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Micromorphology of pores and water erosion in Inceptisol soil after application of pig slurry

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ABSTRACT

The application of pig slurry (PS) to soil is known to change its chemical and physical properties. However, little is known about the alterations that PS causes in pore morphology and water erosion. This research evaluated the influence of PS on the morphology of the pores in the surface layer of the soil and on water erosion in an Inceptisol subjected to simulated rainfall. The soil was cultivated with black oats and the treatments (doses) 0, 50, 100 and 200 m^3 ha^{-1} of PS were applied to the crop residue. The experimental design was completely randomized. Six simulated rainfall lasting 60 minutes and planned constant intensity of 65 mm h^{-1} were applied to the treatments. Undisturbed soil samples were collected in the 0-0.05 m layer, 24 h before and 24 h after the first, third and sixth rainfall events. Image analysis was performed, determining the percentage of macropores and mesopores, number, diameter and shape of the pores, using the micro morphometry technique. PS doses of 100 and 200 m^3 ha^{-1}, combined with simulated rainfall, favored surface sealing and pore rearrangement. There was an increase in the number of small and rounded pores, without interconnection between them, with a consequent increase in water erosion until the moment of stabilization of the superficial crust.

Keywords: micro morphometry, organic fertilizer, porometry.

Micromorfologia de poros e erosão hídrica em Cambissolo após aplicação de dejeto líquido de suínos

RESUMO

O dejeto líquido de suínos (DLS) aplicado no solo reconhecidamente altera as propriedades químicas e físicas. Porém, ainda são pouco conhecidas as alterações que o DLS causa na morfologia dos poros e na erosão hídrica. Com esta pesquisa objetivou-se avaliar a influência do DLS na morfologia dos poros da camada superficial do solo e na erosão hídrica, em um

Cambissolo submetido à chuva simulada. O solo foi cultivado com aveia preta e os tratamentos (dose) 0, 50, 100 e 200 m^3 ha^{-1} de DLS foram aplicados sobre o resíduo da cultura. O delineamento experimental foi o inteiramente casualizado. Seis chuvas simuladas com duração de 60 minutos e intensidade constante planejada de 65 mm h^{-1} foram aplicadas aos tratamentos. Amostras indeformadas de solo foram coletadas na camada de 0-0,05 m, 24 h antes e 24 h após o primeiro, terceiro e sexto eventos de chuva. Foi realizada análise de imagem, determinando-se a porcentagem de macroporos e mesoporos, número, diâmetro e forma dos poros, pela técnica de micromorfometria. As doses 100 e 200 m^3 ha^{-1} de DLS, combinadas com a chuva simulada, favoreceram o selamento superficial e o rearranjo dos poros. Houve aumento do número de poros pequenos e arredondados, sem interligação entre eles, com consequente aumento da erosão hídrica até o momento de estabilização da crosta superficial.

Palavras-chave: fertilizante orgânico, micromorfometria, porometria.

1. INTRODUCTION

Swine farming activity has evolved in Brazil, such that Brazil has become the fourth-largest producer of swine in the world (ABPA, 2018). This activity provides important economic and social benefits to the rural population that works in this area. For some time now, a great concern has been regarding the disposal of pig waste in the environment, due to the large volume generated and its incorrect management (Rosa *et al.*, 2017).

Pig slurry (PS) has been used as a fertilizer in soil, as this is an apparently viable form of disposal, constituting a low-cost fertilizer in small properties in the southern region. Most producers, however, often apply PS above the recommended dose (Kaufmann *et al.*, 2019). This implies a high concentration of nutrients, metals, and pathogens in the soil (Oliveira, *et al.*, 2015). The continuous application of PS in the soil can cause serious problems such as the eutrophication of surface waters, contamination of the groundwater, and changes in soil quality (Cardoso *et al.*, 2015).

The physical properties of the soil can be influenced by the effect of PS applied consecutively in high doses. This effect is not yet fully undertood. Some researchers showed that there was no improvement in the quality of physical properties of the soil with the application of PS (Bandeira *et al.*, 2019; Mergen Júnior *et al.*, 2019); while other research has shown that PS caused soil degradation after the application of high doses (Cherubin *et al.*, 2015; Oliveira *et al.*, 2016).

The effect of PS on soil porosity, specifically, has been contradictory, and therefore there is no consensus in the literature. The volume of macropores, micropores, cryptopores and total soil pores was evaluated after applying PS at doses of 0, 48, 96, 144, 192, and 240 m^3 ha^{-1} $year^{-1}$ for four years in a Oxisol soil, no dose-response (Agne and Klein, 2014). Decrease in total porosity, mainly in macroporosity, was observed in Alfisol soil submitted to PS and chicken litter (Rauber *et al.*, 2018). The authors attributed this effect to the combined influence of soil and PS management. Pore obstruction and the occurrence of hydrophobism on the soil surface were observed by Bertol *et al.* (2007) after applying PS, with reduced water infiltration and increased runoff.

Given the uncertainties regarding the effect of PS on soil porosity, the technique of micro morphometry emerges as a resource that makes it possible to analyze and quantify the volume, the form, and distribution of pore diameter (Fox *et al.*, 2009). This technique allows evaluating the surface crusting in eroded soils (Castilho *et al.*, 2015) and inferring on the soil water movement (Kodesova *et al.*, 2011), being able to process images and obtain parameters of the porous system (Cooper *et al.*, 2016).

Knowledge regarding the influence of PS on the pores in the soil surface, qualitatively and quantitatively, allows the sustainable use of this organic fertilizer. The present research evaluated the modifications caused by PS in the morphology of the superficial porosity of an Inceptisol subjected to simulated rainfall. Thus, the following hypotheses were tested: the diameter, number of pores and the connectivity between soil pores increase and water erosion decreases with the increase of doses of pig slurry applied in the soil. Also, the erosive rainfall successively applied to the soil modifies the pores, changing from an elongated shape to a rounded shape.

2. MATERIALS AND METHODS

The research was carried out in an Inceptisol soil (United States, 2014). The experiment was conducted at coordinates 27º47’S and 50º18’W, at an approximate altitude of 900 meters. The climate of the region is Cfb (wet subtropical), according to the Köppen classification (Alvares *et al.*, 2013), with an average annual rainfall of 1,533 mm Schick *et al.*, 2014a). The average slope of the experimental area is 0.134 m m^{-1}. The soil contains 196 g kg^{1} of sand, 412 g kg^{-1} of silt and 392 g kg^{-1} of clay in the surface layer, whose erodibility is 0.0175 t ha h ha^{-1} MJ^{-1} mm^{-1} (Schick *et al.*, 2014b).

The soil was cultivated with soybean (*Glycine max* L.) between November 2013 and April 2014. At the beginning of the crop cycle PS was applied, according to the treatments. Soybean was harvested on April 25, 2014, and then black oats (*Avena strigosa* Schreb) were sown, in the technique of no-till, and cultivated until November 09, 2014, when it was cut manually. The dry mass of the aerial part of the oats was 1.8 Mg ha^{-1}, 2.1 Mg ha^{-1}, 3.0 Mg ha^{-1}, and 3.2 Mg ha^{-1}, where the doses 0, 50, 100, and 200 m^3 ha^{-1} of PS had been applied, respectively. Then, soil preparation was carried out with a light harrow operation, a scarifying operation, and another light harrow operation. In such condition, the four treatments consisting of doses of PS were installed, in two replications, as follows: without PS (D0 - control), 50 m^3 ha^{-1} of PS (D50), 100 m^3 ha^{-1} of PS (D100), and 200 m^3 ha^{-1} of PS (D200). These doses were applied to the same plots that had received the doses in the soybean cycle, previously.

The doses of PS were applied six times on the residue of black oat remaining from the soil tillage. Thus, treatment D0 did not receive PS, treatment D50 received 300 m^3 ha^{-1} of PS, treatment D100 received 600 m^3 ha^{-1} of PS and treatment D200 received 1,200 m^3 ha^{-1} of PS, throughout the period of search. Each of the applications was preceded by one day each of simulated rainfall. The PS was composed of a mixture of feces, urine, water, and debris from the cleaning of the swine farms. The characteristics in the fraction solid+liquid of the PS was pH (7.0), dry mass (0.38%), and NO_3^- (7.23), NH_4^+ (31.82), NO_2^- (0.22), P (21.31), and K (86.18) mg L^{-1} in the fraction liquid. The PS was manually applied to the soil surface with watering cans.

The experimental unit, or plot, was 11 m long down the slope and 3.5 m wide, delimited on the sides and upper end by galvanized sheets 0.2 m high, buried 0.1 m into the ground. The lower end of the plot was delimited by a collecting gutter connected to a pipe that directed the runoff to a trench, 6 m below, where the flow was measured and samples were collected to determine the losses of soil and water.

During the research, six simulated rainfall tests were carried out in each treatment, on the following dates: Test 1 (T1), in October 25, 2014, Test 2 (T2), in January 17, 2015, Test 3 (T3), in March 20, 2015, Test 4 (T4), in Ma 15, 2015, Test 5 (T5), in July 30, 2015, and Test 6 (T6), in October 13, 2015. Each simulated rainfall had a duration of 60 minutes, a constant intensity planned for 65 mm h^{-1} and was carried out with a thrust-type rotating arms simulator (Bertol *et al.*, 2012). On each date, four rains were carried out, one in each treatment, composing a rain test. The simulated rainfall erosivity index (EI) was calculated according to the methodology proposed by Meyer (1958).

Undisturbed soil samples were collected as a monolith in the upper portion of the plots with a spatula and cotton. The samples were stored in cardboard boxes (0.12 x 0.07 x 0.05 m). The collection took place 24 h before Test 1 of simulated rainfall (Time 0), 24 h after Test 1 (Time 1), 24 h after test 3 (Time 3), and 24 h after test 6 (Time 6). The undisturbed samples were taken to the laboratory, where they dried naturally on countertops.

Later, the samples were impregnated with a solution containing polyester resin, styrene monomer and fluorescent pigment, following the methodology described by Cooper *et al.* (2017). Afterwards, the samples were polished, and image capture was performed with subsequent micro morphometry analysis. Images were captured and thereafter processed using Noesis Visilog software. Then, through digital image analysis, the number, diameter, and type of pores in the samples were determined. Thus, rounded pores (channels and isolated voids), elongated pores (cracks) and complex pores (packing voids) were detected. These determinations followed the methodology described in Cooper *et al.* (2010) and Castilho *et al.* (2015).

Soil porosity was evaluated in the 0.05 m layer of the monolith, which was divided into three sublayers. Each of the sublayers (upper, middle and lower) had a thickness of 0.0167 m. Between five and six microphotographs per sublayer were analyzed, generating a maximum total of 18 images per monolith.

The experimental design was completely randomized, using the Sisvar statistical software (Ferreira, 2010). Differences between means, if any, were detected by analysis using the Tukey test ($p<0.05$). The values of total pores (%) and number of pores (Nº) were correlated with each other, to which the model $y = a + bx$ was fitted.

3. RESULTS AND DISCUSSION

Erosivity (EI) of simulated rainfall varied widely between rainfall tests and among treatments (Table 1). Considering the average of EI values there was greater variation between tests, for the same treatment, than between treatments for the same rainfall test. Between treatments, the values varied between the minimum, 836 MJ mm ha^{-1} h^{-1}, and the maximum, 887 MJ mm ha^{-1} h^{-1}, in the mean of the rainfall tests. For these values, there was no tendency to decrease or increase from one treatment to another, neither from the highest dose of PS to the lowest dose. The variation of EI values between the rainfall tests was between the minimum, 716 MJ mm ha^{-1} h^{-1}, and the maximum, 1,145 MJ mm ha^{-1} h^{-1}, in the average of the treatments, with a tendency to increase the dispersion of data, based on standard deviation (SD), from T1 to T3, as well as from T4 to T6.

Table 1. Erosivity (EI) of simulated rainfall applied over treatments (average of repetitions).

Treatment	T1	T2	T3	T4	T5	T6	Average	SD
				EI (MJ mm ha^{-1} h^{-1})				
D200	953	822	762	677	1,141	966	887	167
D100	925	794	846	712	1,131	762	862	151
D50	864	877	591	742	1,159	935	861	191
D0	837	849	666	780	1,150	735	836	168
Average	895	836	716	728	1,145	850	-	-
SD	54	36	111	44	12	118	-	-

D200: 1,200 m^3 ha^{-1} of PS; D100: 600 m^3 ha^{-1} of PS; D50: 300 m^3 ha^{-1} of PS; D0: without slurry; T1, T2, T3, T4, T5 and T6: tests of simulated rainfall. SD: standard deviation.

Soil losses (SL) did not differ statistically, with little numerical variation between treatments (Table 2). Among the rainfall tests, the SL showed a relatively high numerical variation for the same treatment. Soil cover and oat residue mass, still present on the soil surface at the time of T1, determined the low SL values in all treatments relating to losses occurred in the other rainfall tests. Thus, the SL increased from T1 to T3 for all treatments, and decreased from T3 to T6, although the EI of simulated rainfall was higher in T5 (Table 1), showing the formation and stabilization of the surface seal from T4 on (visual observation carried out by the authors at the time of the rainfall). The surface seal evolved into crust when the soil lost moisture.

The increase in soil consolidation due to the crust effect stabilizes the surface and makes the soil more resistant to erosion (Nearing *et al.*, 1988). Due to the formation of a superficial seal that evolved to consolidated crust, there was a reduction in SL in the final tests (T4 to T6) of simulated rainfall compared to the initial tests (Table 2).

Treatment D200 had the highest water loss (WL) value (Table 2), in the mean of the rainfall tests, demonstrating the influence of this dose of PS. According to Bertol *et al.* (2007) the WL and SL can increase with the increase in the dose of PS due to the hydrophobic effect of the slurry. The increase in WL and the reduction in SL from T3 occurred due to crusting on the soil surface and decreased surface porosity.

Table 2. Soil losses and water losses due to water erosion during tests of simulated rainfall applied in the treatments (average of repetitions).

Soil losses (Mg ha^{-1})							
Treatment	T1	T2	T3	T4	T5	T6	Average
D200	0.2	5.6	16.7	11.6	11.3	8.5	9.0a
D100	0.1	4.1	13.7	10.3	9.4	8.3	7.7a
D50	0.2	3.5	17.3	10.8	10.5	8.3	8.4a
D0	0.3	4.2	11.4	10.4	9.4	9.3	7.5a
Water losses (% of rainfall)							
D200	32.4	64.7	86.4	78.9	84.3	82.3	71.5
D100	26.9	62.3	80.3	74.6	82.4	80.2	67.8
D50	29.8	45.0	73.9	79.3	81.8	84.0	65.6
D0	31.3	51.6	57.1	71.2	77.5	82.2	61.8

D200: 1,200 m^3 ha^{-1} of PS; D100: 600 m^3 ha^{-1} of PS; D50: 300 m^3 ha^{-1} of PS; D0: without slurry; T1, T2, T3, T4, T5 and T6: tests of simulated rainfall.

The biggest numerical differences in SL and WL values occurred at T1, T3 and T6 (Table 2). Therefore, the results of the micro morphometry analysis are presented for the soil samples collected at Time 0 (right before T1) and right after tests Time 1, Time 3, and Time 6, respectively (Table 3).

The percentage of macropores+mesopores (PMM) varied numerically with the simulated rainfall sequence applied (Table 3). The treatments with PS provided the lowest values of PMM compared to the control at all evaluated moments. In treatment D200, there was a reduction in the PMM at Time 3, while at Time 6 this variable was equal to that existing in Time 0. In the D100 treatment, there was a decrease of 11% in the PMM at Time 6 compared to that observed at Time 0. That is justified by the obstruction of the pores caused by the solid fraction of the PS and by the colloidal mineral sediments.

In the D200 treatment, pore obstruction at Time 6 was lower than in D100 (Table 3), due to the reduction in the entry of PS into the soil in the last rainfall tests. At the time of applying the PS, part was lost by runoff because the volume exceeded the infiltration capacity of the soil.

The occurrence of this problem is common in areas of cultivation and configure environmental risk. PS is rich in nitrate and phosphorus that cause eutrophication and contamination of water bodies (Lourenzi *et al.*, 2016).

In treatment D50, the highest values of PMM occurred at Time 0 and Time 6 (Table 3). Initially (Time 0), this was due to soil preparation carried out immediately before starting the rainfall test 1, and finally (time 6), due to the increase in soil shear resistance by action of the runoff. In the same way as occurred in D100, in the D0 treatment there was a tendency for a decrease in the PMM at the end of the research in comparison to the beginning. In this case, the values varied from 33% (time 0) to 28% (time 6). As justification, the action of raindrops on the soil surface, which had a smaller mass of crop residues compared to the other treatments, stands out. The energy of the drops separated the particles from the soil mass that, when adjusted to each other, clogged the pores, by the action of the water, evolving into a surface crust (Dalla Rosa *et al.*, 2013).

Table 3. Percentage of macropores+mesopores (PMM) and total number of pores (TNP) in the 0-0.05 m layer of the soil in the treatments and assays, in an Inceptisol (average of repetitions).

	PMM	SD	CV	TNP	SD	CV
		%			n°	%
			D200			
Tm 0	29 ab	8	27	401 b	100	25
Tm 1	35 a	6	17	347 b	137	40
Tm 3	24 b	10	43	424 b	123	29
Tm 6	29 ab	8	28	788 a	238	30
			D100			
Tm 0	34 a	8	25	550 a	253	46
Tm 1	30 ab	7	23	597 a	247	42
Tm 3	34 a	8	25	525 a	176	34
Tm 6	23 b	6	25	622 a	99	16
			D50			
Tm 0	37 a	10	27	393 b	149	38
Tm 1	27 b	8	30	603 a	263	44
Tm 3	31 ab	9	28	392 b	136	35
Tm 6	34 a	5	15	374 b	130	35
			D0			
Tm 0	33 ab	9	28	434 b	269	62
Tm 1	38 a	9	25	339 b	125	37
Tm 3	37 a	4	10	501 ab	191	38
Tm 6	28 b	7	26	635 a	193	30

D200: 1,200 m^3 ha^{-1} of PS; D100: 600 m^3 ha^{-1} of PS; D50: 300 m^3 ha^{-1} of PS; D0: without pig slurry; Tm 0: time 0, before Test 1 rainfall; Tm 1: after Test 1 rainfall; Tm 3: after Test 3 rainfall; Tm 6: after Test 6 rainfall. SD: standard deviation. CV: Coefficient of variation. Means followed by equal letters do not differ ($p<0.05$) by Tukey's test.

The total number of pores (TNP) increased from Time 0 to Time 6 only in treatments D200 and D0 (Table 3). In D200, the increase was 96.5%, and in D0 it was 46.3%. Therefore, it is possible to state that the dose of PS influenced the porosity, increasing the TNP with the highest dose applied on the soil surface. However, for a better understanding of these changes, it is also important to consider the shape of the pores.

There was change in the morphology and diameter of the pores on the soil surface, depending on the dose of PS in the soil layer and on the number of simulated rainfalls performed (Figure 1, 2, 3 and 4). At the end of the research (Time 6), rounded pores predominated with reduction in complex and elongated pores, compared to the beginning of the research (Time 0), in which there was a predominance of complex and elongated pores with low volume of rounded pores (Figure 1). This occurred due to crusting caused by the impact of raindrops in the soil surface. The crusting was potentialized in the last rainfall tests (Time 6). At this stage of the research, the oat crop residue had been almost completely decomposed, resulting in low surface soil coverage.

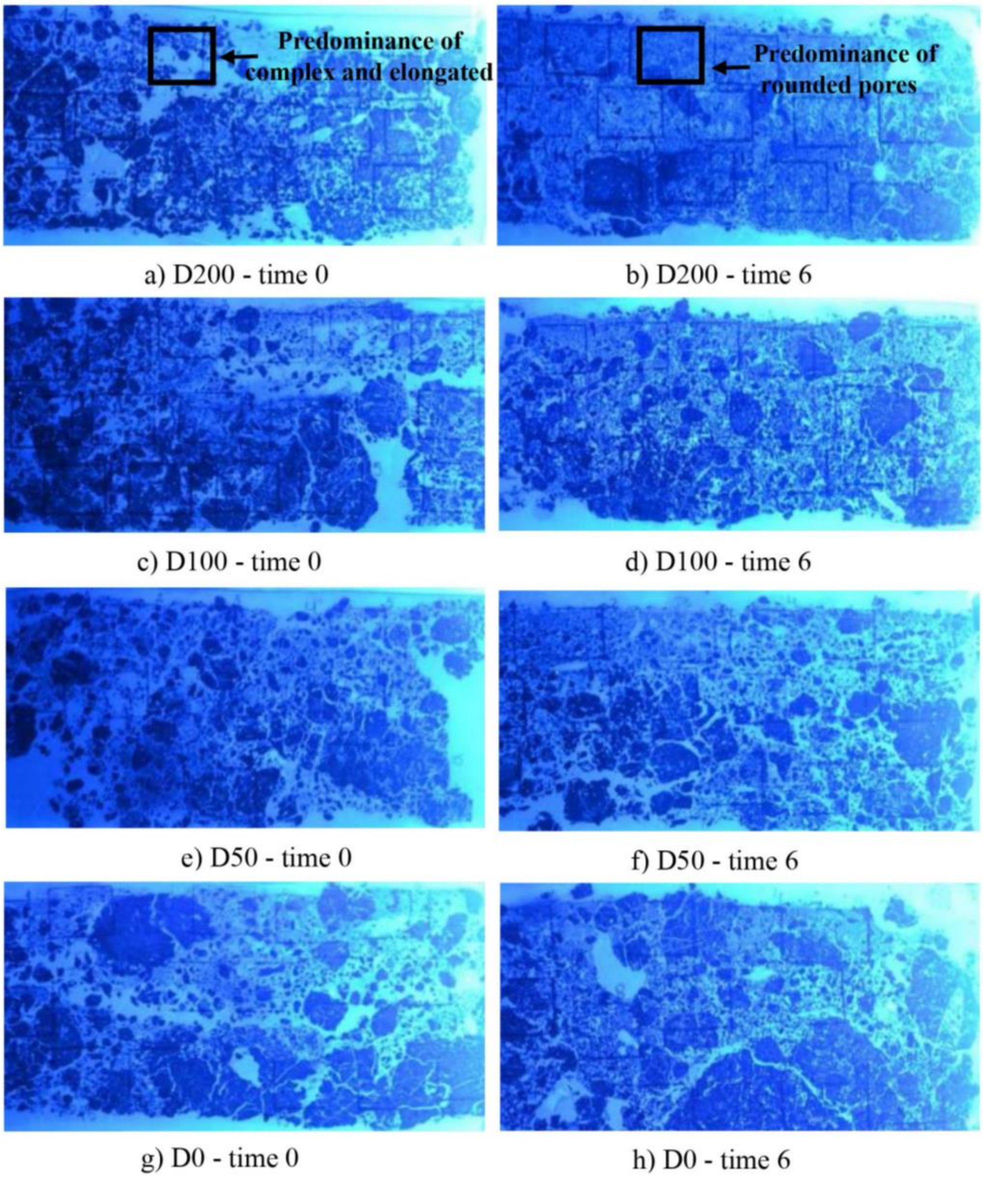

Figure 1. Porous system in the 0-0.05 m layer of the soil, before and after the successive application of PS and simulated rainfall. D200: 1,200 m^3 ha^{-1} of PS; D100: 600 m^3 ha^{-1} of PS; D50: 300 m^3 ha^{-1} of PS; D0: without PS; Time 0: before Test 1 rainfall; Time 6: after Test 6 rainfall.

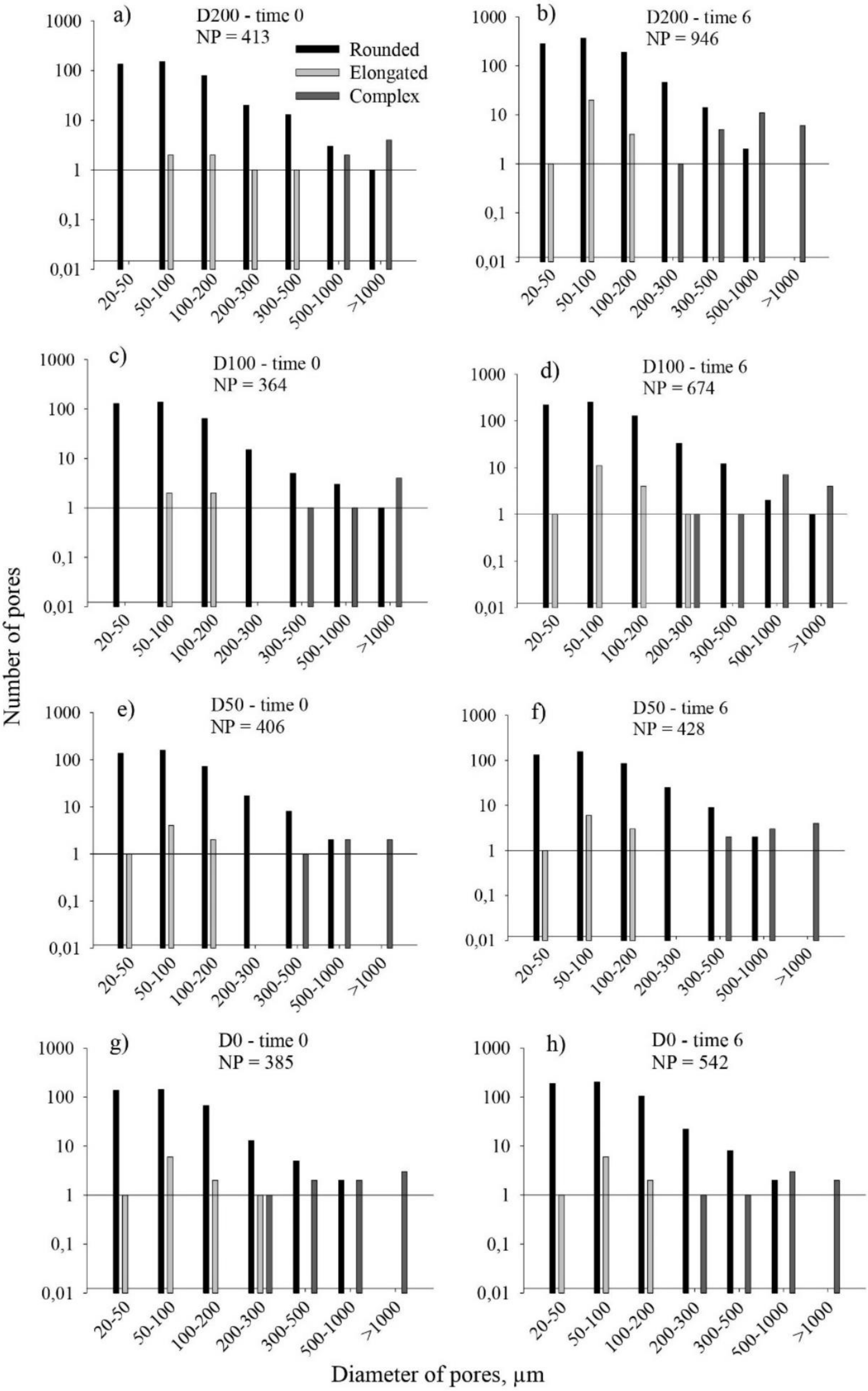

Figure 2. Number, diameter, and type of pores, in the lower layer (0-0.0166 m) before and after application of simulated rainfall and PS doses, in Inceptisol soil.

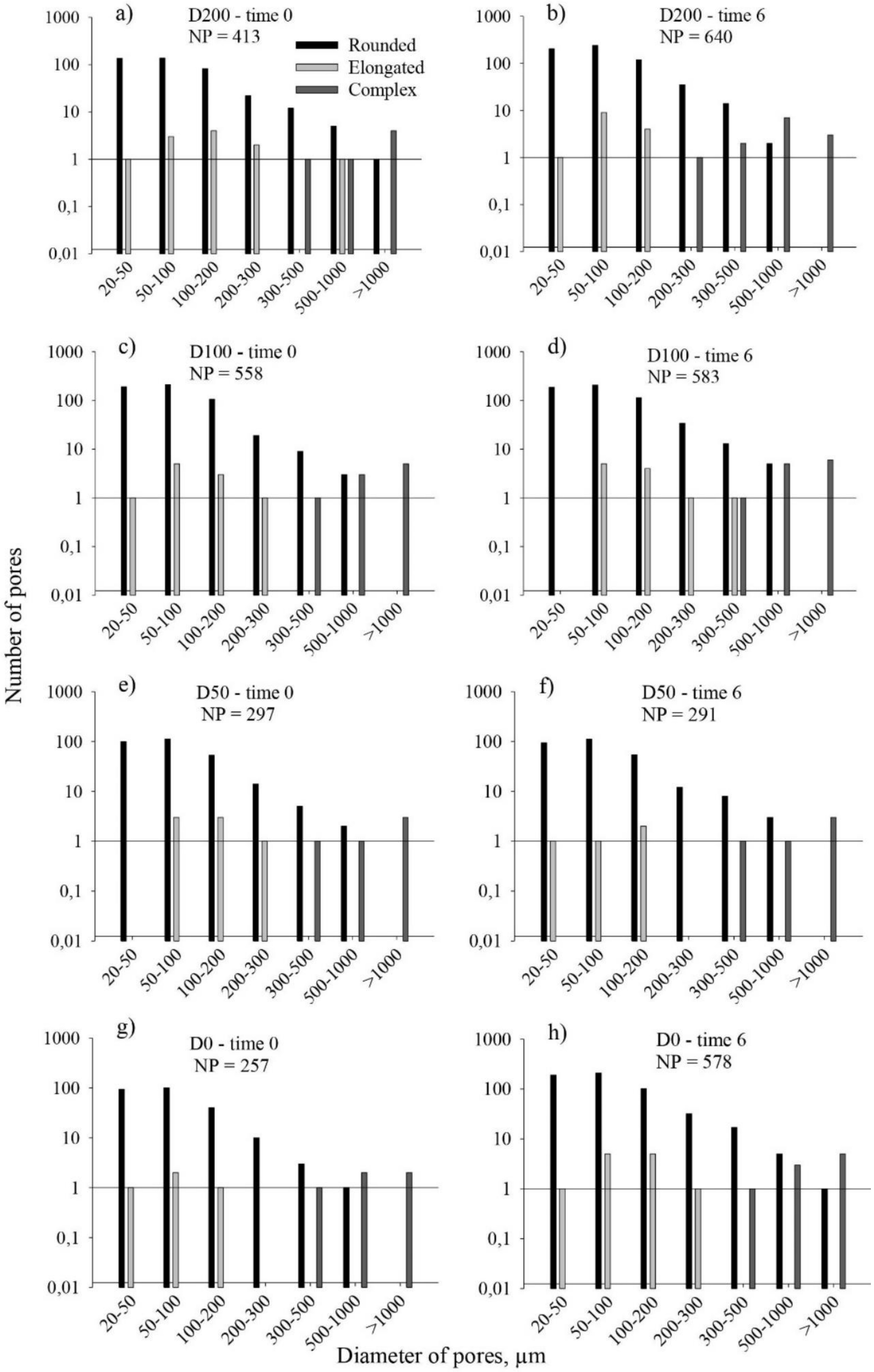

Figure 3. Number, diameter, and type of pores, in the lower layer (0.0166-0.0334 m) before and after application of simulated rainfall and PS doses, in Inceptisol soil.

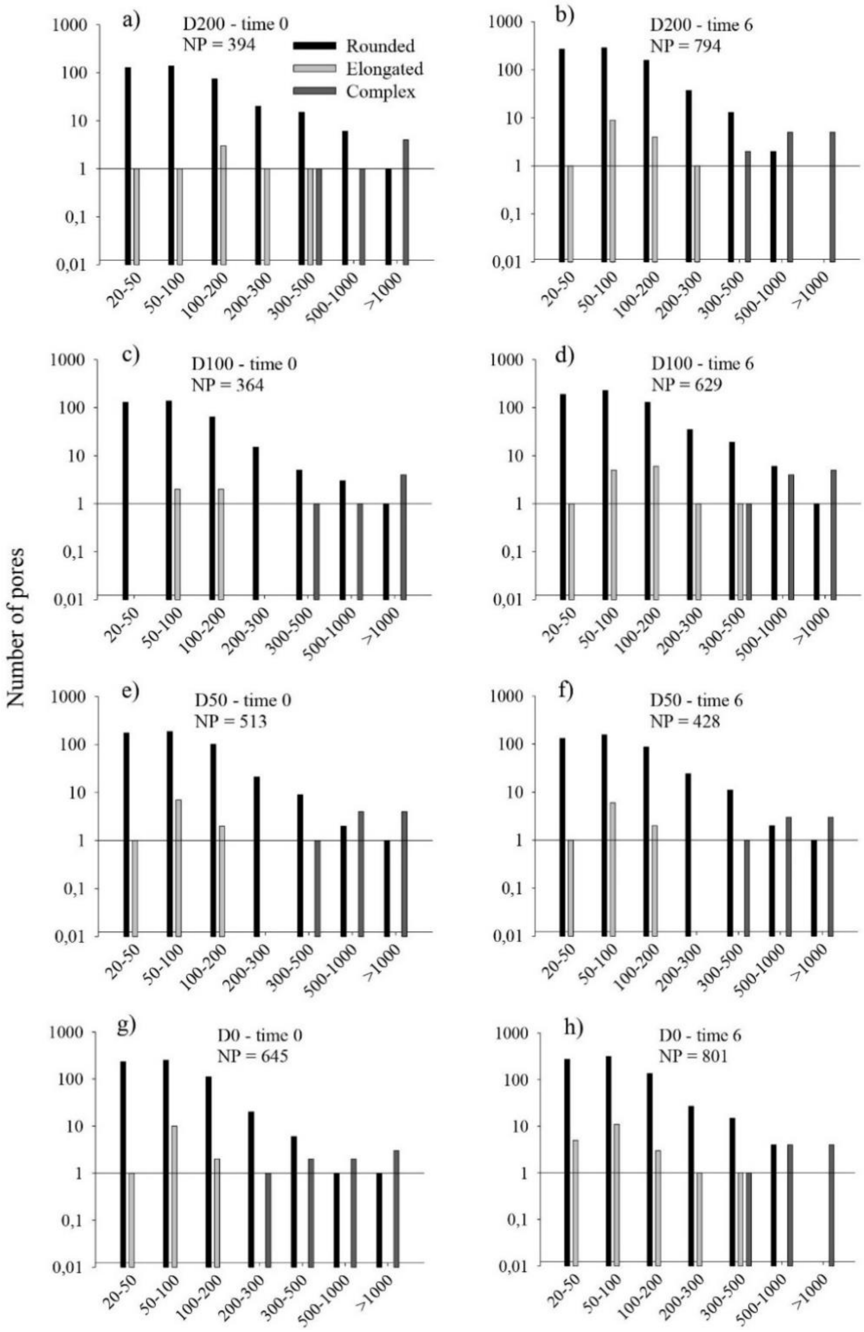

Figure 4. Number, diameter, and type of pores in the lower layer (0.0334-0.0500 m), before and after application of simulated rainfall and PS doses, in Inceptisol soil.

The percentage of macropores+mesopores did not decrease in treatments D200, D50 and D0 (Table 3) at Time 6 compared to Time 0, as occurred in D100, due to the formation of superficial crust. However, there was a morphological change in the pores of these treatments, with a predominance of rounded shapes without interconnection between the Times 0 and 6 (Figures 2, 3 and 4), with a decrease in the movement of water in the soil and an increase in water erosion (Table 2).

Complex pores with diameter > 1,000 μm were preserved and/or formed in the three soil layers in all treatments, after the application of simulated rainfall, even if in smaller numbers when compared to the other types of pores (Figures 2, 3 and 4). The preservation and/or formation of these pores in the soil was due to the action of mechanical preparation, and cultural residue that contributed to dissipating the energy of rainfall and runoff. The decomposition of plant biomass gradually decreased soil protection throughout the study period, and water erosion increased. There was remobilization and redistribution of soil particles that resulted in crusting and consequent alteration of the porous system on the surface.

The presence of elongated pores and large diameter complexes on the soil surface does not guarantee ideal conditions for infiltration and percolation of water in the soil (Silva *et al.*, 2015). The predominance of rounded pores indicates compaction with microstructure degradation and reduced hydraulic flow in the soil (Momoli and Cooper, 2016).

The number of pores (NP) increased at the end of the research (Time 6) compared to the beginning (Time 0), in the upper soil layer (0-0.0167 m) in all treatments of PS doses (Figure 2). The greatest increase in NP occurred at D200 and D100, 129% and 85%, respectively. A morphological change in the pores accompanied the increase in NP, predominating those with a rounded shape and smaller diameter, which provide less water infiltration into the soil and greater runoff compared to non-rounded pores with larger diameters.

The change in soil porosity, in numerical and morphological terms, especially in the most superficial layer, is related to the obstruction of these pores due to the physical action of the PS itself (Bertol *et al.*, 2007; Cherobim *et al.*, 2017) and to the mechanical action resulting from the impact of raindrops (Dalla Rosa *et al.*, 2013; Castilho *et al.*, 2015). Solid particles contained in the PS and soil particles broken down by the impact of raindrops, combined, clog the pores as they are transported into them by the action of water that infiltrates the soil.

The NP variation in the middle and lower layers (Figure 3 and 4) does not allow us to verify the influence of the PS. There was a reduction of NP in D50 at the end of the research compared to the beginning. In general, there was an increase in NP rounded and/or elongated in the 20-50, 50-100 and 100-200 μm classes, considering the treatments and soil layers (Figures 2, 3 and 4). This increase was due to the effect of rainfall that disrupted the soil. This reduced water movement due to the low connectivity between these pores, according to Castilho *et al.* (2015).

The increase in the percentage of pores resulted in an increase in the number of pores, to whose values the linear model was adjusted (Figure 5).

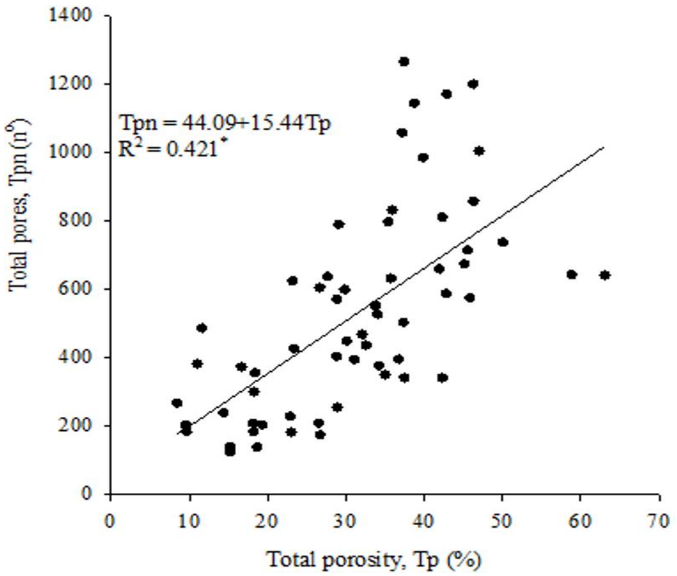

Figure 5. Relation between the total number of pores (Tpn) and the percentage of pores (Tp), including the minimum, average and maximum values of these two pore characteristics and considering the average of the treatment repetitions at Time 0, Time 1, Time 3, and Time 6.

In the case of this research, the increase in the total number of pores in the soil means that there was a significant increase in the percentage of pores with smaller diameter and rounded shape, as shown in Figures 2, 3 and 4. That caused a reduction in the infiltration of the soil water and the intensification of water erosion over time.

4. CONCLUSIONS

The application of pig slurry in successive doses, mainly in total amounts of 600 and 1,200 m^3 ha^{-1} (doses of 100 and 200 m^3 ha^{-1}), favors the formation of surface sealing and the smaller connectivity of pores in the soil. Under the conditions of the research, the number of small, rounded, and non-interconnected pores increases, and the loss of water and soil by water erosion increases until the moment when the superficial crust stabilizes its evolution. The successive occurrence of erosive rainfall favors the formation of round pores without connections.

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