sandy clay loam soil).

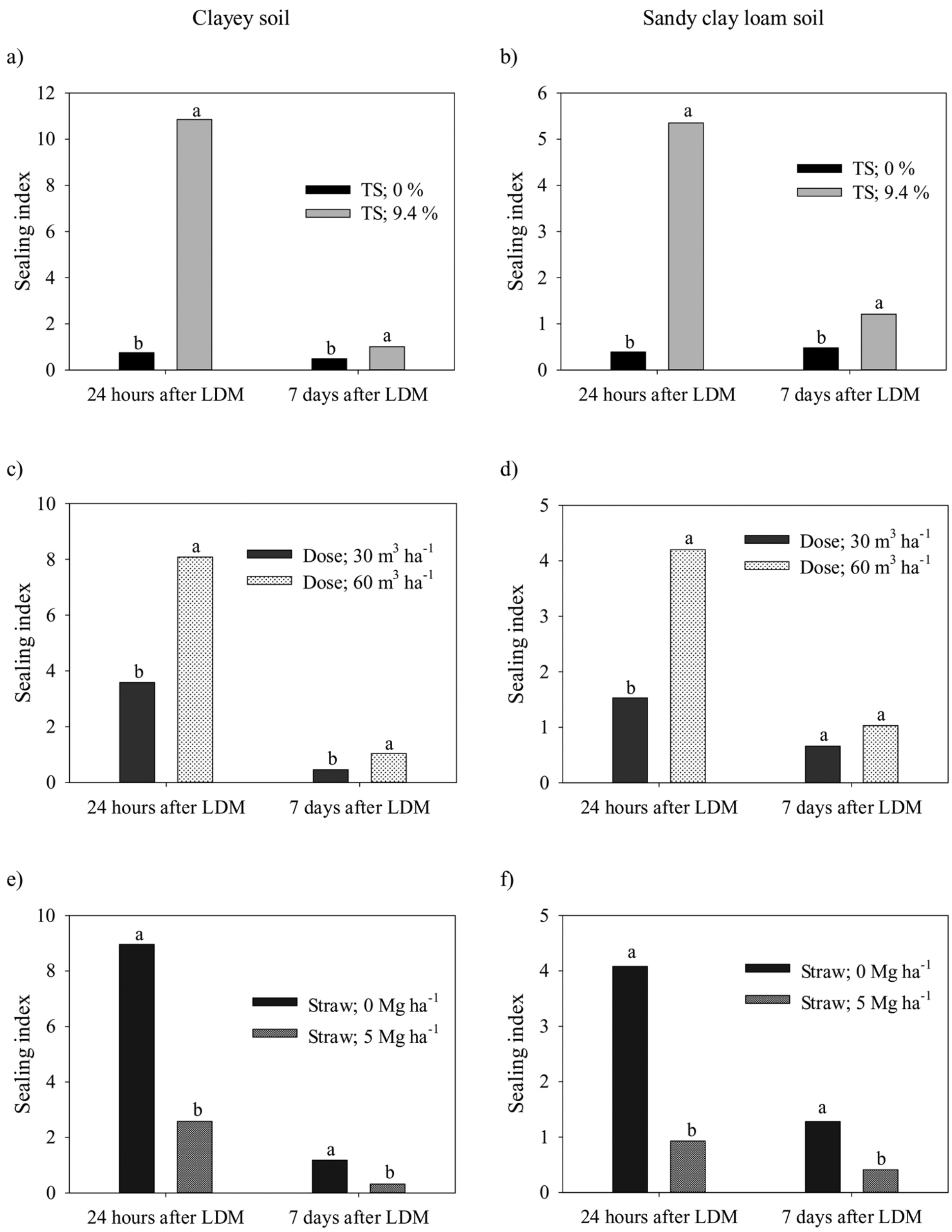

Fig. 1. Sealing index (K_{sat} before LDM − K_{sat} after LDM application), showing effects of total solids (TS), LDM dose, and soil cover (straw) in surface sealing with 24 h and 7 days after LDM application, on clayey soil (left; a, c, and e) and sandy clay loam soil (right; b, d, and f). Means followed by the same letters in each single factor do not differ statistically by Tukey test at 5% probability.

The LDM dose data (Fig. 1c, d) shows greater surface sealing (a higher SI value) with application of 60 $m^3\,ha^{-1}$ LDM at 24 h after LDM application in both soils. The decrease in the SI value with 30 $m^3\,ha^{-1}$ LDM when compared to 60 $m^3\,ha^{-1}$, was around 55% with clayey soil and 63% with sandy clay loam soil.

Soil cover (straw), at both intervals after LDM application (24 h and 7 days), affected surface sealing in clayey soil and sandy clay loam soil (Fig. 1e, f). The higher SI values occurred at 24 h after LDM application with 0 $Mg\,ha^{-1}$ of straw. Comparison of the presence or absence of straw on the soil surface (0 and 5 $Mg\,ha^{-1}$), 5 $Mg\,ha^{-1}$ of straw decreased the SI values by around 70% with clayey soil and 81% with sandy clay loam soil, showing a positive effect of the straw on decreasing surface sealing, mainly in sandy clay loam soil. At 7 days after LDM application, SI values also were greater with 0 $Mg\,ha^{-1}$ than with 5 $Mg\,ha^{-1}$ of straw.

Comparing the soils, the clayey soil was more affected by LDM application than the sandy clay loam soil, mainly at 24 h after application (Fig. 1). For total solids content, the SI value in clayey soil was around 50% greater than sandy clay loam soil with both TS contents (0 and 9.4% TS); for the LDM dose, the SI value increased by 58% with LDM 30 $m^3\,ha^{-1}$ and 48% with LDM 60 $m^3\,ha^{-1}$; while for soil cover, the increase in SI value was 46% with 0 $Mg\,ha^{-1}$ of straw and 65% with 5 $Mg\,ha^{-1}$ of straw.

4. Discussion

The TS content of LDM plays an important role in the surface sealing process because it defines the contribution of each mechanism involved in sealing. It is assumed in this study that LDM containing 9.4% TS defines the physical plus chemical mechanism, while LDM containing 0% TS defines the chemical mechanism (no clogging of pores will occur by manure solid particles in this condition). The results (Fig. 1a, b) indicated that surface sealing was dominated by a physical mechanism involving 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 contribution of the chemical mechanism to surface sealing was not significant in the present study. Chemical forces acting on clay dispersion causing seal formation would be predominant with saline-sodic wastewater application (Shainberg, 1992; Halliwell et al., 2001; Tillman and Surapaneni, 2002). The sealing promoted by the chemical mechanism was possibly due to pH and cation exchange capacity increase caused by organic compounds, and due to the presence of dispersant elements (Na and K; Table 2) which enabled the clay dispersion (Barrington et al., 1987).

The LDM dose affected surface sealing (Fig. 1c, d), mainly at 24 h after LDM application, showing the importance of an adequate interval after manure application. Study with LDM doses and water infiltration showed that the increase in LDM dose applied on the soil surface affected the hydraulic conductivity, decreasing the water infiltration mainly a short time (1 day) after manure application (Cherobim et al., 2015).

In general, surface sealing decreased at 7 days after LDM application (Fig. 1) and this can be explained by the drying of the LDM, partially unclogging the surface pores and allowing the recovery of hydraulic conductivity back to the original (unamended) Ksat value (Chang et al., 1974; Edwards and Daniel, 1993; de Vries, 1972).

The presence of straw on the soil surface is important for protecting the soil surface from the effects of raindrop impact (Donjadeea and Tingsanchalib, 2016). In the case of liquid manure application, straw also prevents direct contact of manure with the pore space and, consequently, prevents surface sealing and the decrease in hydraulic conductivity (Fig. 1e, f).

Soil texture plays an important role in surface sealing. The breakdown of soil aggregates caused by raindrop impact and clay dispersion caused by chemical forces are closely dependent on clay content and mineralogy. Seal formation occurs more readily on sandy loams than on clay loams due to the lower aggregate stability of the former (Bradford and Huang, 1992; Shainberg, 1992). However, in this study, the difference in SI values between the soils (Fig. 1) indicates that the surface sealing by LDM application in the clayey soil was greater than in sandy clay loam soil. In this study, without raindrop impact, it appears that the clay soil was more affected by clogging of micropores due the fine particulate material present in the liquid manure.

5. Conclusions

Application of liquid dairy manure on the soil surface promotes 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 conditions for surface sealing was at an interval of 24 h after LDM application, higher total solids content of LDM (9.4% TS), higher dose of LDM (60 $m^3 ha^{-1}$) and less soil cover (0 $Mg ha^{-1}$ of straw).

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