Nutr Cycl Agroecosyst (2015) 101:259–269
DOI 10.1007/s10705-015-9677-6

ORIGINAL ARTICLE

Nutrient accumulation and availability and crop yields following long-term application of pig slurry in a Brazilian Cerrado soil

Henrique Gualberto Vilela Penha · June Faria Scherrer Menezes · Carlos Alberto Silva · Guilherme Lopes · Camila de Andrade Carvalho · Silvio Junio Ramos · Luiz Roberto Guimarães Guilherme

Received: 4 July 2014 / Accepted: 19 January 2015 / Published online: 25 January 2015

Abstract Long-term applications of pig slurry may change nutrient status and availability through the soil profile, especially in highly weathered Brazilian soils, which present low pH and nutrient availabilities as well as high Al contents. This study evaluated the effects of long-term applications of pig slurry on soil phosphorus, potassium, copper, manganese, and zinc at different soil depths, as follow: 0–0.10, 0.10–0.20, 0.20–0.40, 0.40–0.60, 0.60–0.90, and 0.90–1.20 m and on soybean and corn yields in a Brazilian Cerrado soil. Pig slurry was applied during 9 years, as follow: 0, 25, 50, 75, and 200 m^3 ha^{-1} $year^{-1}$ for corn and 0, 25, 50, 75, and 100 m^3 ha^{-1} $year^{-1}$ for soybean. An additional treatment using NPK fertilizer was also included for comparison. Phosphorus and potassium availabilities increased following pig slurry application. However, this increase for phosphorus occurred only in soil surface while potassium was distributed along the soil profile, showing that potassium is prone to be leached. Total and available zinc, copper, and manganese contents increased upon increasing the applied pig slurry rates. However, total contents remain below the maximum regulatory levels suggested for Brazilian soils. Maximum soybean yields were obtained with 88 m^3 ha^{-1} $year^{-1}$ of pig slurry while corn required a rate of 127 m^3 ha^{-1} $year^{-1}$ for maximum grain yield. Considering the production system with soybean and corn in the Cerrado soil, we recommend applications of low pig slurry rates combined with the use of mineral fertilizer, which is advantageous for both, agriculture and waste disposal.

Keywords Cerrado soils · Nutrient availability · Pig slurry disposal · Sustainability

Electronic supplementary material The online version of this article (doi:10.1007/s10705-015-9677-6) contains supplementary material, which is available to authorized users.

H. G. V. Penha
Federal Institute of Triangulo Mineiro, Campina Verde, MG 38270-000, Brazil

J. F. S. Menezes
University of Rio Verde, PO Box 104, Rio Verde, GO 75901-970, Brazil

C. A. Silva · G. Lopes · C. de Andrade Carvalho · L. R. G. Guilherme (✉)
Soil Science Department, Federal University of Lavras, PO Box 3037, Lavras, MG 37200-000, Brazil
e-mail: guilherm@dcs.ufla.br

S. J. Ramos
Mining, Vale Institute of Technology, Ouro Preto, MG 35400-000, Brazil

Introduction

Pig farms in Brazil were historically concentrated in the southern region till the end of the twentieth century, particularly in the states of Rio Grande do Sul and Santa Catarina (Mattias et al. 2010). In the

Cerrado region, pig production systems have been intensified since the 1990s and have been continuously modernized, with increasing productivity each year. In fact, this region had about 13 % of the total Brazilian pig inventory, i.e., more than 5 million pigs in 2009 (IBGE 2009). Thus pig slurry generation in the Cerrado region has been increasing due to high pig productivity, which is relevant, taking into account the possibility of using this material as an important source of nutrients for crop production in soils of the Brazilian Cerrado.

The Cerrado biome occupies 2 million km^2 (23 % of the Brazilian territory) and at least 50 % of the soils located in this biome are suitable for sustainable agricultural use. These soils present as main characteristics high aluminum levels, as well as low pH, organic matter contents and availability of nutrients, such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), boron (B), copper (Cu), manganese (Mn), and zinc (Zn). Also, it is well-known that these soils are highly weathered, having high contents of kaolinite as well as iron (Fe) and aluminum (Al) oxides, which results in high P-fixing capacity (Lopes et al. 2012).

Pig slurry is a liquid organic residue containing mainly organic matter, N, P, and K. Pig slurry may also be enriched with Cu, Zn, Mn, and selenium (Se), which are elements used to stimulate physiological processes, increasing animal growth and preventing diseases (Benke et al. 2008). Because of its nutrient content, pig slurry has been normally used as a fertilizer for annual crops and pastures in Brazil and elsewhere (Lourenzi et al. 2013). However, pig slurry applications should be made with caution due to the possibility of accumulating excessive amounts of nutrients in soils following the use of high rates of this organic fertilizer (Adeli et al. 2008; Girotto et al. 2013), or also because of nutrient losses by surface runoff or leaching (Ceretta et al. 2010a; Johnson et al. 2011; Liu et al. 2012). Therefore, pig slurry applications must follow technical criteria to achieve crop nutritional requirements without causing negative environmental impact, i.e., without increasing nutrients to levels that may cause toxicity to plants or environmental problems. This is relevant, taking into consideration that besides supplying nutrients to plants, pig slurry can also improve chemical, physical, and biological soil characteristics (Scherer et al. 2007; Girotto et al. 2013).

Increasing soil accumulation and availabilities of trace elements (e.g., Cu, Zn, and Mn) to levels that are toxic to plants due to long-term applications of pig slurry have become a concern in Brazil and elsewhere (Ceretta et al. 2003; Mattias et al. 2010; Guardini et al. 2012). In terms of contamination, much attention has been addressed to Cu and Zn, following the application of pig slurry enriched with these elements (Kabala and Singh 2001; Girotto et al. 2010). However, accumulation of Cu and Zn are limited to soil surface, while other trace elements such as Mn and cobalt (Co) may be found in higher concentrations in deep soil profile due to the leaching process (L'Herroux et al. 1997).

Considering changes in major nutrients, data from southern Brazil have shown that available P and K levels increased down to 0.60 m of soil depth following successive applications of pig slurry (Lourenzi et al. 2013). Also, labile forms of P tend to increase after pig slurry application, which is important in order to improve the efficiency of P fertilization (Ceretta et al. 2010b). However, results obtained in south Brazil may not be applicable to the Cerrado biome, where the soil and climate conditions are quite different.

Taking into account the importance of the soils from the Cerrado region for food, feed, fiber, and fuel production in Brazil, studies evaluating the effects of long-term pig slurry application on nutrient accumulation and availability and, on crop yield, are still required. Thus, this study aimed to investigate the effects of successive applications of pig slurry rates upon corn and soybean yields, as well as upon Cu, Zn, Mn, P, and K accumulations and availabilities in a soil from the Brazilian Cerrado biome. Following successive use of pig slurry, changes in the cation exchange capacity (CEC) at pH 7 and in carbon contents were also investigated.

With that, we want to assess not only the agronomical and environmental effects of long-term application of pig slurry in tropical agroecosystems, but also to discuss a better technical criteria to recommend pig slurry as a fertilizer for corn and soybean grown in Cerrado soils from Brazil.

Materials and methods

Field trails were carried out in a Brazilian Cerrado area at the FESURV experimental farm in the municipality of Rio Verde, State of Goiás, Brazil (29°43′12″ S, 53°43′4″ W). The soil was classified as a Typic Clayey Oxisol, with a slope of 0.04 m m^{-1}, presenting, at the 0–0.20 m depth, 420, 110, and 470 g kg^{-1} of sand, silt, and clay, respectively. The main soil characteristics (0–0.20 m depth, under natural conditions) were: pH in water, 4.5; Ca^{2+}, 1.6 $cmol_c$ dm^{-3}; K^+, 0.14 $cmol_c$ dm^{-3}; P (Mehlich-1), 3 mg dm^{-3}; base saturation, 21 %, and organic matter, 23 g kg^{-1}. The climate of the region is classified as Aw (tropical), according to the Köppen-Geiger classification, with a long dry season (from April to October), an annual average precipitation of 1,550 mm and an annual average temperature of 23.3 °C (Siqueira Neto et al. 2011).

The experiment was established in the 1999/2000 cropping season. The soil was ploughed and soil acidity was corrected with limestone (2.242 t ha^{-1}), as it is usually done in the Cerrado, in order to reach a soil pH of 5.5–6.0 and a base saturation of 60 %, which is recommended for corn and soybean cultivation. No-tillage was adopted in the subsequent agricultural years.

Soybean and corn were grown in succession and pig slurry was applied annually at the following rates: 0 (control), 25, 50, 75, and 100 m^3 ha^{-1}, when soybean was cultivated, and 0, 25, 50, 100 and 200 m^3 ha^{-1} for corn cultivation. For comparison, additional treatments with application of NPK fertilizers were also set during all years (Table 1).

Table 2 Composition of the pig slurry applied in this experiment (mean ± standard deviation)

Composition	Application year	
	2000–2004	2005–2009
N (mg g^{-1})	1.84 ± 0.62	1.45 ± 0.38
P (mg g^{-1})	0.89 ± 0.66	0.32 ± 0.53
K (mg g^{-1})	1.24 ± 0.18	1.08 ± 0.01
Cu (mg kg^{-1})*	674.4	555.6
Zn (mg kg^{-1})*	246.0	530.3
Mn (mg kg^{-1})*	–	176.8
pH	7.70 ± 0.707	7.66 ± 0.230
Bulky density (kg m^{-3})	1,012 ± 0.003	1,007 ± 0.001

Data provided by Dr. J.F.S. Menezes, following the methodology described by Menezes et al. (2007) and Menezes et al. (2009)

* Contents calculated on a dry basis

Pig slurry was applied on soil surface without incorporation. Table 2 shows the average composition of the pig slurry applied during the experimental period. Soil nutrient content and availability were assessed in 2010, following 9 applications of pig slurry, using soil samples taken after a soybean crop, in 5 trenches, for each plot, at the 0–0.10, 0.10–0.20, 0.20–0.40, 0.40–0.60, 0.60–0.90, and 0.90–1.20 m soil depths.

The experiment was conducted in a randomized block scheme. Three replicates of each treatment for checking accuracy of data have been taken so that all treatments appeared in all experimental blocks. The area of each plot comprised 150 m^2 (15 m × 10 m) and samples were collected 1.0 m away from the edge of each side of the plot.

Table 1 Crops and NPK fertilizers used in the 9 years of pig slurry application

Year	Plant	Cultivar	Additional fertilization
2000/2001	Soybean	Engopa 316	300 kg ha^{-1} of 0-20-20 + 3 % FTE
2001/2002	Corn	Pioneer 3021	390 kg ha^{-1} of 08-20-18 + 90 kg ha^{-1} of N
2002/2003	Soybean	–	350 kg ha^{-1} of 02-20-20
2003/2004	Corn	BRS 1010	370 kg ha^{-1} of 08-20-18 + 100 kg ha^{-1} of N
2004/2005	Soybean	Lusiânia	370 kg ha^{-1} of 02-20-18
2005/2006	Corn	Coodetec 308	570 kg ha^{-1} of 04-14-08 + 100 kg ha^{-1} of N
2006/2007	Soybean	Monsoy 8008 RR	350 kg ha^{-1} of 02-20-18
2007/2008	Corn	–	–
2008/2009[a]	Soybean	Favorita RR	520 kg ha^{-1} of 04-17-08 + 0.33 % of Cu + 0.11 % of Zn

Pig slurry was applied in the following rates: 0 (control), 25, 50, 75 and 100 m^3 ha^{-1} $year^{-1}$ when soybean was cultivated and 0, 25, 50, 100, and 200 m^3 ha^{-1} $year^{-1}$ for the years with corn cultivation

[a] Soil samples were collected after this agricultural year with cultivation of soybean

Soil samples were analyzed for available P, K, Cu, Zn, and Mn following the Mehlich-1 method (0.05 mol L^{-1} HCl + 0.0125 mol L^{-1} H_2SO_4) (EMBRAPA 1997), while CEC at pH 7 was determined by adding exchangeable bases with soil potential acidity. Total contents of Cu, Zn, and Mn in soil samples were determined in a Perkin Elmer AAnalyst 800 atomic absorption spectrophotometer (Perkin Elmer Inc., San Jose, USA), with either flame or electrothermal atomization by (pyrolytic) graphite furnace, following the analytical protocol for soil digestion described at the USEPA 3051A method (USEPA 1998).

Briefly, samples (0.5 g) were weighed and acid-digested in 0.005 L of HNO_3 in Teflon PTFE flasks (Corporation, Matthews, USA) and submitted to 0.76 MPa during 10 min in a microwave oven (CEM, model Mars 5 CEM Corporation, Matthews, USA). After cooling to room temperature, the extract was filtered (Whatman No. 40 filter) and diluted by adding 0.005 L of bi-distilled water. A standard reference material from the Institute for Reference Materials and Measurements (BCR 143R—Sewage sludge amended soil) was used in order to check the accuracy of the obtained analytical results. Blank and certified reference samples were analyzed in all digestion batch.

Soil total carbon (TC) was determined in an elementary combustion dry analyzer (Elementar, Vario TOC cube model). Briefly, soil samples were grounded in an agate mortar and passed through a 0.15-mm sieve and dried at 65 °C until they reached constant weight. Then, the dry soil samples (0.009–0.015 g) were encapsulated and sealed in tin capsules and incinerated at 950 °C during 5 min, in a combustion quartz tube. Oxygen with 99.998 % of purity was used as carrier gas and carbon evolved from the samples as CO_2 was measured in a NDIR detector.

Statistical analyses of the data were performed using variance analysis (ANOVA) at 5 % of probability level to test for significant difference among treatment means. The results were expressed as means of three replicates with their corresponding standard deviations (±SD). Due to the alternation of pig slurry rates depending on the crop (75 and 100 m^3 ha^{-1} applied for soybean changes to 100 and 200 m^3 ha^{-1} for corn), for statistical tests, the weighted average of rates was made, getting the following rates: 0, 25, 50, 86.11, and 144.44 m^3 ha^{-1}. All statistical analyses were performed using SISVAR (Ferreira 2008).

Results and discussion

Carbon (C) and CEC at pH 7

Total carbon contents were higher at soil surface and decreased with soil depth, as indicated by the vertical distribution patterns of C in the soil (Fig. 1a). Regardless of the soil depth analyzed, C contents were not influenced by the pig slurry rates annually added to soil. This might be related to the fact that the organic carbon content in pig slurries are usually small, ranging from 1 to 60 mg g^{-1} fresh weight (Bernal et al. 1991), i.e., such low levels of C in the pig slurry do not change soil C contents or may slightly change it, especially in the soil surface (Scherer et al. 2010; Ellerbrock et al. 1999). Indeed, due to low levels of C in the pig slurry, a field experiment carried out in Santa Catarina (Brazil) has shown that, following successive pig slurry applications, the levels of organic matter did not change in the evaluated soils, even when the pig slurry was applied in high rates (Scherer et al. 2010). In contrast, other studies have reported opposite results, showing that the total C content increased in a soil treated with swine effluent. The authors found also that the long-term application of swine effluent resulted in a decrease in soil pH (Adeli et al. 2008).

The CEC at pH 7 slightly increased (approximately 0.5 $cmol_c$ dm^{-3}) when the highest rate of pig slurry was applied, when compared with the untreated control soil (without pig slurry application) (Fig. 1b and Online Resource 1), which agrees with results reported elsewhere (Queiroz et al. 2004; Ndayegamiye and Côté 1989). An increase in CEC after pig slurry applications in soils may be attributed to an input of humic materials as the soil organic matter is build-up (Ndayegamiye and Côté, 1989), as well as to changes in soil pH, which impact the charge densities in organic colloids and in variable-charge minerals (e.g., kaolinite and Fe–Al oxides).

Phosphorus (P)

Phosphorus availabilities following the application of pig slurry for all evaluated soil depths are shown in Fig. 2a. Increases in available P as the pig slurry rate increased were limited to the upper layers. At depths of 0–0.10 and 0.10–0.20 m, available P contents were

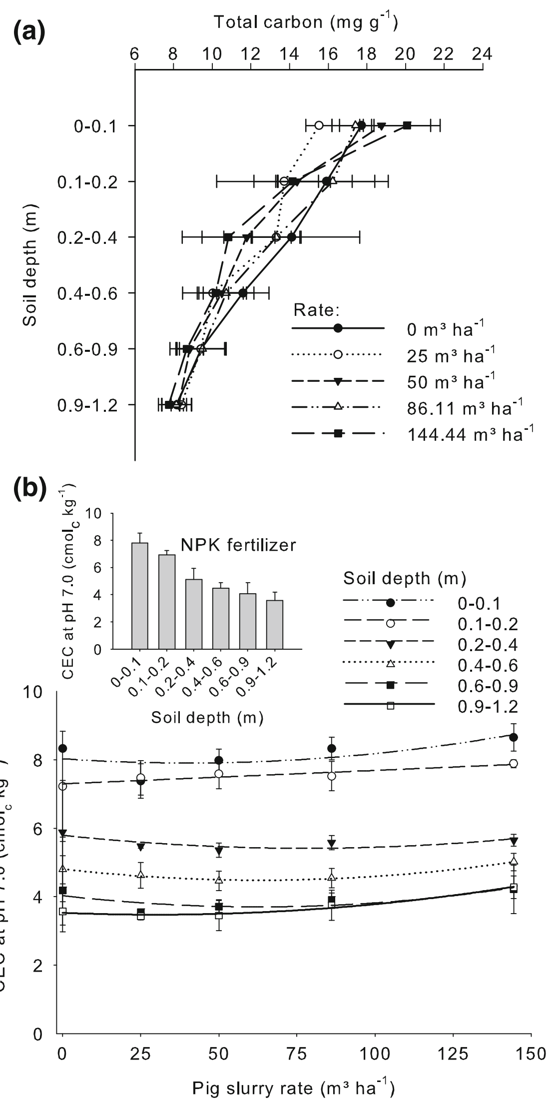

Fig. 1 Soil total carbon content (**a**) and CEC at pH 7.0 (**b**) as a function of soil depth and long-term application of pig slurry rates. The *bar graph* refers to the additional treatment using chemical fertilizer

around six- and two-fold higher compared with the untreated soil control, respectively, when pig slurry was applied at the rate of 144.44 $m^3\ ha^{-1}$ (Fig. 2a). According to Angers et al. (2010), the amount of P stored in the soil profile increased linearly with increasing the pig slurry rate; in fact, in a 20-years pig slurry application period, the total soil P reached values that correspond to 850 kg ha^{-1} when a pig slurry rate of 100 $m^{-3}\ ha^{-1}\ year^{-1}$ was applied.

In the investigated soil surface depths, the available P increases when the pig slurry rates were greater or

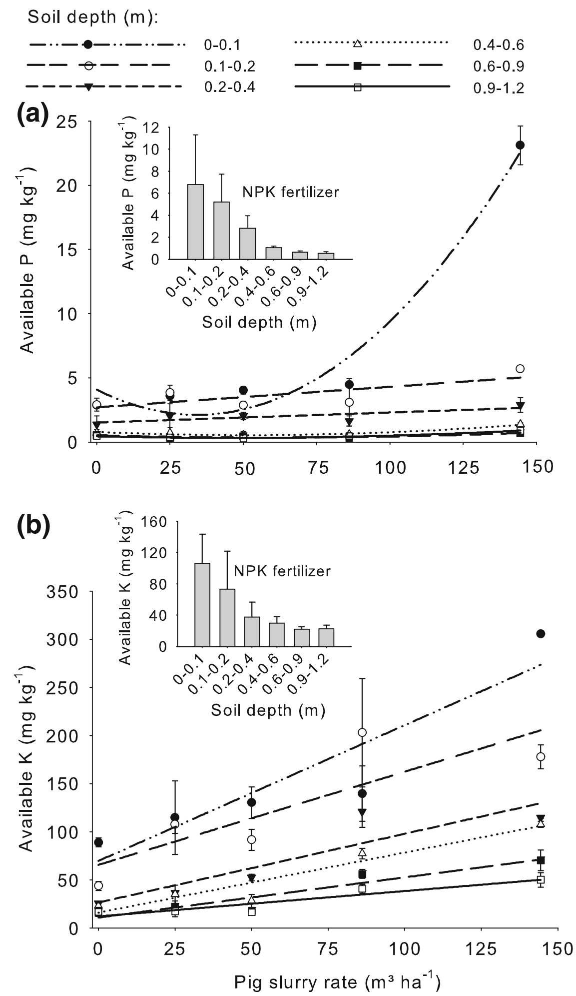

Fig. 2 Contents of available P (**a**) and K (**b**) (Mehlich-1) at different soil depths as a function of long-term application of pig slurry rates. The *bar graph* refers to the additional treatment using chemical fertilizer

equal to 86.1 $m^3\ ha^{-1}$. On the other hand, no changes on plant-available P were found in the deeper soil depths (Fig. 2a), which can be explained due to the low mobility of P, i.e. high P retention (fixation) in Fe–Al oxides found in tropical soils (Conte et al. 2003; Fontes and Weed 1991; Smith 1965). Higher contents of available P were also reported on soil surface layers elsewhere in Brazil, following the addition of 40 $m^3\ ha^{-1}$ of pig slurry (Ceretta et al. 2003).

The increase in P availability due to the application of pig slurry can be attributed not only to the P content of this organic residue, but also to a decrease of P fixation in mineral colloids due to competition with organic compounds (from pig slurry) that are able to be adsorbed on soil colloids, thus decreasing P fixation, mainly in oxide-rich soils, such as the studied soil (Oxisol) (Pinto et al., 2013). Also, an increase in soil available P may be due to the greater lability of P derived from organic residues, as well as to changes in soil pH caused by the addition of pig slurry (Hue 1991; McBride 1994; Ceretta et al. 2010a; Guardini et al. 2012).

Considering the soil surface and the largest pig slurry rate investigated in this study, the P contents found in the soil were higher than the critical level set for adequate P nutrition in Cerrado soils by Sousa and Lobato (2004), which is 8 mg dm^{-3}. In contrast, such critical level is not achieved with the application of 50 and 86 m^3 ha^{-1} of pig slurry, as the available P contents were 4.02 and 4.46 mg kg^{-1} respectively, which are considered very low values to achieve high crop yields in Cerrado soils. Therefore, the use of pig slurry to achieve adequate P content for most crops in Brazil would require rates greater than 86.11 m^3 ha^{-1}, yet the effect would be limited to the 0–0.10 m soil depth. However, as can be seen in the present study, the addition of such high pig slurry rates is not acceptable taking into account the changes that occur in other soil attributes.

Potassium (K)

Available K contents increased linearly upon increasing the pig slurry rates for all evaluated soil depths. For each 1 m^3 ha^{-1} of pig slurry applied, there was an increase of 1.18 and 0.75 mg kg^{-1} on the contents of available K for the soil depths of 0–0.10 and 0.10–0.20 m, respectively (Fig. 2b and Online Resource 2). The available K contents found in these two surface depths following the application of pig slurry are considered "high" for tropical soils (>80 mg kg^{-1}), according to Sousa and Lobato (2004).

Greater increases in available K contents following continuous pig slurry applications occurred mainly in the 0–0.10 m depth, accounting for a three-fold increase with the use of 144.44 m^3 ha^{-1} of pig slurry compared with the untreated soil control (without pig slurry application). Available K contents for the other soil depths reached levels approximately two fold higher than those found for the control (Fig. 2b). The effectiveness of using pig slurry to increase K availability in soils could also be observed comparing the treatments that have received pig slurry with the treatment where the NPK fertilizer was used. Actually, the lowest rate of pig slurry applied increased the available K contents to levels comparable to those obtained with the use of chemical fertilizers (Fig. 2b).

The use of pig slurry as an organic fertilizer to increase available K, thus improving soil fertility with respect to this nutrient, is noteworthy and could be explained due to the high concentration of K that is normally found in liquid manures, such as pig slurry (Legros et al. 2010). Indeed, K contents as high as 2,602 mg L^{-1} have been reported for Korean swine slurries (Suresh and Choi 2011).

As the soil depth increases, K contents are smaller but still influenced by the rate of pig slurry used. When 144 m^3 ha^{-1} of pig slurry was applied, the available K contents in soil surface reached values five-fold greater than those contents measured in the deeper soil profile (Fig. 2b). These results agree with studies conducted by Scherer et al. (2010). To better distinguish K contents found in the different soil depths, we have assessed enrichment factors (EF), which were obtained by dividing the K content found at the 0–0.10 m depth by K contents considered at the 0.10–0.40 or 0.40–1.20 m depths (Table 3). As expected, EF values calculated for the 0.40–1.20 m depth were nearly two times higher than those found for the 0.10–0.40 m depth.

Cu, Zn, and Mn

Due to the presence of Cu, Zn, and Mn in the pig slurry, the available contents of these elements increased following the application of pig slurry, especially in the upper soil depths (Fig. 3a, b, c). Cabral et al. (1998) reported also that increased additions of pig slurry significantly enhanced the contents of Cu, Zn, Fe, and Mn in the topsoil. Likewise, another study has also point out high Cu and Zn accumulation in soil surface (L'Herroux et al. 1997). Mallmann et al. (2012) showed that successive pig slurry application could lead to a significantly accumulation of Cu in the soil surface, which may, in future, exceed the Brazilian threshold for Cu in agricultural soils, which is 200 mg kg^{-1} according to CONAMA (2009). However, the authors emphasized that Zn and Cu did not offer high risks in terms of groundwater pollution.

In this work, following the application of 144 m^3 ha^{-1} of pig slurry, Cu and Zn contents found

Table 3 Enrichment factor (EF) of Zn, Cu, and K (chemical elements with high concentrations in PS) in the 0–0.1 m soil depth in relation to soil depths of 0.1–0.4 and 0.4–1.2 m

Treatment	EF for the 0.1–0.4 m depth			EF for the 0.4–1.2 m depth		
	Zn	Cu	K	Zn	Cu	K
25 m^3 ha^{-1}	1.52c[a]	1.142b	2.36a	8.51c	1.31b	4.35b
50 m^3 ha^{-1}	5.23a	1.201b	2.56a	18.77b	1.44b	5.26a
86.11 m^3 ha^{-1}	1.68c	1.273b	1.56a	11.43c	1.60b	3.04b
144.44 m^3 ha^{-1}	4.24a	1.724a	1.93a	27.92a	2.27a	3.17a
NPK fertilizer[b]	1.12c	1.009b	2.07a	8.57c	1.06b	3.92b
Control[c]	2.69b	1.479b	1.33a	7.61c	1.60b	2.58b

[a] Means followed by the same letter in the column are not significantly different by the Scott-Knott test at $P > 0.05$

[b] Represents the plots where NPK fertilizer was applied

[c] Refers to the control plot (without pig slurry application)

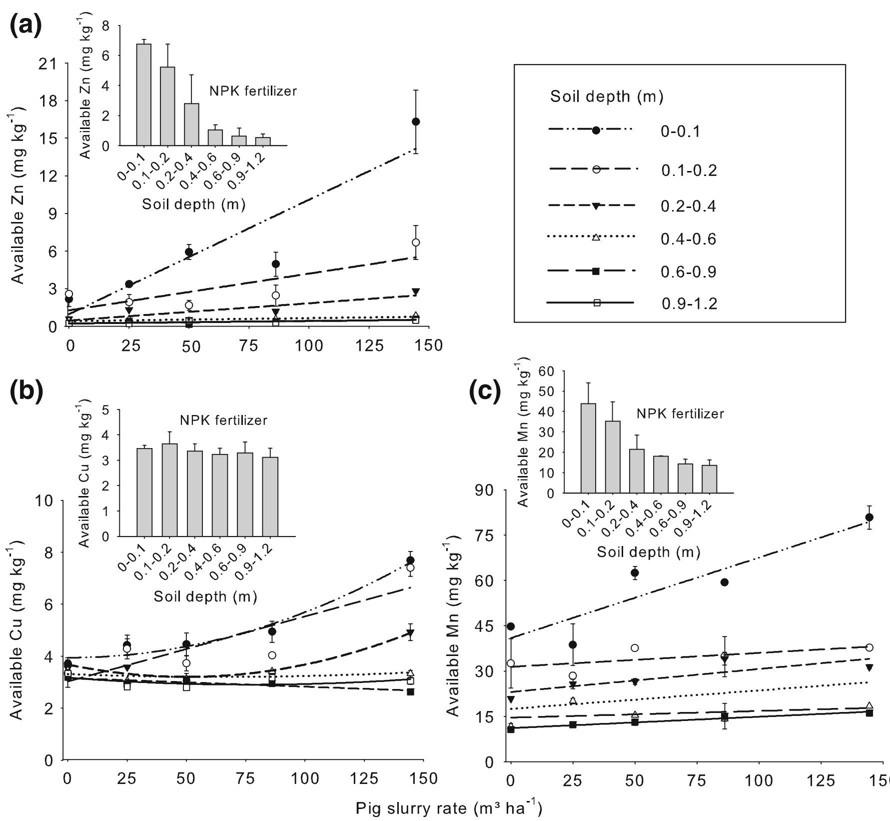

Fig. 3 Contents of available Zn (**a**), Cu (**b**) and Mn (**c**) (Mehlich-1) at different soil depths as a function of long-term application of pig slurry rates. The *bar graph* refers to the additional treatment using chemical fertilizer

at the 0–0.10 m depth were at least two-fold higher than the contents observed for the untreated soil control (0 m^3 ha^{-1}), while Mn has increased by 81 %. Increases in Mn availability due to the application of pig slurry were also observed elsewhere (Mattias et al. 2010). Also, we have observed that at the 0.10–0.20 m depth each 1 m^3 ha^{-1} of pig slurry applied resulted in increases of approximately 0.025 and 0.019 mg kg^{-1} of Zn and Cu, respectively (Online Resource 3). Following pig slurry applications, Girotto et al. (2010) found also increases in the contents and availabilities of Zn and Cu in surface soil depths in southern Brazil.

Similarly, another study has measured increases of 15.6 and 188 % for Cu and Zn, respectively, following 4 years of swine waste application (Lucas et al. 2013).

Reference critical levels (Mehlich-1) for Cu, Zn, and Mn in Cerrado soils are in the range of 0.5–0.8, 1.1–1.6, and 2.0–5.0 mg dm^{-3}, respectively (Sousa and Lobato 2004). Based on these values, data obtained in this study showed that such critical levels were achieved already with the smallest pig slurry rate (Fig. 3a, b, c). These results indicate the effectiveness of pig slurry in improving the status of these micronutrients in the soil, which is relevant taking into account that usually these elements are deficient in Brazilian tropical soils. However, it has to be noted that Cu, Zn, and Mn requirements are small and, as a result, successive applications of pig slurry may increase the contents of these nutrients in soil surface up to levels that might become toxic to plants.

Besides evaluating micronutrient availabilities, we have determined also total Cu, Zn, and Mn contents in order to show the effect of long-term pig slurry applications upon the accumulation of such trace elements in a Brazilian Cerrado soil. Considering the highest rate of pig slurry applied during all 9 years (1,300 m^3 ha^{-1}), the total Cu, Mn, and Zn contents at the 0–0.10 m depth in the soil reached, respectively, the following values: 36.6, 473.1, and 54.7 mg kg^{-1} (Fig. 4). Such values are below the maximum contents established by the Brazilian legislation (CONAMA 2009) and also smaller than those reported by Legros et al. (2013), who obtained concentrations of total Cu and Zn in pig slurry plots higher than those measured in control plots in three soil depths of a tropical soil.

Crop yields

Soybean and corn yields were evaluated, respectively, in the agricultural years of 2008–2009 and 2009–2010. Yields of both soybean and corn increased following quadratic equations upon increasing the rate of pig slurry applied (Fig. 5). Under such circumstances, maximum economic yields for soybean and corn would be obtained with the application of 50 and 86 m^3 ha^{-1} of the pig slurry, respectively.

However, for both crops, especially soybean, the yields have decreased in the highest rates of pig slurry. Thus, before using pig slurry as a source of nutrients one should keep in mind that the application rate will vary according to the crop requirement. Although soybean yields have decreased with the highest rates of pig slurry, applying 25, 50, 86, and 144 m^3 ha^{-1} of pig slurry increased corn yields by 25.4, 52.6, 85, and 86 %, respectively, compared with the untreated control soil (without pig slurry application).

Maximum corn (7,556 kg ha^{-1}) and soybean (4,111 kg ha^{-1}) yields were achieved when 127 and 88 m^3 ha^{-1} of pig slurry were applied. Positive effects in crop yields following the application of pig slurry have been reported for soybean (Sartor et al. 2012) and corn (Ceretta et al. 2005), as well as other crops, in Brazil and elsewhere (Seidel et al. 2010; Vasconcelos

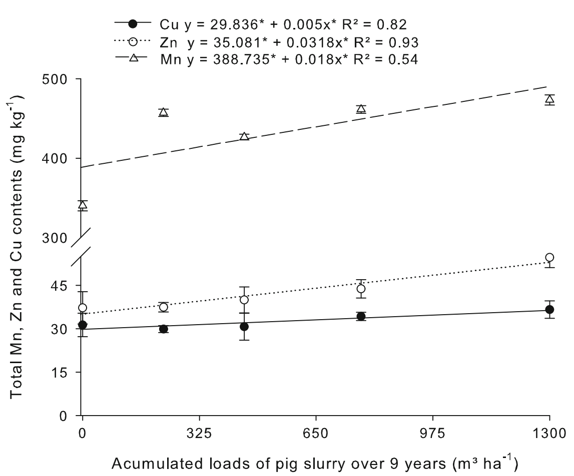

Fig. 4 Total contents of Cu, Mn, and Zn at the 0–0.10 m depth as a function of long-term accumulation of pig slurry

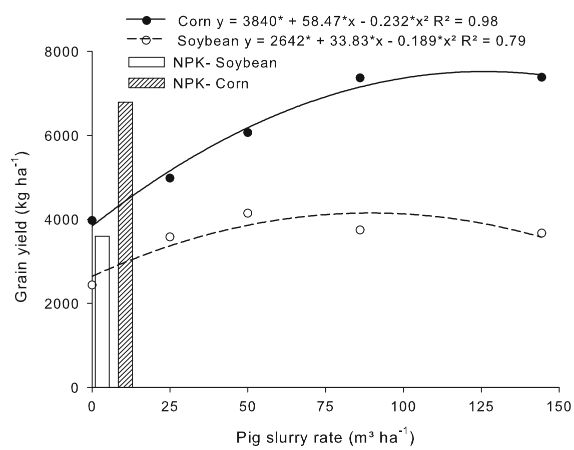

Fig. 5 Soybean (crop 2008–2009) and corn (crop 2009–2010) yields as a function of long-term application of pig slurry rates. The *bars* refer to the use of chemical fertilizer for the corn and soybean as additional treatments

and Cabral 1996; Yagüe and Quílez 2010; Lourenzi et al. 2014).

From Fig. 5 it is also possible to note that the use of 25 m^3 ha^{-1} of pig slurry for soybean and 86 m^3 ha^{-1} for corn resulted in grain yields similar to those achieved using chemical fertilizers (NPK fertilizer). Taking into account that the generation of pig slurry in Brazil has lead to environmental pollutions due to the large amounts produced, this fact indicates the potential of using pig slurry as a fertilizer to increase grain yields in Brazilian soils of the Cerrado biome. This represents an excellent alternative for both, crop fertilization and waste disposal.

Conclusions

Long-term applications of pig slurry in a Brazilian Cerrado soil have shown to affect chemical characteristics of the soil, as well as soybean and corn yields, which depend of the pig slurry rate. High pig slurry rates increased P contents only in the soil surface, while the contents of K increased throughout the soil profile. This fact shows the marked difference in terms of P and K behaviors in tropical soils, indicating that K is more prone to be leached in a Cerrado soil following successive applications of pig slurry.

Successive pig slurry additions increased the available contents of Cu, Zn, and Mn, but risks of these nutrients to leach are limited due to their preference to accumulate in soil surface. In addition, total Cu, Mn, and Zn contents that have been accumulated following 9 years of the pig slurry applications were below the maximum contents established by the Brazilian legislation. Data have point out that applying pig slurry may result in increased grain yields of soybean and corn. Yet, the optimal agronomic pig slurry rate is crop-specific and higher for corn when compared with soybean. Therefore, considering a production system with soybean and corn, the pig slurry application rate should not be performed only for corn, because, in this case, the high pig slurry rate required for this crop may cause nutrient imbalances, adding high amounts of K, Cu, Mn, and Zn, which can decrease soybean yields, as well as affect the environment.

Finally, this study has shown that the long-term application of pig slurry presents benefits on both, agriculture and waste disposal. Thus, bearing in mind the specific characteristics of the Brazilian Cerrado soils, we recommend the application of small pig slurry rates combined with mineral fertilizers—mainly with nitrogen—for corn. Also, taking into account the high K and Zn availabilities that can occur when elevated pig slurry rates are used, the best strategy to recommend pig slurry for agricultural purposes in Cerrado soils should be to consider the availability of K, Mn, Cu, and Zn in soil, the crop grown and the use of mineral fertilizers in combination with pig slurry rates when corn is the crop to be fertilized.

Acknowledgments The authors thank the National Council for Scientific and Technological Development (CNPq), the Brazilian Federal Agency for Support and Evaluation of Graduate Education (CAPES), and the Minas Gerais State Research Foundation (FAPEMIG) for financial support and scholarships. Special acknowledgements to all students and technicians responsible for the maintenance of the FESURV experimental area and for soil and crop sampling.

References

Adeli A, Bolster CH, Rowe DE, McLaughlin MR, Brink GE (2008) Effect of long-term swine effluent application on selected soil properties. Soil Sci 173:223–235

Angers DA, Chantigny MH, MacDonald JD, Rochette P, Côté D (2010) Differential retention of carbon, nitrogen and phosphorus in grassland soil profiles with long-term manure application. Nutr Cycl Agroecosyst 86:225–229

Benke MB, Indraratne SP, Hao X, Chang C, Goh TB (2008) Trace element changes in soil after long-term cattle manure applications. J Environ Qual 37:798–807

Bernal MR, Roig A, Cegarra J (1991) Effect of pig slurry additions on the organic carbon of calcareous soils. Bioresour Technol 37:223–228

Cabral F, Vasconcelos E, Cordovil CMDS (1998) Effects of solid phase from pig slurry on iron, copper, zinc and manganese content of soil and wheat plants. J Plant Nutr 21:1955–1966

Ceretta CA, Durigonet R, Basso CJ, Barcellos LAR, Vieira FCB (2003) Características químicas de solo sob aplicação de dejeto líquido de suínos em pastagem natural. Pesq Agropec Bras 38:729–735

Ceretta CA, Basso CJ, Pavinato PS, Trentin EE, Girotto E (2005) Produtividade de grãos de milho, produção de matéria seca e acúmulo de nitrogênio, fósforo e potássio na rotação aveia preta/milho/nabo forrageiro com aplicação de dejeto líquido de suínos. Ciênc Rural 35:1287–1295

Ceretta CA, Girotto E, Lourenzi CR, Trentin G, Vieira RCB, Brunetto G (2010a) Nutrient transfer by runoff under no tillage in a soil treated with successive applications of pig slurry. Agric Ecosyst Environ 139:689–699

Ceretta CA, Lorensini F, Brunetto G, Girotto E, Gatiboni LC, Lourenzi CR, Tiecher TL, Conti L, Trentin G, Miotto A (2010b) Frações de fósforo no solo após sucessivas aplicações de dejetos de suínos em plantio direto. Pesq Agropec Bras 45:593–602

Conte E, Anghinoni I, Rheinheimer DS (2003) Frações de fósforo acumuladas em Latossolo argiloso pela aplicação de fosfato no sistema plantio direto. R Bras Ci Solo 27:893–900

CONAMA. Resolução no 420, de 28 de dezembro de 2009 (2009) Dispõe sobre critérios e valores orientadores de qualidade do solo quanto à presença de substâncias químicas e estabelece diretrizes para o gerenciamento ambiental de áreas contaminadas por essas substâncias em decorrência de atividades antrópicas. http://www.mma.gov.br/port/conama/legiabre.cfm?codlegi=620. Accessed 12 Dec 2013

Ellerbrock RH, Höhn A, Rogasic J (1999) Functional analysis of soil organic matter as affected by long-term manurial treatment. Eur J Soil Sci 50:65–71

EMBRAPA-CNPS (1997) Manual de métodos e análise de solo. EMBRAPA Solos, Rio de Janeiro

Ferreira DF (2008) SISVAR: um programa para análises e ensino de estatística. Rev Symp 6:36–41

Fontes MPF, Weed SB (1991) Iron oxides in selected Brazilian Oxisols: I. Mineralogy. Soil Sci Soc Am J 55:1143–1149

Girotto E, Ceretta CA, Brunetto G, Rheinheimer DS, Silva LS, Lourensini F, Lourenzi CR, Vieira RCB, Schmatz R (2010) Acúmulo e formas de cobre e zinco no solo após aplicações sucessivas de dejeto líquido de suínos. Rev Bras Ciênc Solo 34:955–965

Girotto E, Ceretta CA, Lourenzi CR, Lorensini F, Tiecher TL, Vieira RCB, Trentin G, Basso CJ, Miotto A, Brunetto G (2013) Nutrient transfers by leaching in a no-tillage system through soil treated with repeated pig slurry applications. Nutr Cycl Agroecosyst 95:115–131

Guardini R, Comin JJ, Schmitt DE, Tiecher T, Bender MA, Santos DR, Mezzari CP, Oliveira BS, Gatiboni LC, Brunetto G (2012) Accumulation of phosphorus fractions in typic Hapludalf soil after long-term application of pig slurry and deep pig litter in a no-tillage system. Nutr Cycl Agroecosyst 93:215–225

Hue NV (1991) Effects of organic acids/anions on phosphorus sorption and phytoavailability in soils with different mineralogies. Soil Sci 152:463–471

IBGE (2009) Pesquisa pecuária municipal—PPM. [s.l.]: IBGE

Johnson KN, Kleinman PJA, Beegle DB, Elliott HA, Saporito LS (2011) Effect of dairy manure slurry application in a no-till system on phosphorus runoff. Nutr Cycl Agroecosyst 90:201–212

Kabala C, Singh BR (2001) Fractionation and mobility of copper, lead, and zinc in soil profiles in the vicinity of a copper smelter. J Environ Qual 30:485–492

Legros S, Chaurand P, Rose J, Masion A, Briois V, Ferrasse J, Macary HS, Bottero J, Doelsch E (2010) Investigation of copper speciation in pig slurry by a multitechnique approach. Environ Sci Technol 44:6926–6932

Legros S, Doelschb E, Feder F, Moussarda G, Sansoulet J, Gaudetc J-P, Rigaud S, BasileDoelschd I, Saint Macaryb H, Bottero J-Y (2013) Fate and behavior of Cu and Zn from pig slurry spreading in a tropical water–soil–plant system. Agr Ecosyst Environ 164:70–79

L'Herroux L, Roux SL, Appriou P, Martinez J (1997) Behaviour of metals following intensive pig slurry applications to a natural field treatment process in Brittany (France). Environ Pollut 97:119–130

Liu J, Aronsson H, Ulén B, Bergström L (2012) Potential phosphorus leaching from sandy topsoils with different fertilizer histories before and after application of pig slurry. Soil Use Manag 28:457–467

Lopes AS, Guilherme LRG, Ramos SJ (2012) The Saga of the Agricultural Development of the Brazilian Cerrado. International Potash Institute, e-ifc no 32 November. IPI 60 Anniversary Issue

Lourenzi CR, Ceretta CA, Silva LS, Girotto E, Lorensini F, Tiecher TL, De Conti L, Trentin G, Brunetto G (2013) Nutrients in soil layers under no-tillage after successive pig slurry applications. Rev Bras Ciênc Solo 37:157–167

Lourenzi CR, Ceretta CA, Brunetto G, Girotto E, Tiecher TL, Vieira RCB, Cancian A, Ferreira PAA (2014) Pig slurry and nutrient accumulation and dry matter and grain yield in various crops. Rev Bras Ciênc Solo 38:949–958

Lucas SDM, Sampaio SC, Uribe-Opazo MA, Gomes SD, Kessler NCH, Prado NV (2013) Long-term behavior of Cu and Zn in soil and leachate of an intensive no-tillage system under swine wastewater and mineral fertilization. Afr J Agric Res 8(7):639–647. doi:10.5897/ajar12.2063

Mallmann FJK, dos Santos DR, Ceretta CA, Cella C, Simunek J, van Oort F (2012) Modeling field-scale vertical movement of zinc and copper in a pig slurry-amended soil in Brazil. J Hazard Mater 243:223–231

Mattias JL, Ceretta CA, Nesi CN, Trentin EE, Lourenzi CR, Vieira RCB (2010) Copper, zinc and manganese in soils of two watersheds in Santa Catarina with intensive use of pig slurry. Rev Bras Ciênc Solo 34:1445–1454

McBride MB (1994) Environmental chemistry of soils. University Press, New York

Menezes JFS, Proner SCP, Benites VM, Silva GP, Konzen EA, Dutra RA (2007) Estimativa da composição química de dejetos líquidos de suínos da região de Rio Verde-GO em função da densidade. Boletim Técnico, 5. Rio Verde: FESURV

Menezes JFS, Rodrigues RC, Lima LUS, Silva GP, Simon GA (2009) Residual de P e K de um Latossolo Vermelho sob sucessivas adições de dejetos líquidos de suínos. I Simpósio Internacional sobre Gerenciamento de Resíduos de Animais. Uso dos Resíduos da Produção Animal como Fertilizante 11 a 13 de Março de 2009 – Florianópolis, SC – Brasil

Ndayegamiye A, Côté D (1989) Effect of long-term pig slurry and solid cattle manure application on soil chemical and biological properties. Can J Soil Sci 69(1):39–47

Pinto FA, Souza ED, Paulino HB, Curi N, Carneiro MAC (2013) P-sorption and desorption in savanna Brazilian soils as a support for phosphorus fertilizer management. Ciênc Agrotecnol 37:521–530

Queiroz FM, Matos AT, Pereira OG, Oliveira RA (2004) Características químicas de solo submetido ao tratamento com esterco líquido de suínos e cultivado com gramíneas forrageiras. Ciênc Rural 34:1487–1492

Sartor LR, Assmann AL, Assmann TS, Bigolin PE, Miyazawa M, Carvalho PCF (2012) Effect of swine residue rates on

corn, common bean, soybean and wheat yield. Rev Bras Ciênc Solo 36:661–669
Scherer EE, Baldissera IT, Nesi CN (2007) Propriedades químicas de um Latossolo Vermelho sob plantio direto e adubação com esterco de suínos. Rev Bras Ciênc Solo 31:123–131
Scherer EE, Nesi CN, Massotti Z (2010) Atributos químicos do solo influenciados por sucessivas aplicações de dejetos suínos em áreas agrícolas de Santa Catarina. Rev Bras Ciênc Solo 34:1375–1383
Seidel EP, Gonçalves Júnior AC, Vanin JP, Strey L, Schwantes D, Nacke H (2010) Aplicação de dejetos de suínos na cultura do milho cultivado em sistema de plantio direto. Acta Sci Technol 32(2):113–117. doi:10.4025/actascitechnol.v32i2.5312
Siqueira Neto M, Piccolo MC, Costa C Jr, Cerri CC, Bernoux M (2011) Emissão de gases do efeito estufa em diferentes usos da terra no bioma Cerrado. Rev Bras Ciênc Solo 35:63–76. doi:10.1590/S0100-06832011000100006
Smith AW (1965) Aluminum and iron phosphates in soils. J Aust Inst Agr Res 31:110–126
Sousa DMG, Lobato E (2004) Cerrado: correção do solo e adubação, 2nd edn. Embrapa Cerrados, Planaltina, p 416
Suresh A, Choi HL (2011) Estimation of nutrients and organic matter in Korean swine slurry using multiple regression analysis of physical and chemical properties. Bioresour Technol 102:8848–8859
United States Environmental Protection Agency (USEPA) (1998) Method 3051A: microwave assisted acid digestion of sediments, sludges, soils, and oils. In: SW-846. Test methods for evaluating solid waste, physical/chemical methods, Office of solid Waste. U. S. Washington, Environmental Protection Agency, pp 1–20
Vasconcelos E, Cabral F (1996) Influence of the concentrated pig slurry on soil and corn fodder yield and chemical composition in presence of N top dressing. Fertil Res 45:25–29
Yagüe MR, Quílez D (2010) Cumulative and residual effects of swine slurry and mineral nitrogen in irrigated maize. Agron J 102:1682–1691