

Changes in soil chemical and physical properties in pasture fertilised with liquid swine manure

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ABSTRACT: Chemical and physical properties of soil can be altered with the successive application of liquid swine manure (LSM), also known as slurry. Therefore, monitoring the impact of LSM is essential to an assessment of the potential agronomic and environmental benefits and risks associated with management practices. The aim of this study was to evaluate the effects of LSM on the chemical and physical attributes of soil under pasture (*Cynodon* spp.), located in southern Brazil. Four areas were sampled: three areas cultivated with *Cynodon* spp. pasture with successive applications of 200 m³ ha⁻¹ y⁻¹ of LSM for three, eight and 15 years; and untreated native forest as a reference. The soil attributes evaluated were: organic carbon (OC), active (pH water) and potential acidity (H + Al³⁺), nutrient availability (i.e., P, K, Ca, Mg, Cu and Zn), soil bulk density, macro, micro and total porosity. Successive applications of LSM on pasture reduced soil active acidity, and increased the soil organic C and plant-available N, P, Ca, Mg, Cu and Zn contents. These effects were more intense with time and in the shallowest layers, i.e. 0-10 cm. Excessive increases in P, Cu and Zn in the soil should be carefully monitored to minimize the contamination risks to soil, ground and surface waters. Soil physical attribute changes were more associated with land use (pasture versus native forest) than LSM use, and LSM applications induced slight improvements in the soil structural quality over time.

Keywords: management of organic residues, organic carbon, nutrient availability, soil compaction, soil chemistry

Introduction

The production of pork meat is concentrated in family farms in southern Brazil, and plays a fundamental role in the socio-economic development of the region. However, the environmental impacts associated with large amounts of manure produced by intensive swine production in small farms have caused intense debates, threatening the sustainability of this productive chain. In Brazil, 43 million animals are slaughtered annually (FAO, 2019), producing ~300 million liters of liquid swine manure (LSM) daily (Oliveira et al., 2017). Therefore, to define an environmentally correct fate for LSM is one of the major challenges faced in the last decades by swine producers and stakeholders.

Historically, LSM has been used as organic fertilizer, mainly as a source of N (Woli et al., 2013), in areas cultivated with pastures and annual crops (Freitas et al., 2018; Guardini et al., 2012; Oliveira et al., 2017). Successive applications of LSM, as organic fertilizer, enhance the growth and accumulation of dry matter biomass of *Cynodon* sp. cv. Tifton 85 (Ames et al., 2014), which is well-adapted to the subtropical climate conditions of southern Brazil, and is characterized by rapid growth and high digestibility (Burton, 2001).

Nutrient recycling from the application of LSM in the soil is important to increasing the sustainability of the production system (Guardini et al., 2012). Several studies have revealed that successive applications of LSM can increase soil P, K, Mg, Ca, Cu, Mn and Zn con-

tents, mainly in the surface layers, i.e., 0-10 cm (Formentini et al., 2015; Lourenzi et al., 2015; Grohskopf et al., 2016a; Boitt et al., 2018), and influence the attributes of soil acidity (Lourenzi et al., 2015). Long-term use of LSM may increase soil C (Oliveira et al., 2017), with positive implications for chemical and physical properties of the soil (Cherubin et al., 2016). In the short term, LSM promotes few or even no changes in soil physical attributes, i.e. soil bulk density, macroporosity, total porosity (Freitas et al., 2018; Cherubin et al., 2015). However, the increasing C probably does have positive implications for physical quality (Johannes et al., 2017), which may result in increased soil resilience and resistance to compaction (Bonetti et al., 2017), the main cause of pasture degradation (Drewry et al., 2008).

Based on this, the hypothesis was that long-term use of LSM improves not only the soil chemical attributes, but also the soil physical attributes, offering a strategy for the sustaining of soil quality in cultivated pastures. Thus, a field study was conducted to evaluate changes in the chemical and physical attributes of soil in *Cynodon* pasture areas under successive LSM application for different lengths of time.

Materials and Methods

Description of the study field

The study areas are located in Nova Candelária, Rio Grande do Sul, Brazil (27°36' 22" S and 54°4'42" W) (Figure 1A), approximately 226 m above sea level.

The regional climate is subtropical humid with hot summers, Cfa type (Köppen climate classification) (Alvares et al., 2014), presenting an average annual temperature of 18 °C and average annual precipitation of 1,800 mm. The soil in the area was characterized as a Hapludox (Soil Survey Staff, 2014), with 510 g kg⁻¹ of clay. The mineralogy of the clay-size fraction is composed mainly of clay minerals (i.e., kaolinite) and iron and aluminum oxides (Schaefer et al., 2008) in a ratio of 1:1.

The study was conducted on three adjacent areas cultivated with cv. Tifton 85 (*Cynodon* spp.) for animal grazing, which were subjected to annual applications of LSM for three, eight and 15 years, respectively, (Figure 1B) plus an undisturbed native forest area which was sampled as a reference. The LSM-amended areas presented a slope of 3 %, and there were terraces to prevent runoff and potential loss of soil and manure. Historically, before the pasture was planted, the areas had been cultivated with annual crops, such as corn, sorghum and soy-bean in the summers, and oats and ryegrass for grazing in the winters. The pasture was planted including soil tillage down to a depth of 30 cm followed by light harrowing. The next stage was for these areas to receive broadcast application of approximately 200 m³ ha⁻¹ yr⁻¹ of LSM. Although there were no records of the exact composition of the LSM applied over the years, the amount of nutrients and organic C added in the areas was estimated based on available data in the literature (Table 1).

Soil sampling

In each of the areas studied (i.e., three, eight and 15 years of LSM use and native forest), six sample points were randomly demarcated. At each point, both disturbed and undisturbed samples were collected for chemical and physical analysis, respectively. Soil sam-

ples were taken from the soil in Oct 2014, and the samples with preserved structure were collected using metal cylinders (5 cm high × 4.8 cm diameter), from layers 2-7; 10-15; 15-20 and 20-25 cm. Disturbed samples were collected from layers 0-5; 5-10; 10-15; 15-20 and 20-25 cm, each sample being composed of three subsamples. Both disturbed and undisturbed samples were stored in identified plastic bags and transported to the soil chemical and physical laboratory for preparation and analysis.

Soil chemical and physical attributes

Disturbed samples were oven dried at 40 °C for 72 h and then sieved and the 2 mm mesh portion collected. Organic C was determined according to the methodology employed by Yeomans and Bremner (1988), in which 0.5 g of soil was digested with 5 mL of potassium dichromate solution (1N) plus 7.5 mL of concentrated sulphuric acid (H₂SO₄) at 170 °C for 30 min. Afterwards, the solution was titrated with Mohr's salt solution (0.2N). The pH was determined by potentiometry in the soil suspension and water (1:1). Soil available P and K were extracted by the Mehlich-1 solution (HCl 0.05 mol L⁻¹ + H₂SO₄ 0.0125 mol L⁻¹). Briefly, for each sample, 3 cm⁻³

Table 1 – Estimate of nutrient and organic carbon (OC) inputs via liquid swine manure (LSM) in the *Cynodon* areas.

Area	LSM		Nutrients*					OC*
	Annual	Total	N	P	K	Cu	Zn	
	m ³ ha ⁻¹		kg ha ⁻¹					
3 years	200	600	1926	876	900	8.16	26.82	8520
8 years	200	1600	5136	2336	2400	22.4	71.52	22720
15 years	200	3000	9630	4380	4500	42.0	137.1	42600

*Amounts of nutrients and Organic Carbon (OC) added to soil were estimated based on Broetto et al. (2014), Grohskopf et al. (2016b) and Nicolosso et al. (2016). Amount of nutrient is the total input for three, eight and 15 years.

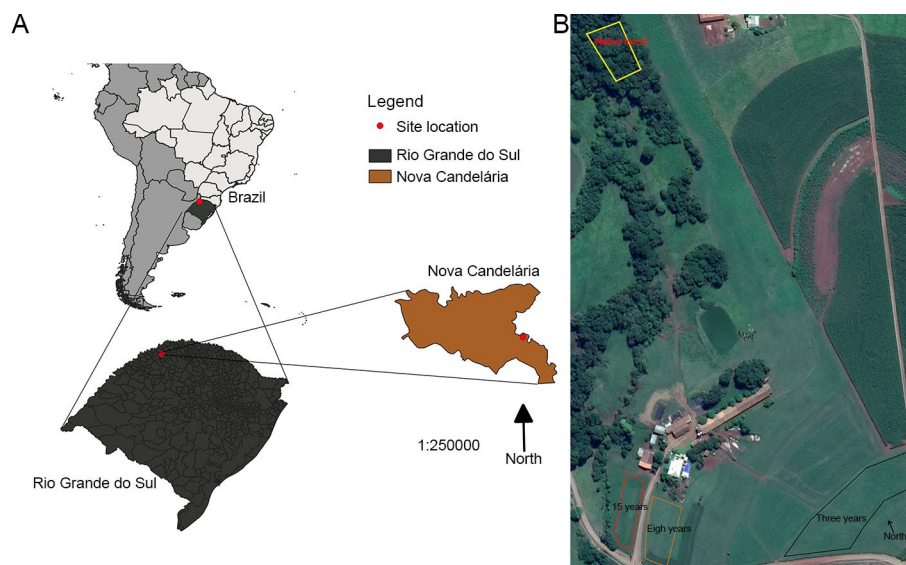


Figure 1 – Location map of experimental site (A) and aerial image of the native forest and areas under three, eight and 15 years of *Cynodon* spp. cultivation with annual application of liquid swine manure (B).

of soil was added with 30 mL of Mehlich-1 solution in a glass snap-cap vial, agitated for 5 min and left to sediment overnight. Next day, 3 to 6 mL of supernatant were extracted to quantify available P and K by the flame photometry and colorimetry method, respectively. Exchangeable soil Ca and Mg were extracted from 2.5 cm⁻³ of soil by 50 mL of KCl solution (1 mol L⁻¹). The solution was agitated for 30 min, left to sediment overnight, and then, 5 mL was extracted to quantify Ca and Mg by atomic absorption spectrometry. The available Cu and Zn were extracted from 10 cm⁻³ of soil by 40 mL of HCl solution (0.1 mol L⁻¹). The solution was agitated for 30 min, left to sediment overnight and then, these elements were quantified by atomic absorption spectrometry. All the chemical analysis methodologies are described in detail in Teixeira et al. (2017).

Undisturbed samples were saturated with water by capillarity in plastic trays, and afterwards equilibrated in the matrix potential of -6 kPa in a tension table. Soil bulk density (ρ_b) was calculated by dividing the dry soil mass by the cylinder volume. Total porosity (Tp) was determined by calculation, where $Tp = 1 - (\rho_b/Dp)$, ρ_b is bulk density and Dp soil particle density. The Dp was determined by the volumetric balloon method for each area. The determined Dp were 2.94 kg dm⁻³, 2.90 kg dm⁻³, 2.75 kg dm⁻³ and 2.94 kg dm⁻³ for the areas under three, eight and 15 years of LSM applications, and native forest, respectively. Soil macroporosity was determined by the difference between the water content in the saturated sample and the retained water of the sample submitted to the matrix potential -6 kPa, whereas the estimation of microporosity was based on the water content retained in the sample submitted to the matrix potential of -6 kPa. These methodologies are also described in Teixeira et al. (2017).

Statistical analysis

The data were subjected to analysis of variance (ANOVA) considering the layers evaluated as a variation factor. Where significant (F test $p < 0.05$), the means were compared by Tukey's test ($p < 0.05$) using the R software program (R Core Team, version 3.3).

Results and Discussion

Organic C and attributes of soil acidity

The successive applications of LSM for 15 years in *Cynodon* spp. cultivation promoted increases in soil organic C levels at levels equivalent to those found in native forest (Figure 2A and Table 2). However, this increase was focused on the shallowest 0-5 cm layer, with no changes observed in the layers of 10-15, 15-20 and 20-25 cm. Increases in organic C induced by the use of LSM has been reported in the literature (Lourenzi et al., 2011; Brunetto et al., 2012; Mafra et al., 2015), especially in studies on pastures (Oliveira et al., 2017). In general, these soil organic C increases in areas under LSM application can be attributed to two aspects: i) direct organic

C inputs by LSM, despite the low solids concentration of this manure (Table 1); ii) indirect contribution through nutrient inputs, especially N (Table 1), which enhances soil fertility, sustaining higher above- and below ground biomass yields, and consequently increase soil organic C by the decomposition of roots and crop residues (Brunetto et al., 2012; Oliveira et al., 2017).

Higher increments in soil organic C in the surface layer can be explained by the surface applications of LSM associated with higher root turnover in the soil depth and absence of soil mobilization in the pasture since planting. However, after 20 years of LSM application, Oliveira et al. (2017) showed that increases in organic C in *Cynodon* spp. pasture reached a depth of 40 cm. In addition to the application duration, soil texture also affects the vertical movement of organic C in the profile. In sandy soils, high doses of LSM can saturate the surface functional groups of mineral particles (Brunetto et al., 2012), and stimulate the migration of these

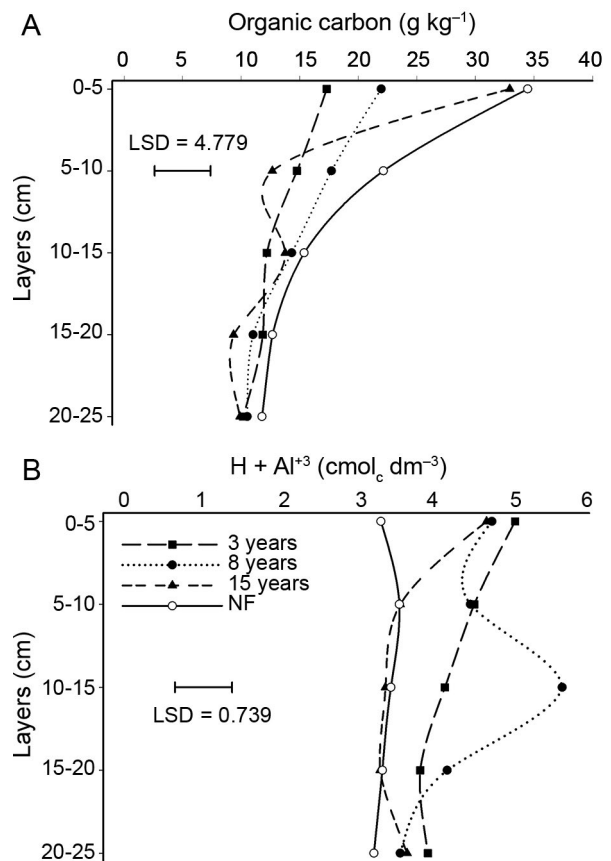


Figure 2 – Soil organic carbon (A) and potential acidity (B) in the native forest (NF) and areas under three, eight and 15 years of *Cynodon* cultivation with annual application of liquid swine manure. *Horizontal line indicates the least significant difference (LSD) of Tukey's test ($p < 0.05$). When the difference between the points is greater than the line there is a significant difference between the treatments.

Table 2 – Soil available phosphorus, potassium, calcium, magnesium, copper, zinc, organic carbon and potential acidity content in the native forest (NF) and areas under three, eight and 15 years of *Cynodon* cultivation with annual application of liquid swine manure.

Layer	P				K			
	3 years	8 years	15 years	NF	3 years	8 years	15 years	NF
cm	mg dm ⁻³				K			
0-5	97.03 Ba*	81.19 Cc	259.86 Aa	6.1 Da	161.68 Ca	304.15 Bb	703.37 Aa	47.43 Ca
5-10	59.43 Cb	218.08 Ab	79.25 Bb	3.08 Da	149.39 Ca	388.4 Bb	526.39 Ab	49.86 Ca
10-15	32.28 Cc	248.19 Aa	59.78 Bc	1.84 Da	144.32 Ca	376.67 Bb	566.36 Aab	45.72 Ca
15-20	12.54 Bd	42.77 Ad	33.78 Ad	1.83 Ba	185.97 BCa	592.49 Aa	258.02 Bc	58.76 Ca
20-25	4.23 Bd	21.44 Ae	29.03 Ad	2.51 Ba	128.11 Ba	343.48 Ab	162.09 Bc	43.11 Ba
CV (%)	8.59				23.63			
Layer	Ca				Mg			
cm	cmol _c dm ⁻³				Mg			
0-5	6.66 Ca	6.94 Cab	10.43 Ba	12.79 Aa	3.73 BCa	3.92 Bab	4.64 Aa	3.48 Cab
5-10	6.37 Ba	6.76 Bb	9.05 Ab	9.71 Ab	3.51 BCab	3.88 Bab	4.66 Aa	3.15 Cbc
10-15	6.02 Ba	8.08 Aa	8.30 Abc	7.87 Ac	3.37 Cab	4.04 Ba	4.44 Aab	2.94 Dc
15-20	6.45 BCa	6.23 Cb	7.53 Abc	7.71 Bc	3.38 Bab	3.56 Bbc	4.21 Ab	3.30 Babc
20-25	6.01 C	6.27 BCb	7.45 ABc	8.24 Ac	3.19 Cb	3.44 BCc	4.07 Ab	3.57 Ba
CV (%)	7.26				4.57			
Layer	Cu				Zn			
cm	mg dm ⁻³				Zn			
0-5	41.03 Ba*	38.71 Bb	56.54 Aa	12.56 Cd	24.27 Ba	21.91 Bc	77.74 Aa	12.22 Ca
5-10	34.47 Bb	38.74Ab	33.15Bb	19.51Cc	14.52 Cb	32.42 Ab	20.08 Bb	8.48 Dab
10-15	30.32 Bbc	49.80 Aa	32.03 Bb	25.72 Cb	9.13 Cc	61.85 Aa	17.94 Bb	5.94 Ab
15-20	28.07 BCc	32.22 Ac	24.98 Cc	31.62 Aba	5.33 ABcd	9.72 Ad	8.3 Ac	3.46 Bb
20-25	28.50 BCc	31.03 Abc	26.02 Cc	32.94 Aa	3.09 Bd	6.68 ABd	8.8 Ac	3.67 Bb
CV (%)	5.52				12.13			
Layer	OC				H+Al ⁺³			
cm	g kg ⁻¹				cmol _c dm ⁻³			
0-5	17.3 Ba	21.97 Aa	32.94 Aa	34.47 Aa	5.04 Aa	4.74 Aab	4.67 Aa	3.3 Ba
5-10	14.76 Bab	17.71 ABab	12.66 Bb	22.15 Ab	4.51 Aab	4.46 Abc	3.55 Ab	3.54 Aa
10-15	12.19 Bab	14.32 Bbc	13.76 Bb	15.38 Bc	4.13 Bab	5.65 Aa	3.36 Bb	3.43 Ba
15-20	11.84 Aab	11.02 Abc	9.35 Ab	12.67 Ac	3.81 Ab	4.16 Abc	3.29 Ab	3.32 Aa
20-25	10.16 Ab	10.52 Ac	9.9 Ab	11.78 Ac	3.91 Ab	3.55 A c	3.64 Aab	3.21 Aa
CV (%)	18.29				11.31			

*Means followed by same letter, uppercase in the row and lowercase in the column, do not differ from each other according to Tukey's test ($p < 0.05$).

organic components/molecules in the soil profile, i.e., up to 30 cm (Brunetto et al., 2012) or 60 cm (Lourenzi et al., 2011). Therefore, the application of LSM and other animal wastes becomes an important alternative for increasing soil organic C stocks both locally and globally (Maillard and Angers, 2014). Potential acidity (H + Al) was higher in the areas with LSM application in the 0-5 cm layer compared to the native forest, while in the 10-15 cm layer only the area with LSM application for eight years was different from the others (Figure 2B and Table 2). These results differ from those of Lourenzi et al. (2011) and Brunetto et al. (2012), which reported no change in potential acidity after successive LSM applications. Increments in potential acidity observed in this study are likely associated with increases in soil organic C (Figure 2A, Table 2), which present carboxylic and phenolic groups in humic and fulvic acids from the organic compounds of LSM (Lourenzi et al., 2011; Brunetto et al., 2012). Considering that negative electric charges present in tropical soils are directly associated with soil organic matter, organic C in-

crements verified from the use of LSM are important for the retention of nutrients and pollutants in the soil.

The values of pH and base saturation had no significant interaction between the areas and the layers; thus, a simple effect of LSM application was shown in Figures 3A and 3B. Higher pH values (Figure 3A) and base saturation percentages (Figure 3B) were observed in the area with 15 years of LSM application, which presented no differences from native forest (Figure 3A). In the long term, successive LSM applications attenuated soil acidity (Lourenzi et al., 2011), as well as increasing the base saturation of the soil (Oliveira et al., 2017) due to alkaline properties and dissociation of carbonates present in LSM (Chantigny et al., 2004). The reduction in active acidity can also be related to increases in soil organic C (Brunetto et al., 2012; Lourenzi et al., 2011), since it stimulates the adsorption of H⁺ in the functional groups of the organic molecules, converging with higher pH values found in the areas with a greater amount of soil organic C in the surface layer (Figure 2A).

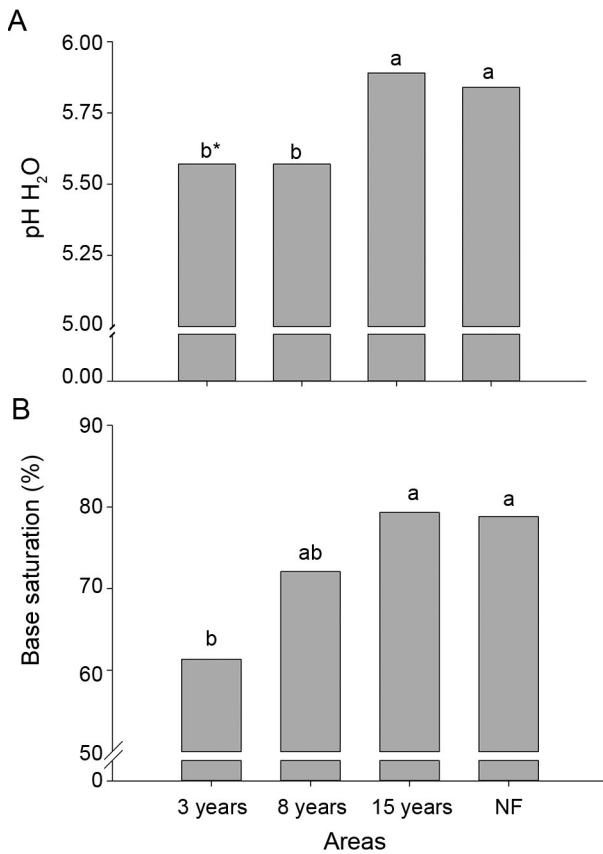


Figure 3 – Soil active acidity (pH in H₂O) (A) and base saturation (B) in the native forest (NF) and areas under three, eight and 15 years of *Cynodon* cultivation with annual application of liquid swine manure (mean of layer 0-25 cm). *Means followed by the same letter do not differ from each other according to Tukey's test ($p < 0.05$).

Soil nutrient availability

The application of LSM promoted an increase in available soil P contents in pasture areas, compared to native forest (Figure 4A and Table 2). These increases were most noticeable down to the 10-15 cm layer, reaching 100, 270 and 250 mg dm⁻³ in areas under three, eight and 15 years with the use of LSM in the 0-5 cm layer, while in the native forest soil P content was 6.1 mg dm⁻³. In deeper layers (15-20 and 20-25 cm), available P contents were lower than 45 mg dm⁻³ in all areas.

In tropical soils, the great majority of soil P is adsorbed in Fe and Al oxides through the ligand exchange mechanism with high energy, a unidirectional process that makes P unavailable to plants (Guardini et al., 2012; Cherubin et al., 2016; Rodrigues et al., 2017). Therefore, P is immobile in the soil profile, which explains its high concentration in the shallowest layers with successive additions of LSM, as has also been reported in the literature (Ceretta et al., 2010; Lourenzi et al., 2015; Oliveira et al., 2017; Boitt et al., 2018). However, excessive increments of P in soil solution

associated with presence of organic acids may saturate surface functional groups in the topsoil, which may increase P vertical migration (Pavinato and Rosolem, 2008; Fink et al., 2016).

Studies have shown that the concentration of P in the surface layers is higher with the application of LSM, increasing down to the 20-25 cm layer (Ceretta et al., 2010; Boitt et al., 2018). The increase of P at depth with the application of manure occurs mainly in inorganic form (Koopmans et al., 2007; Ojekanmi et al., 2011), without affecting the partition between inorganic and organic forms after seven years of application of LSM (Ceretta et al., 2010). In addition, about 48 % of the P in LSM is found in water-soluble form (Li et al., 2014). Thus, the successive application of LSM increases the amount of P in the labile forms in the soil solution (Ceretta et al., 2010), which are susceptible to movement and loss with the percolation water. Boitt et al. (2018) point out that 58-83 % of the P added through 15 years of LSM application remained in the soil, whereas 6 to 38 % was not recovered, possibly being lost by leaching.

The concentration of P in the soil reached values of 250 mg kg⁻¹, and was classified as "very high" according to soil fertility standards for suitable crop nutrition (CQFS-RS/SC, 2016). Thus, the amount of P above the crop requirement corresponds to overfertilization and may exceed the critical environmental limit of the soil nutrient (Gatiboni et al., 2015), thereby increasing the risk of movement of this contaminant, especially through surface runoff (Lourenzi et al., 2015) to water bodies, and becoming an important source of environmental pollution (Gatiboni et al., 2015). A study conducted by Lourenzi et al. (2015) revealed that the main forms of P carried by runoff were available P, soluble P and particulate P. Therefore, monitoring soil P levels in areas under successive LSM applications should be carried out periodically, so that excessive increase of P levels under pasture can be carefully evaluated (Oliveira et al., 2017). These precautions are even more important in undulating landscapes, which are typical in swine farms in southern Brazil, since they intensify the risks of P transfer via runoff to watercourses close to the areas of LSM application.

The use of LSM for eight and 15 years promoted an increase in K content in soil relative to areas with three years of LSM application or native forest (Figure 4B and Table 2), even under forage cultivation with a large amount of K (Brink et al., 2003). In the 15 years of LSM-amended area, the K content was higher in the 0-5, 5-10 and 10-15 cm layers, while in the eight-year area the highest levels were found in the 15-20 and 20-25 cm layers. Despite being numerically higher, soil K content in the three-year area of LSM application did not significantly differ from the native forest, except for the 15-20 cm layer, where K levels are higher in the LSM-amended areas (Figure 4B and Table 2).

K presents lower retention in soil colloids in comparison to Ca and Mg, due to its monovalence and greater hydration radius, making it more mobile in the

soil. This explains the increase in K with greater depth following successive applications of LSM (Lourenzi et al., 2013; Grohskopf et al., 2016a; Oliveira et al., 2017). However, increases in negative charges in the soil induced by higher organic C content and pH values in the surface layer may also reduce K translocation to deeper soil layers (Ernani et al., 2012), as observed for the area fertilised for 15 years compared to the area fertilised for eight years (Figure 4B and Table 2). Increases in soil K induced by LSM application agree with results reported by Oliveira et al. (2017), which verified that K levels in pasture areas fertilised with LSM over 15 years were 2, 3 and even 4 times higher in the 0-10, 10-20 and 20-40 cm layers respectively, compared to those quantified in the native forest. As discussed for P, the excess of K in soil can also become a problem, due to the imbalance in relationships with other cations, such as Ca and Mg in the exchange complex.

The Ca and Mg contents of the soil were also increased by the application of LSM (Figure 4C and D, Table 2), although the absolute increases were less than those observed for P and K. Despite this, 15 years of LSM application were not enough to increase Ca content in the surface layer (0-5 cm) to levels similar to those verified in native forest (Figure 4C and Table 2). However, in the deeper layers, Ca content did not differ between areas under 15 years of LSM application and native forest. The use of LSM promoted gradual increases in Mg content over time; however, regardless of the LSM application time, the values remained lower than those observed in native forest soil. In sandy soil (17 % of clay), Lourenzi et al. (2011) observed increases in Ca and Mg down to a depth of 20 cm after 19 applications of LSM. In very clayey soil, Oliveira et al. (2017) found increases down to a depth of 40 cm under pasture with more than 15 years of LSM applications. Thus, cation movement in

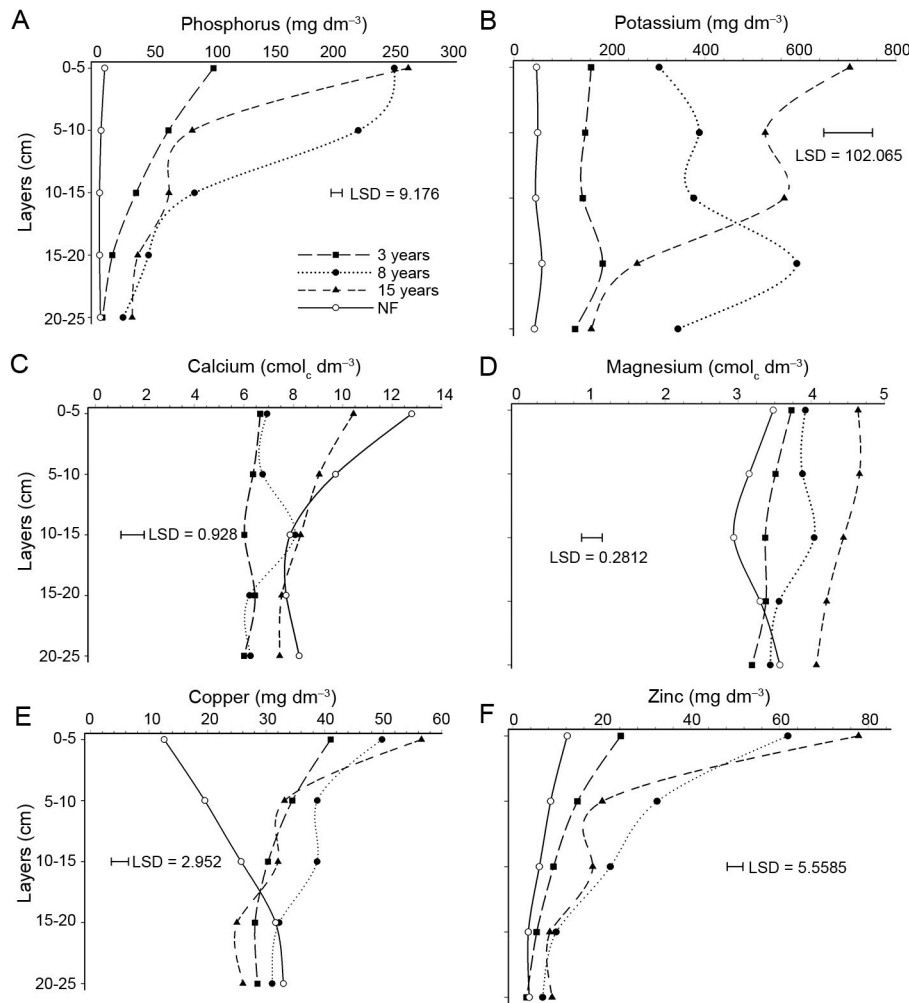


Figure 4 – Soil available phosphorus (A), potassium (B), calcium (C), magnesium (D), copper (E) and zinc (F) content in the native forest (NF) and areas under three, eight and 15 years of *Cynodon* cultivation with annual application of liquid swine manure. Horizontal line indicates the least significant difference (LSD) according to Tukey's test ($p < 0.05$).

sandy soils is explained by the LSM load and the length of time management has had this strategy in force.

With regard to the Cu and Zn concentrations, soils under pasture with successive applications of LSM showed high concentrations of these micronutrients, up to six and four times higher than the native forest in the surface layers (Figure 4E and F and Table 2) - the longer the use time of LSM, the higher the nutrient content in the soil. The concentrations reduced with depth, and from the 15-20 cm layer there were no measurable differences between soils under pasture or native forest. The LSM had high concentrations of Cu and Zn as they were supplemented via swine feed and later excreted in the feces (Li et al., 2007). These elements have little mobility in the soil, therefore, successive LSM applications have been associated with accumulations in the surface layers (Formentini et al., 2015; De Conti et al., 2016; Oliveira et al., 2017). Cu has a high affinity for forming stable complexes with functional groups of soil organic matter (De Conti et al., 2016), while Zn is primarily adsorbed on surface functional groupings of mineral particles, such as iron oxides (Grohskopf et al., 2016b). Furthermore, the pH of soil solution affects the solubility of both elements (De Conti et al., 2016).

The soil contents of Cu > 0.4 and Zn > 0.5 mg dm⁻³ are classified as "very high" in terms of plant nutrition (CQFS-RS/SC, 2016), and it was observed that the natural background is also rich in these elements. For example, the native forest soil content of these elements is very high. A high level of Cu and Zn can be associated with an abundance of these elements in the basalt, which is the parental material of the soils in the area studied (Formentini et al., 2015). However, when using LSM these levels increased significantly, raising concerns about soil contamination, as well as the transfer of these elements to the watercourses nearby (Formentini et al., 2015; Broetto et al., 2014; Pereira et al., 2016; De Conti et al., 2016; Oliveira et al., 2017).

Therefore, the monitoring of these areas of continuous use of LSM is fundamental to properly planned LSM application (i.e., reducing the applied volume or even ceasing the application) in a way that avoids problems related to contamination of heavy metals in pasture areas as well as its transfer within the trophic chain of the production system.

Impacts of LSM applications on soil physical attributes

Soil bulk density was significantly higher in the area with three years of LSM, decreasing with increasing time of use of LSM, especially in the shallower layer (2-7 cm) (Table 3). In the deeper layers, soils under pasture, regardless of the time of LSM use, presented ρ_b values higher than the native forest soil. Variations in ρ_b caused by the soil management directly affected pore distribution in the soil. Thus, higher ρ_b values were associated with a reduction in porous space in the soil, especially in relation to macroporosity (Table 3), which was lower by 10 % in the pasture areas, indicating potential restriction of the diffusion of oxygen in the soil and, consequently, to plant growth. The highest ρ_b in the area with three years of LSM application may be an effect of animal trampling (Ambus et al., 2018) and associated soil compaction from soil tillage and machine traffic. In this situation, the use of LSM for three years seems not to have been enough to provide improvements in the structural quality of the soil, not even in the surface layer. Cherubin et al. (2015) also showed that the application of up to 80 m³ ha⁻¹ yr⁻¹ of LSM in no-tillage areas did not reduce ρ_b to levels similar to native forest. However, results reported by Freitas et al. (2018), where the application of LSM up to a dosage of 480 m³ ha⁻¹ yr⁻¹, for four years in perennial pasture, reduced ρ_b in the superficial layer.

In the eight and 15 year areas, the time elapsed after planting the pasture and the action of the *Cynodon*

Table 3 – Soil bulk density (ρ_b), total porosity, macroporosity and microporosity in the native forest (NF) and areas under three, eight and 15 years of *Cynodon* cultivation with annual application of liquid swine manure.

Layer cm	3 years	8 years	15 years	NF	3 years	8 years	15 years	NF
	ρ_b kg dm ⁻³				Total porosity %			
2-7	1.47 Aa*	1.32 Ba	1.23 Bb	1.18 Ba	49.81 Ca	55.83 Bab	57.36 ABa	60.32 Aa
5-10	1.41 Aa	1.43 Aa	1.37 Aa	1.21 Ba	51.88 Ba	51.19 Bc	50.71 Bb	59.23 Aa
10-15	1.42 Aa	1.39 Aa	1.40 Aa	1.14 Ba	52.20 Ba	52.03 Bbc	49.79 Bb	60.36 Aa
15-20	1.38 Aa	1.33 Aa	1.38 Aa	1.14 Ba	53.09 BCa	56.42 Ba	50.14 Cb	61.08 Aa
CV (%)	6.92				4.62			
Layer cm	Macroporosity %				Microporosity %			
2-7	5.06 Ba	9.53 ABab	8.61 ABa	12.68 Ab	44.75 Aa	46.30 Aa	48.75 Aa	47.64 Aa
5-10	7.60 Ba	7.97 Bb	7.20 Ba	16.96Aab	44.27 Aa	43.23 Aa	43.51 Ab	42.28 Ab
10-15	6.14 Ba	7.35 Bb	6.14 Ba	21.03 Aa	45.39 Aa	44.68 Aa	43.65 Ab	39.34 Bb
15-20	7.16 Ba	13.30 Aa	7.16 Ba	19.07 Aa	46.02 Aa	43.12 Aa	42.98 Ab	42.01 Ab
CV (%)	33.92				5.66			

*Same letters, uppercase in the row and lowercase in the column, do not differ from each other according to Tukey's test ($p < 0.05$).

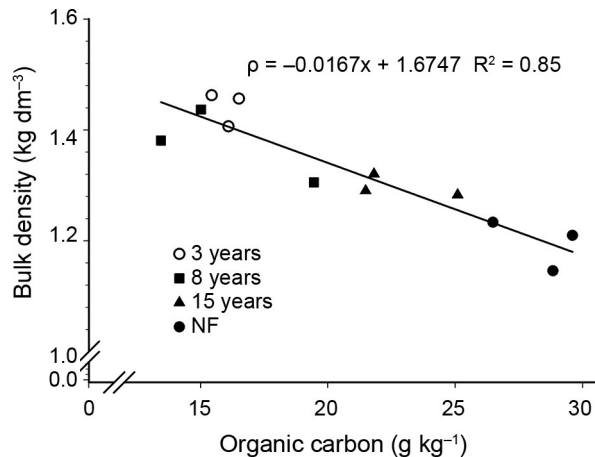


Figure 5 – Relationship between soil density and organic C in native forest (NF) and areas under three, eight and 15 years of *Cynodon* cultivation with application of liquid swine manure.

root system probably led to a better restructuring of the surface soil layer. In addition, prolonged use of LSM allowed for C increases in the surface layers (Figure 2A), which favors the formation of organomineral complexes (Six et al., 2004) and biological activity, which positively affect the process of soil aggregation (Lehmann et al., 2017). Consequently the structural quality of the soil showed that an increase in C was positively associated with the reduction in ρ_b (Figure 5). However, taking into consideration the high values of ρ_b and reduced macroporosity, and values observed in the pasture areas (Table 3), these benefits to the soil structure provided by the successive use of LSM are still very limited and are insufficient to fully alleviate limiting conditions induced by soil compaction to ensure suitable root growth (Moraes et al., 2018).

Conclusions

Successive applications of LSM ($200 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) in the *Cynodon* spp. pasture areas reduces active acidity and increases the organic C content and plant-available nutrient (P, K, Ca, Mg, Cu and Zn) contents in the soil. However, most of these effects were only significant in the surface layers (0-10 cm) and increased according to the duration of application of LSM in the area (15 > eight > three years). Despite the benefits promoted by the use of LSM to soil chemical quality, excessive increases in P, Cu and Zn should be monitored to minimize the risks of soil pollution as well as surface and groundwater contamination.

Changes in soil physical attributes were more related to the land use (pasture versus native forest) than to the duration of application of LSM. Soil physical quality was slightly enhanced by the long-term use of LSM (15 years), with small reductions in ρ_b and increases in porosity of the soil surface layer. Therefore,

the effect of LSM in the period evaluated is not enough to significantly attenuate the physical degradation of the soil imposed by continuous animal grazing in *Cynodon* pasture areas.

Authors' Contributions

Conceptualization: Scheid, D.L.; Silva, R.F.; Da Ros, C.O.; Rodrigues, V.R. Data acquisition: Scheid, D.L.; Pinto, M.A.B.; Gabriel, M. Data analysis: Scheid, D.L.; Cherubin, M.R. Design of methodology: Scheid, D.L.; Silva, R.F.; Da Ros, C.O.; Rodrigues, V.R. Writing and editing: Scheid, D.L.; Cherubin, M.R.; Silva, R.F.; Da Ros, C.O.; Rodrigues, V.R.; Pinto, M.A.B.; Gabriel, M.

References

- Alvares, C.A.; Stape, J.L.; Sentelhas, P.C.; Gonçalves, J.L.M.; Sparovek, G. 2014. Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift* 22: 711-728.
- Ambus, J.V.; Reichert, J.M.; Gubiani, P.G.; Carvalho, P.C.F. 2018. Changes in composition and functional soil properties in long-term no-till integrated crop-livestock system. *Geoderma* 330: 232-243.
- Ames, J.P.; Neres, M.A.; Castagnara, D.D.; Mufatto, L.M.; Jobim, C.C.; Tres, T.T. 2014. Dry matter production, chemical composition, dry matter digestibility and occurrence of fungi in Bermuda grass hay (*Cynodon dactylon*) under different fertilization systems or associated with pea plantings in winter. *Ciencia e Investigación Agraria* 41: 163-174.
- Boitt, G.; Schmitt, D.E.; Gatiboni, L.C.; Wakelin, S.A.; Black, A.; Sacomori, W.; Cassol, P.C.; Condrón, L.M. 2018. Fate of phosphorus applied to soil in pig slurry under cropping in southern Brazil. *Geoderma* 321: 164-172.
- Bonetti, J.A.; Anghinoni, I.; Moraes, M.T.; Fink, J.R. 2017. Resilience of soils with different texture, mineralogy and organic matter under long-term conservation systems. *Soil Tillage Research*. 174: 104-112.
- Brink, G.E.; Rowe, D.E.; Sistani, K.R.; Adeli, A. 2003. Bermudagrass cultivar response to swine effluent application. *Agronomy Journal* 95: 597-601.
- Broetto, T.; Tornquist, C.G.; Bayer C.; Campos, B.C.; Merten, C.G.; Wottrich, B. 2014. Soils and surface waters as affected by long-term swine slurry application in oxisols of southern Brazil. *Pedosphere* 24: 585-594.
- Brunetto, G.; Comin, J.J.; Schmitt, D.E.; Guardini, R.; Mezzari, C.P.; Oliveira, B.S.; Moraes, M.P.; Gatiboni, L.C.; Lovato, P.E.; Ceretta, C.A. 2012. Changes in soil acidity and organic carbon in a sandy typic hapludalf after medium-term pig-slurry and deep-litter application. *Revista Brasileira de Ciência do Solo* 36: 1620-1628.
- Burton, G.W. 2001. Tifton bermudagrass: early history of its creation, selection, and evaluation. *Crop Science* 41: 5-6.
- Ceretta, C.A.; Lorensini, F.; Brunetto, G.; Girotto, E.; Gatiboni, L.C.; Lourenzi, C.R.; Tiecher, T.L.; De Conti, L.; Trentin, G.; Miotto, A. 2010. Phosphorus fractions in soil after successive pig slurry applications in no-tillage system. *Pesquisa Agropecuária Brasileira* 45: 593-602 (in Portuguese, with abstract in English).

- Chantigny, M.H.; Rochette, P.; Angers, D.A.; Masseé, D.; Côte, D. 2004. Ammonia volatilization and selected soil characteristics following application of anaerobically digested pig slurry. *Soil Science Society of America Journal* 68: 306-312.
- Cherubin, M.R.; Eitelwein, M.T.; Fabbris, C.; Weirich, S.W.; Silva, R.F.; Silva, V.R.; Basso, C.J. 2015. Physical, chemical, and biological quality in an oxisol under different tillage and fertilizer sources. *Revista Brasileira de Ciência do Solo* 39: 615-625 (in Portuguese, with abstract in English).
- Cherubin, M.R.; Franco, A.L.C.; Cerri, C.E.P.; Karlen, D.L.; Pavinato, P.S.; Rodrigues, M.; Davies, C.A.; Cerri, C.C. 2016. Phosphorus pools responses to land-use change for sugarcane expansion in weathered Brazilian soils. *Geoderma* 265: 27-38.
- Comissão de Química e Fertilidade do Solo do Rio Grande do Sul e Santa Catarina [CQFS-RS/SC]. 2016. Manual of Liming and Fertilization for the states of Rio Grande do Sul and Santa Catarina = Manual de Calagem e Adubação para os Estados do Rio Grande do Sul e Santa Catarina. 11ed. Sociedade Brasileira de Ciência do Solo, Santa Maria, RS, Brazil (in Portuguese).
- De Conti, L.; Cerreta, C.A.; Ferreira P.A.A.; Lourenzi, C.R.; Giroto, E.; Lourensini, F.; Tiecher, T.L.; Marchezen, C.; Anchieta, M.G.; Brunetto, G. 2016. Soil solution concentrations and chemical species of copper and zinc in a soil with a history of pig slurry application and plant cultivation. *Agriculture, Ecosystems and Environment* 216: 374-386.
- Drewry, J.J.; Cameron, K.C.; Buchan, G.D. 2008. Pasture yield and soil physical property responses to soil compaction from treading and grazing: a review. *Australian Journal of Soil Research* 46: 237-256.
- Ernani, P.R.; Mantovani, A.; Scheidt, F.R.; Nesi, C. 2012. Liming decreases the vertical mobility of potassium in acidic soils. *Communications in Soil Science and Plant Analysis* 43: 2544-2549.
- Food and Agriculture Organization [FAO]. 2019. FAOSTAT: food and agriculture data; livestock primary. Available at: www.fao.org/faostat/en/#home [Accessed Jan 23, 2019]
- Fink, J.R.; Inda, A.V.; Bavaresco, J.; Barrón, V.; Torrent, J.; Bayer, C. 2016. Adsorption and desorption of phosphorus in subtropical soils as affected by management system and mineralogy. *Soil Tillage Research* 155: 62-68.
- Formentini, T.A.; Mallmann, F.J.K.; Pinheiro, A.; Fernandes, C.V.S.; Bender, M.A. Veiga, M.; Santos, D.R.; Doelsch, E. 2015. Copper and zinc accumulation and fractionation in a clayey Hapludox soil subject to long-term pig slurry application. *Science of the Total Environment* 536: 831-839.
- Freitas, J.A.S.; Silva, V.R.; Luz, F.B.; Kaiser, D.R.; Zwirtes, A.L. 2018. Soil carbon and physical-mechanical properties after successive applications of swine and poultry organic waste. *Pesquisa Agropecuária Tropical* 48: 390-398.
- Gatiboni, L.C.; Smyth, T.J.; Schmitt, D.E.; Cassol, P.C.; Oliveira, C.M.B. 2015. Soil phosphorus thresholds in evaluating risk of environmental transfer to surface waters in Santa Catarina, Brazil. *Revista Brasileira de Ciência do Solo* 39: 1225-1234.
- Grohskopf, M.A.; Cassol, P.C.; Corrêa, J.C.; Albuquerque, J.A.; Ernani, P.R.; Mafra, M.S.H.; Mafra, A.L. 2016a. Soil solution nutrient availability, nutritional status and yield of corn grown in a typical Hapludox under 12 years of pig slurry fertilizations. *Revista Brasileira de Ciência do Solo* 40: e0150341.
- Grohskopf, M.A.; Correa, J.C.; Cassol, P.C.; Nicoloso, R.S.; Fernandes, D.M. 2016b. Copper and zinc forms in soil fertilized with pig slurry in the bean crop. *Revista Brasileira de Engenharia Agrícola e Ambiental* 20: 823-829.
- Guardini, R.; Comin, J.J.; Santos, D.R.; Gatiboni, L.C.; Tiecher, T.; Schmitt, D.; Bender, M.A.; Belli, P.; Oliveira, P.A.V.; Brunetto, G. 2012. Phosphorus accumulation and pollution potential in a Hapludult fertilized with pig manure. *Revista Brasileira de Ciência do Solo* 36: 1333-1342.
- Johannes, A.; Matter, A.; Schulin, R.; Weisskopf, P.; Baveye, P.C.; Boivin, P. 2017. Optimal organic carbon values for soil structure quality of arable soils. Does clay content matter? *Geoderma* 302: 14-21.
- Koopmans, G.F.; Chardon, W.J.; McDowell, R.W. 2007. Phosphorus movement and speciation in a sandy soil profile after long-term animal manure applications. *Journal of Environmental Quality* 36: 305-315.
- Lehmann, A.; Zheng, W.; Rilling, M.C. 2017. Soil biota contributions to soil aggregation. *Nature Ecology & Evolution* 1: 1828-1835.
- Li, G.; Li, H.; Leffelaar, P.A.; Shen, J.; Zhang, F. 2014. Characterization of phosphorus in animal manures collected from three (dairy, swine, and broiler) farms in China. *Plos One* 9: e102698.
- Li, Y.X.; Li, W.; Wu, J.; Xu, L.C.; Su, Q.H.; Xiong, X. 2007. Contribution of additives Cu to its accumulation in pig feces: study in Beijing and Fuxin of China. *Journal of Environmental Sciences* 19: 610-615.
- Lourenzi, C.R.; Ceretta, C.A.; Silva, L.S.; Giroto, E.; Lorensini, F.; Tiecher, T.L.; De Conti, L.; Trentin, G.; Brunetto, G. 2013. Nutrients in soil layers under no-tillage after successive pig slurry applications. *Revista Brasileira de Ciência do Solo* 37: 157-167.
- Lourenzi, C.R.; Ceretta, C.A.; Silva, L.S.; Trentin, G.; Giroto, E.; Lorensini, F.; Tiecher, T.L.; Brunetto, G. 2011. Soil chemical properties related to acidity under successive pig slurry application. *Revista Brasileira de Ciência do Solo* 35: 1827-1836.
- Lourenzi, C.R.; Ceretta, C.A.; Tiecher, T.L.; Lorensini, F.; Cancian, A.; Stefanello, L.; Giroto, E.; Vieira, R.C.B.; Ferreira, P.A.A.; Brunetto, G. 2015. Forms of phosphorus transfer in runoff under no-tillage in a soil treated with successive swine effluents applications. *Environmental Monitoring and Assessment* 187: 209.
- Mafra, M.S.H.; Cassol, P.C.; Albuquerque, J.A.; Grohskopf, M.A.; Andrade, A.P.; Rauber, L.P.; Friederichs, A. 2015. Organic carbon contents and stocks in particle size fractions of a typical Hapludox fertilized with pig slurry and soluble fertilizer. *Revista Brasileira de Ciência do Solo* 39: 1161-1171.
- Maillard, É.; Angers, D.A. 2014. Animal manure application and soil organic carbon stocks: a meta-analysis. *Global Change Biology* 20: 666-679.
- Moraes, M.T.; Bengough, A.G.; Debiasi, H.; Franchini, J.C.; Levien, R.; Schnepf, A.; Leitner, D. 2018. Mechanistic framework to link root growth models with weather and soil physical properties, including example applications to soybean growth in Brazil. *Plant and Soil* 428: 67-92.

- Ojekanmi, A.; Ige, D.; Hao, X.; Akinremi, O. 2011. Phosphorus mobility in a soil with long term manure application. *Journal of Agricultural Science* 3: 25-38.
- Oliveira, D.M.S.; Lima, R.P.; Barreto, M.S.C.; Verburg, E.E.J.; Mayrink, G.C.V. 2017. Soil organic matter and nutrient accumulation in areas under intensive management and swine manure application. *Journal of Soils and Sediments* 17: 1-10. DOI 10.1007/s11368-016-1474-6
- Pavinato, P.S.; Rosolem, C.A. 2008. Effects of organic compounds produced by plants on soil nutrient availability. *Revista Brasileira de Ciência do Solo* 32: 911-920 (in Portuguese, with abstract in English).
- Pereira, P.A.M.; Sampaio, S.C.; Reis, R.R.; Rosa, D.M.; Correa, M.M. 2016. Swine farm wastewater and mineral fertilization in corn cultivation. *Revista Brasileira de Engenharia Agrícola e Ambiental* 20: 49-54.
- Rodrigues, M.; Rabêlo, F.H.S.; Castro, H.A.; Roboredo, D.; Carvalho, M.A.C.; Roque, C.G. 2017. Changes in chemical properties by use and management of an Oxisol in the Amazon biome. *Revista Caatinga* 30: 278-286.
- Schaefer, C.E.G.R.; Fabris, J.D.; Ker, J.C. 2008. Minerals in the clay fraction of Brazilian Latosols (Oxisols): a review. *Clay Minerals* 43: 137-154.
- Six, J.; Bossuyt, H.; Degryze, S.; Deneff, K. 2004. A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. *Soil Tillage Research* 79: 7-31.
- Soil Survey Staff. 2014. *Keys to Soil Taxonomy*, 12ed. USDA-Natural Resources Conservation Service, Washington, DC, USA.
- Teixeira, P.C.; Donagemma, G.K.; Fontana, A.; Teixeira, W.G. 2017. *Manual of Soil Analysis Methods = Manual de Métodos de Análises de Solo*. Embrapa, Brasília, DF, Brazil (in Portuguese).
- Woli, K.P.; Rakshit, S.; Lundvall, J.P.; Sawyer, J.E.; Barker, D.W. 2013. On-farm evaluation of liquid swine manure as a nitrogen source for corn production. *Agronomy Journal* 105: 248-262.
- Yeomans, J.C.; Bremner, J.M. 1988. A rapid and precise method for routine determination of organic carbon in soil. *Communications in Soil Science and Plant Analysis* 19: 1467-1476.