Comissão 3.3 - Manejo e conservação do solo e da água

PIG SLURRY AND NUTRIENT ACCUMULATION AND DRY MATTER AND GRAIN YIELD IN VARIOUS CROPS[1]

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SUMMARY

Pig slurry (PS) represents an important nutrient source for plants and using it as fertilizer makes greater nutrient cycling in the environment possible. The aim of this study was to assess how PS application over a period of years can affect grain yield, dry matter production and nutrient accumulation in commercial grain and cover crops. The experiment was carried out in an experimental area of the Universidade Federal de Santa Maria, in Santa Maria, RS, Brazil, from May 2000 to January 2008. In this period, 19 grain and cover crops were grown with PS application before sowing, at rates of 0, 20, 40 and 80 m^3 ha^{-1}. The highest PS rate led to an increase in nutrient availability over the years, notably of P, but also of nutrients that are potentially toxic to plants, especially Cu and Zn. The apparent recovery of nutrients by commercial grain and cover crops decreased with the increasing number of PS applications to the soil. Accumulated dry matter production of the crops and maize grain yield were highest at an annual application rate of 80 m^3 ha^{-1} PS. However, common bean yield increased up to 20 m^3 ha^{-1} PS, showing that the crop to be grown should be considered to define the application rate.

Index terms: manure, yield, crop rotation.

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[1] Received for publication on January 21, 2013 and approved on March 27, 2014.

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RESUMO: *DEJETO LÍQUIDO DE SUÍNOS E O ACÚMULO DE NUTRIENTES E MATÉRIA SECA E A PRODUÇÃO DE GRÃOS DE CULTURAS DIVERSIFICADAS*

O dejeto líquido de suínos (DLS) representa importante fonte de nutrientes às plantas e sua utilização como adubo para as culturas significa a possibilidade de maior ciclagem de nutrientes no ambiente. Este trabalho objetivou avaliar como as doses de DLS, aplicadas ao longo de alguns anos, podem impactar a produção de grãos, de matéria seca e o acúmulo de nutrientes em culturas de grãos comerciais e em plantas de cobertura do solo. O experimento foi realizado na área experimental da Universidade Federal de Santa Maria, em Santa Maria, RS, no período de maio de 2000 a janeiro de 2008. Nesse período, foram implantadas 19 culturas de grãos e de cobertura de solo, sendo aplicado DLS antes da semeadura de cada cultura, nas doses de 0, 20, 40 e 80 m^3 ha^{-1}. O aumento da dose de DLS aplicada ao longo de anos promoveu o incremento da disponibilidade de nutrientes, notadamente de P, mas também de nutrientes que podem ser potencialmente tóxicos às plantas, especialmente Cu e Zn. A recuperação aparente de nutrientes pelas culturas de grãos comerciais e de cobertura do solo diminuiu à medida que aumentou o número de aplicações de doses de DLS no solo. A produção de matéria seca acumulada das culturas e a produção de grãos de milho foram maiores com a dose anual de 80 m^3 ha^{-1} de DLS. Entretanto, a produtividade de grãos de feijão elevou até 20 m^3 ha^{-1} de DLS, evidenciando que, na definição da dose, deve ser considerada a cultura a ser estabelecida.

Termos de indexação: dejeto, produtividade, rotação de culturas.

INTRODUCTION

In the South of Brazil, pigs are raised predominantly in confined systems, and in Rio Grande do Sul, RS, approximately 38,000 m^3 of pig slurry (PS) is produced daily (FEPAM, 2008). This PS contains a variable and often low dry matter percentage, with approximately 60 % of the N in the form of ammonium (NH_4^+) (Payet et al., 2009), more than 60 % of the P in inorganic form (Cassol et al., 2001), and all K in the mineral form (Ceretta et al., 2003). Thus, due to the wide availability on farms and its composition, PS has been used as fertilizer of cover and commercial grain crops.

Successive PS applications may lead to a rapid increase in N-NO_3^- contents in soils and, over the years, especially in degraded soils, to increases in organic matter contents, providing greater availability of N forms to crops (Lourenzi et al., 2011; Brunetto et al., 2012). In addition, PS applications may cause an increase in labile inorganic P forms in the soil, which are readily available to plants (Gatiboni et al., 2008; Ceretta et al., 2010); raise exchangeable K, Ca and Mg contents in the soil; higher pH; and induce Al^{3+} complexation, as a result of its adsorption to humic and functional groups of fulvic acid of soil organic matter (Lourenzi et al., 2011; Brunetto et al., 2012).

The improvement in soil chemical characteristics by PS applications may stimulate healthy plant root growth in a greater soil volume, intensifying the water and nutrient uptake, which is reflected in higher grain yields of crops such as maize (*Zea mays* L.) and common bean (*Phaseolus vulgaris* L.), and increased dry matter of the aerial part of cover crop species, e.g., of black oat (*Avena strigosa*), common vetch (*Vicia sativa* L.), pearl millet (*Pennisetum americanum* L.), and sunn hemp (*Crotalaria juncea* L.) (Ceretta et al., 2005; Chantigny et al., 2008). This is desirable since in no-tillage systems (NTS), the crop residues are left on the soil surface, protecting the soil against raindrop impact, for example, reducing soil surface runoff and promoting nutrient cycling (Doneda et al., 2012; Guillou et al., 2012). However, if soil nutrient contents, as of those applied to the soil in PS, exceed the crop sufficiency levels (CQFSRS/SC, 2004), an accumulation (e.g., of N, P and K) above the physiological nutrient requirements of the crop in the plant tissue is expected (Kaminski et al., 2007).

The utility of PS as crop fertilizer was shown in various studies, e.g., that of Giacomini & Aita (2008), who observed an increase of up to 243 % in maize grain yield when the crop was grown on a soil fertilized with PS at 63.6 m^3 ha^{-1}, corresponding, in this case, to the application of 140 kg ha^{-1} N. In addition, PS application can increase grain yield in other crops such as common bean (Scherer, 1998), the dry matter production of cover crop species such as black oat, as well as forage production (Ceretta et al., 2005; Aita et al., 2006). Nevertheless, the crop response is associated with the PS application rate and time and, consequently, with an increase in the soil nutrient availability (Adeli et al., 2008; Scherer et al., 2010; Lourenzi et al., 2013) and, especially, with crop nutrient requirements.

The aim of this study was to evaluate how long-term PS application can affect grain yield, dry matter production and nutrient accumulation in commercial grain and cover crops.

MATERIAL AND METHODS

The experiment was carried out from May 2000 to January 2008 in the experimental area of the Agricultural Engineering Department of the Universidade Federal de Santa Maria (UFSM) in Santa Maria, in the Central Lowlands of Rio Grande do Sul, Brazil (latitude 29° 43' S; longitude 53° 42' W). The climate in the region is humid subtropical, classified as Cfa, according to the Köppen classification, and has a mean annual temperature of 19.3 °C and mean annual rainfall of 1,561 mm. The soil was classified as an Hapludalf (Soil Survey Staff, 1999) and contains 170 g kg^{-1} clay, 300 g kg^{-1} silt and 530 g kg^{-1} sand in the 0-10 cm layer. The soil chemical characteristics in May 2000, prior to the experiment, and in January 2008, after 19 PS applications, are shown in table 1. Nineteen PS applications were made in a crop rotation system, at rates of 0, 20, 40 and 80 m^3 ha^{-1}. The PS was broadcast on the surface over the litter from the previous crop and before planting each crop in the rotation. The PS was the sole nutrient source of the crops. A randomized block design with three replications was used, on experimental plots of 4 × 3 m. The characteristics of the PS and nutrient quantities applied to each crop are shown in table 2.

Over the time of the experiment, the following species were grown in rotation: black oat (*Avena strigosa*), maize (*Zea mays L.*) and oilseed radish (*Raphanus sativus* L.) in the 2000/2001 and 2001/2002 growing seasons; black oat, pearl millet (*Pennisetum americanum* L.) and black bean (*Phaseolus vulgaris* L.) in 2002/2003; black oat+common vetch (*Vicia sativa* L.) and maize in 2003/2004 and 2004/2005; black oat, black bean and sunn hemp (*Crotalaria juncea L.*) in 2005/2006; black oat, maize and black oat in 2006/2007. Black oat was broadcast, using 100 kg ha^{-1} of seeds. When intercropped with common vetch, 100 kg ha^{-1} of seeds was sown at a proportion of 60/40 of black oat/common vetch. Maize was sown in a row spacing of 0.90 m, with five plants per meter, for a total of approximately 55,500 plants ha^{-1}. Oilseed radish and sunn hemp were sown in a row spacing of 0.40 m and 25 plants m^{-1} (approximately 625,000 plants ha^{-1}). Pearl millet was sown in a row spacing of 0.40 m and five plants m^{-1} (approximately 125,000 plants ha^{-1}). Black bean was sown in rows spaced 0.45 m apart, with 12 plants m^{-1} (approximately 266,500 plants ha^{-1}). The results of the first two experimental years were reported by Ceretta et al. (2005), which is why only the results of the last five years of the experiment are reported in this study.

Grain yield of maize and common bean was assessed on an area of 6.3 and 7.2 m^2 per plot, respectively. The dry matter (DM) and the total N, P and K contents in the plant tissue were determined based on fresh matter collection from a useful area of 0.25 m^2 for the cover crops, and from five plants per plot in full flowering, for the grain crops. Dry matter was determined after drying to constant weight in an air circulation oven at 65 °C. The nutrient contents in DM were determined according to Tedesco et al. (1995). Apparent recovery of N, P and K by the plants over the five growing seasons was estimated based on nutrient accumulation until full flowering, comparing the nutrient quantity taken up by the plants in the presence of PS minus the quantity taken up by the plants in the absence of PS to the total quantity added through PS. For this, the equation proposed by Mitchell & Teel (1977) was used (Equation 1):

$$RaN = \frac{[(NAPf - NAPsf)]}{Naf} \times 100 \qquad (1)$$

in which RaN is the apparent recovery of nutrients (N, P and K) from PS by the crop in %; NAPf is the nutrient quantity taken up by crops at the respective application rates of PS; NAPsf is the nutrient quantity taken up by crops in the treatment without PS application, and Naf is the nutrient quantity applied via PS.

The data obtained were subjected to analysis of variance and, when significant, polynomial regressions were fitted between the manure application rates and the variables assessed. Linear models of the plateau

Table 1. Chemical characteristics of the soil in the 0-10 cm layer in May 2000 prior to the experiment and in January 2008, after 19 applications of pig slurry (PS)

Application rate of PS	$pH(H_2O)$	OM	P	K^+	Cu	Zn	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	CEC_{ef}	CEC_{pH7}	m[1]	V[2]
m^3 ha^{-1}		g kg^{-1}	mg dm^{-3}				$cmol_c$ dm^{-3}						%	
Chemical characteristics of the soil prior to the experiment														
	4.70	16.0	15.0	96	1.2	1.6	2.70	1.10	0.80	5.6	4.8	9.6	17.00	42.00
Soil chemical characteristics in January 2008 after 19 PS applications														
0	5.16	19.0	12.8	51	3.2	3.9	2.19	1.90	0.34	5.6	4.6	9.8	7.88	42.96
20	5.24	26.6	122.0	60	10.4	10.8	2.46	2.20	0.22	5.0	5.0	9.8	4.64	49.48
40	5.42	28.0	276.0	66	17.6	17.6	3.06	2.56	0.21	4.5	6.0	10.2	3.59	56.34
80	5.45	37.6	753.9	86	37.5	38.3	3.45	3.06	0.14	4.4	6.9	11.2	2.08	60.96

(1) Al saturation; (2) Bases saturation.

Table 2. Characteristics of pig slurry (PS) and the quantity of nutrients applied before putting in each crop over the 93 months of the experiment

Characteristic	Nutrients applied before each crop											
	Third growing season (2002/2003)											
	Black oat				Pearl millet				Black bean			
Dry matter (%)	0.47				6.68				4.82			
	Pig slurry rate (m^3 ha^{-1})											
		20	40	80		20	40	80		20	40	80
	Nutrient quantity applied											
	%	kg ha^{-1}			%	kg ha^{-1}			%	kg ha^{-1}		
Total N(1)	0.11	22.0	44.0	88.0	0.75	150.0	300.0	600.0	0.22	44.0	88.0	176.0
Total P(2)	2.12	2.0	4.0	8.0	1.19	15.9	31.8	63.6	2.95	28.4	56.8	113.6
Total K(2)	0.41	0.4	0.8	1.6	0.72	9.6	19.2	38.5	1.50	14.5	28.9	57.8
	Fourth growing season (2003/2004)											
	Black oat + common vetch				Maize							
Dry matter (%)	2.37				2.07							
	Pig slurry rate (m^3 ha^{-1})											
		20	40	80		20	40	80				
	Nutrient quantity applied											
	%	kg ha^{-1}			%	kg ha^{-1}						
Total N(1)	0.28	56.0	112.0	224.0	0.40	80.0	160.0	320.0				
Total P(2)	3.41	16.2	32.3	64.6	3.33	13.8	27.6	55.2				
Total K(2)	2.90	13.7	27.5	55.0	4.58	19.0	38.0	76.0				
	Fifth growing season (2004/2005)											
	Black oat + common vetch				Maize							
Dry matter (%)	1.0				7.2							
	Pig slurry rate (m^3 ha^{-1})											
		20	40	80		20	40	80				
	Nutrient quantity applied											
	%	kg ha^{-1}			%	kg ha^{-1}						
Total N(1)	0.06	12.0	24.0	48.0	0.37	74.0	148.0	296.0				
Total P(2)	4.22	8.4	16.8	33.6	5.58	80.3	160.6	321.2				
Total K(2)	10.13	20.3	40.5	81.0	1.27	18.3	36.6	73.2				
	Sixth growing season (2005/2006)											
	Black oat				Black bean				Sunn hemp			
Dry matter (%)	6.8				8.9				12.14			
	Pig slurry rate (m^3 ha^{-1})											
		20	40	80		20	40	80		20	40	80
	Nutrient quantity applied											
	%	kg ha^{-1}			%	kg ha^{-1}			%	kg ha^{-1}		
Total N(1)	0.30	60.0	120.0	240	0.12	24.0	48.0	96.0	0.10	20.0	40.0	80.0
Total P(2)	2.95	40.1	80.2	160.4	4.43	60.2	120.5	241.0	4.79	116.3	232.6	465.2
Total K(2)	0.91	12.4	24.8	49.6	2.44	33.2	66.4	132.8	1.01	24.5	49.0	98.0
	Seventh growing season (2006/2007)											
	Black oat				Maize				Black oat			
Dry matter (%)	9.94				1.91				3.52			
		20	40	80		20	40	80		20	40	80
	Nutrient quantity applied											
	%	kg ha^{-1}			%	kg ha^{-1}			%	kg ha^{-1}		
Total N(1)	0.10	20.0	40.0	80.0	0.16	32.0	64.0	128.0	0.32	64.0	128.0	256.0
Total P(2)	5.37	106.7	213.5	427.0	5.18	19.8	39.6	79.2	5.77	40.6	81.2	162.4
Total K(2)	1.85	36.8	73.6	147.2	3.56	13.6	27.2	54.4	3.58	25.2	50.4	100.8

(1) Analyses and calculations on a wet basis; (2) Analyses and calculations on a dry basis.

and quadratic types were tested, and the choice of the model which best fit was based on significance (p<0.05).

The mathematical expression of the plateau linear model is as follows. Linear-plateau model, defined by equations 2 and 3:

$$\hat{y} = a + bx,\ if\ x < C \quad (2)$$

$$\bar{y} = P,\ if\ x \geq C \quad (3)$$

in which $\hat{y}$ and $\bar{y}$ is the common bean yield (kg ha^{-1}); a and b are linear intercept and coefficient, respectively; x is the pig slurry application rate (m^3 ha^{-1}); the constant C is the point of intersection of the linear model with the plateau; P is the yield when the plateau is reached.

RESULTS AND DISCUSSION

The 19 PS applications over 93 months induced an increase in organic matter content of 40 and 47 % in the soil at rates of 20 and 40 m^3 ha^{-1} of PS, respectively, whereas the increase of 98 % in the soil fertilized with 80 m^3 ha^{-1} of PS was outstanding (Table 1). The soil pH (H_2O) increased with PS application - approximately 5.37 in the soil fertilized with PS and 5.16 in the soil without PS application. Thus, the increase of up to 59 times the soil available P content under PS application, in comparison to soil without PS application, stands out. This may promote P transfer by surface runoff, in the soil solution, or adsorbed to the surface of inorganic particles (Guardini et al., 2012). In contrast, the exchangeable K content in the soil under PS application was 69 % in comparison to the soil without PS application. More detailed information regarding the impact of PS on soil parameters was compiled by Lourenzi et al. (2011; 2013). The increases in Cu contents of 3.2, 5.5 and 11.7 times and in Zn contents of 2.8, 4.5 and 9.8 times with the use of 20, 40 and 80 m^3 ha^{-1} of PS, respectively, are pronounced, as discussed in detail by Girotto et al. (2010). Tiecher et al. (2013) also reported an increase in the Cu and Zn contents in soil subjected to PS application, which may lead to toxicity to plants, but also to the transfer of more soluble Cu and Zn forms in the runoff solution on the soil surface. It is also worth mentioning that according to the CONAMA resolution No. 375 (CONAMA, 2005), which regulates the agricultural use of sewage sludge, the maximum period of PS application to the soil of this study would be limited to only 15 years, due to the presence of Cu in the soil fertilized with 80 m^3 ha^{-1}, since this regulation determines a maximum load of 137 kg ha^{-1} of Cu in soil applications.

Common bean responded to the PS application - the maximum yield in the 2002/2003 growing season was 1.36 Mg ha^{-1} as a result of PS application of 80 m^3 ha^{-1} (Figure 2a). However, in 2005/2006, the yield reached 3.06 Mg ha^{-1} at a PS rate of 40 m^3 ha^{-1} (Figure 2a), favored by adequate rainfall of approximately 350 mm (Figure 1) during the period of common bean

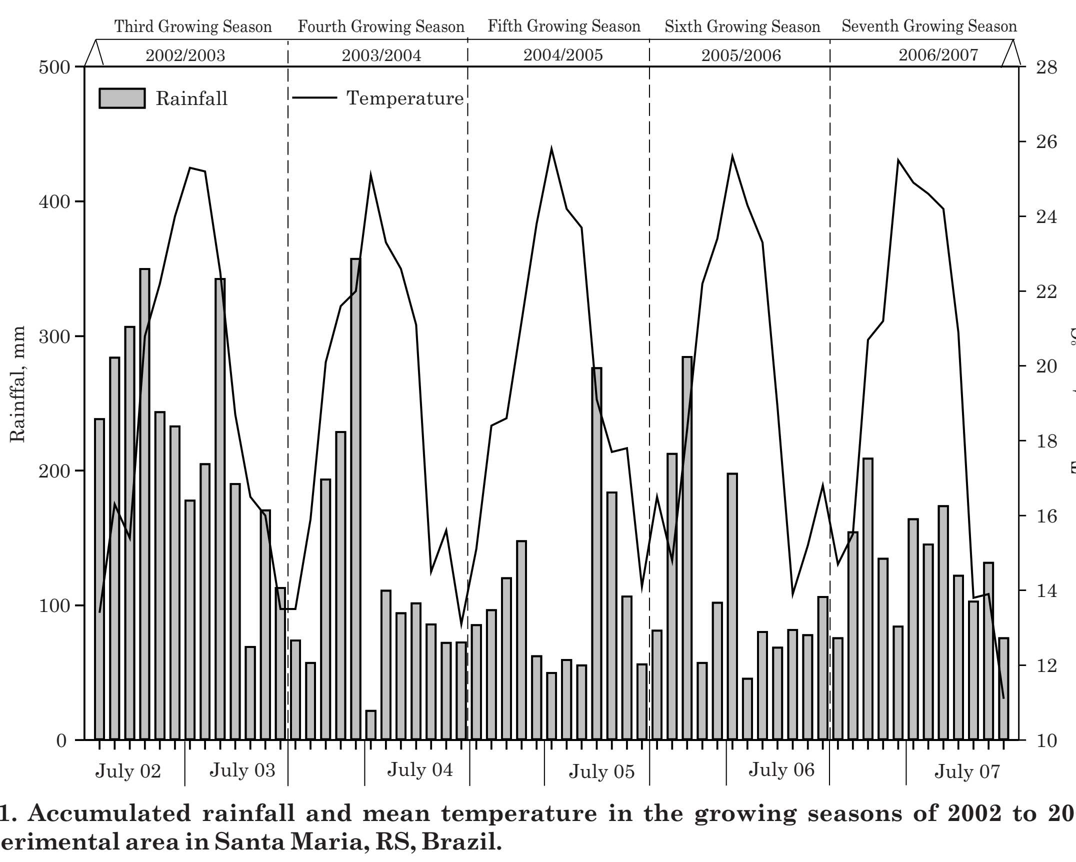

Figure 1. Accumulated rainfall and mean temperature in the growing seasons of 2002 to 2007 in the experimental area in Santa Maria, RS, Brazil.

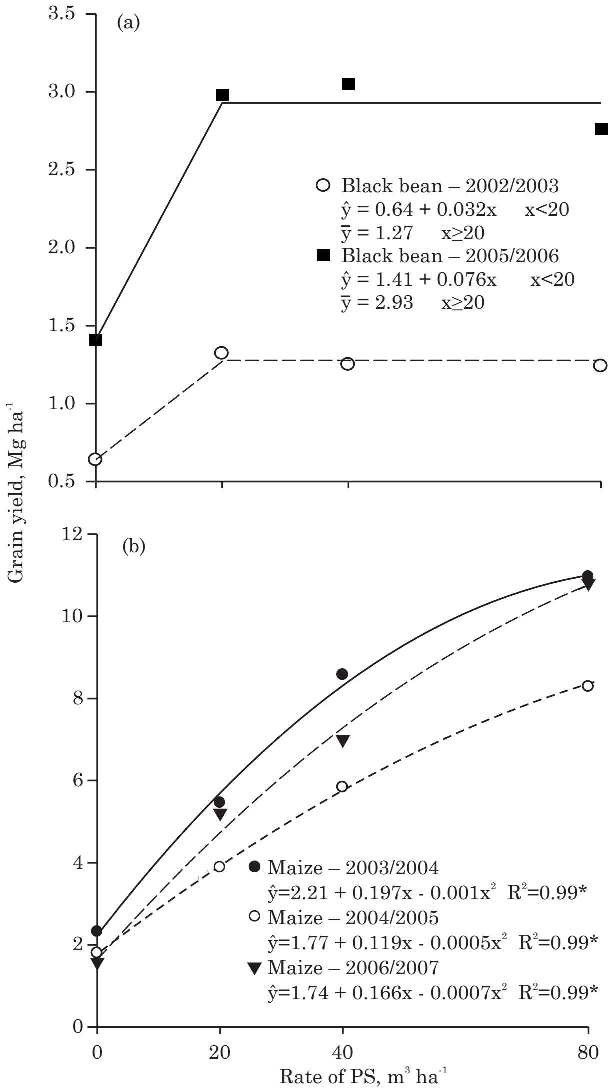

Figure 2. Grain yield of black bean (a) and maize (b) fertilized with 0, 20, 40 and 80 m^3 ha^{-1} pig slurry (PS) in different growing seasons. * indicates that the coefficients of determination were significant by the F test at 5%.

development (November 2005 to January 2006). For an adequate growth and development of common bean, 350 to 450 mm of water should be available during the growing period (Paula Junior & Venzon, 2007). In contrast, in 2002/2003, rainfall volumes were very high in the growing period (January to April 2003), with approximately 900 mm (Figure 1), hampering common bean development, especially at flowering.

For maize, the increasing PS rates led to an increase in grain yield in the three growing seasons (Figure 2b). The maximum maize grain yield was 10.96, 8.28 and 10.81 Mg ha^{-1} in the 2003/2004, 2004/2005 and 2006/2007 growing seasons, respectively, for the maximum PS application to the soil (Figure 2b), which was above the mean yield for the state of RS (CONAB, 2010). In addition, the weather conditions were favorable to the vegetative and reproductive development of maize in the three growing seasons because the maximum temperature remained below 31 °C and the minimum temperature above 18 °C, as well as rainfall amounts which ranged from approximately 830 mm in 2004/2005 to 1,100 mm in 2003/2004 (Figure1). It should be noted that irrigation was carried out in the case of water deficit.

Accumulated DM production in the 13 crops from 2002 to 2007 was 44.1 Mg ha^{-1} without PS application, and 74.7, 85.0 and 110.2 Mg ha^{-1} with PS rates of 20, 40 and 80 m^3 ha^{-1}, respectively (Figure 3a). Accumulated grain yield in the three maize and two common bean crops, on the other hand, was 7764 kg ha^{-1} without PS application, and 17786, 22204 and 31396 kg ha^{-1} with the addition of 20, 40 and 80 m^3 ha^{-1} of PS, respectively (Figure 3b).

The very high DM production of the aerial part of common bean at 80 m^3 ha^{-1} PS (Table 3) led to plant lodging in the flowering stage and increased the vegetative period of the plants, resulting in reduced grain filling in the two growing seasons (Figure 1a). This is an example of the importance of considering the nutritional requirements of the crop in recommendation of PS as a fertilizer, especially in relation to N. Even though N is required in large quantities by common bean, an excess may cause a series of negative aspects for the crop, such as lodging and an increase in the vegetative period of the plants.

The use of PS needs to be evaluated within a perspective of nutrient cycling, and the results for common bean showed that the expressive increase in the nutrient quantity applied through an increase in the PS rate reduced the nutrient use efficiency of the plants (Table 2). However, higher PS rates, in this case, would only make sense if the nutrient contents in the soil were below the desirable levels, recommended by the CQFSRS/SC (2004), since there would be an increase in the soil nutrient contents (Adeli et al., 2008; Ceretta et al., 2010; Scherer et al., 2010; Lourenzi et al., 2013). This would allow a partial or sometimes even total substitution of the mineral fertilizers for subsequent crops, reducing production costs on properties with swine production (Ceretta et al., 2005; Giacomini & Aita, 2008).

Maize grain yield had a significant increase with increasing PS rates, showing that this crop is one of the most adequate to grow in areas with a history of PS application (Figure 2b). Species of the grass family are generally more demanding in N than legumes since they do not establish an efficient symbiosis with N-fixing bacteria (Moreira & Siqueira, 2006). The use of grasses in the areas where PS is spread represents the possibility of applying higher rates, as seen in this study, reducing distribution costs and often making PS

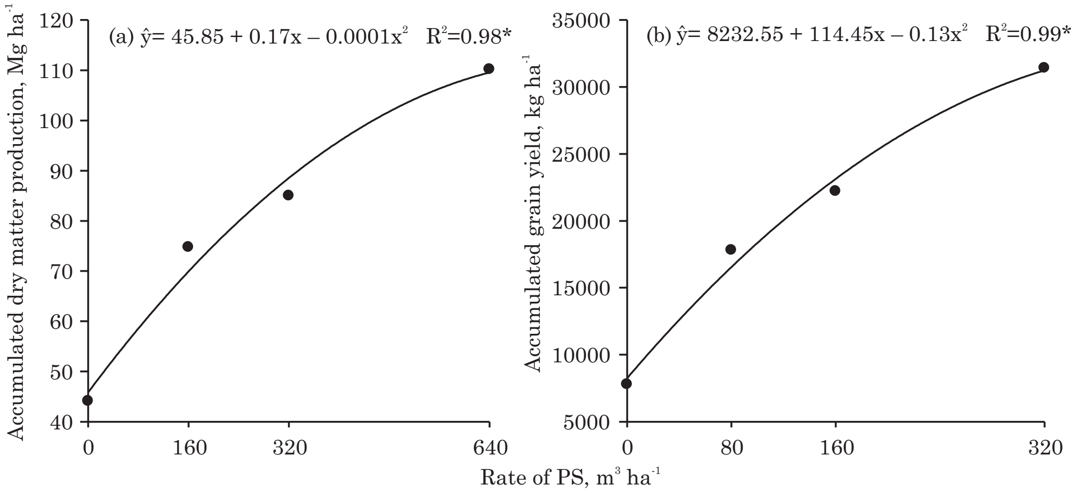

Figure 3. Accumulated dry matter production of the aerial part of cover crops, maize and common bean (a), and accumulated grain yield of black bean and maize in the growing seasons from 2002 to 2007 (b), on soil fertilized with accumulated amounts of pig slurry (PS). * indicates that the coefficients of determination were significant by the F test at 5 %.

distribution possible on the same property where PS is generated. However, it is essential to observe that, in most years, the apparent recovery of N, P and K decreases with increasing PS application rates (Table 3), which reflects accumulation of nutrients in the soil (Table 1).

In many cases, there is a direct relationship between grain yield and the nutrient quantity applied to the soil in PS, especially for N and P (Ceretta et al., 2005). However, with successive applications, the expectation of response to the application rates decreases because of the increase in the nutrient contents in the soil, which would justify the use of PS only to meet the demand and replace the nutrients exported by the maize plants. In these cases, if the nutrient content in the soil exceeds the sufficiency level (CQFSRS/SC, 2004), as occurs in the soil of the different treatments (Table 1), such that under these conditions, it is possible to obtain high grain yield with the addition of low amounts of nutrients added through PS. This occurred in the 2006/2007 growing season when, even with the application of lower N and P quantities to maize, the grain yield was similar to that of 2003/2004 and greater than that of 2004/2005, when higher nutrient quantities, especially of N and P, were applied (Table 2).

One of the explanations for these results is the accumulation of nutrients from successive PS applications, as observed in the soil throughout the experiment (Table 1). The data provided here show that successive PS applications over eight years increased the organic matter contents, exchangeable K, Ca and Mg contents, and the P content available to plants, as also observed by Ceretta et al. (2010), Lourenzi et al. (2011; 2013). Nevertheless, the apparent recovery of nutrients by crops was generally inversely proportional to the PS rate (Table 3). For N, the apparent recovery was on average 73, 63 and 55 % of the total N applied at 20, 40 and 80 m^3 ha^{-1} of PS, respectively. The apparent recovery of P was on average 23, 21 and 18 % for the same rates, respectively, and the recovery percentages were greatest in the first growing seasons. This is due to the high P amounts added to the soil in PS (Table 2) and the lower P demand of the crops (compared to N and K), leading to an accumulation of this nutrient in the soil as successive PS applications were made (Table 1), as observed by Ceretta et al. (2010). Thus, the subsequent crop will be less dependent on the P applied through PS, reducing apparent recovery over time. In contrast, the apparent recovery of K was on average 287, 186 and 184 %, at PS rates of 20, 40 and 80 m^3 ha^{-1}, respectively. This showed that, in addition to the K applied in PS, the crops took up exchangeable K from the soil (Ceretta et al., 2003; Lourenzi et al., 2013).

The DM production of the cover crops grown over the years, increased with PS application (Table 4), especially for pearl millet, with 16.2 Mg ha^{-1} in the 2002/2003 growing season when fertilized with 80 m^3 ha^{-1} of PS (Table 3). The DM production of black oat (2003/2004) and the intercropped oat+common vetch (2003/2004) was very high, i.e., greater than 10 Mg ha^{-1}. The mean increases in DM production with PS fertilization were 84, 108 and 168 %, at rates of 20, 40 and 80 m^3 ha^{-1}, respectively, in all crops. Similar results were obtained by Aita et al. (2006), who observed an increase of 104 % in oat DM production with the application of 80 m^3 ha^{-1} of PS. The presence of cover plants in rotation with commercial crops is very important because it means greater nutrient cycling (Rocha et al., 2012). In

Table 3. Dry matter production and accumulated quantity of N, P and K in the plant tissues of crops fertilized with 0, 20, 40 and 80 m³ ha-1 pig slurry (PS) before crop planting over five growing seasons

PS rate	Dry matter production and nutrient accumulation														
	Third growing season (2002/2003)														
	Black oat				Pearl millet				Black bean				Apparent Rec.(1)		
	DM	N	P	K	DM	N	P	K	DM	N	P	K	N	P	K
m^3 ha^{-1}	Mg ha^{-1}	kg ha^{-1}			Mg ha^{-1}	kg ha^{-1}			Mg ha^{-1}	kg ha^{-1}			%		
0	3.64	67.2	8.7	58.6	4.51	37.7	8.1	72.8	0.68	24.7	2.2	13.7	-	-	-
20	7.58	134.1	18.2	125.1	9.96	86.5	19.0	165.7	1.37	46.3	5.1	27.5	64	50	707
40	9.50	168.3	24.5	156.8	9.50	81.7	23.1	182.9	2.30	87.9	9.3	46.8	48	41	494
80	10.00	171.4	28.5	191.1	16.20	177.7	35.2	311.8	3.07	99.9	11.7	76.0	37	30	443
F test	*(2)	**	**	**	*	**	**	**	*	**	**	**			
	Fourth growing season (2003/2004)														
	Black oat + Common vetch				Maize										
	Mg ha^{-1}	kg ha^{-1}			Mg ha^{-1}	kg ha^{-1}							%		
0	4.71	108.2	7.9	69.1	6.57	58.1	8.1	57.8					-	-	-
20	7.94	210.2	18.9	134.3	8.94	78.5	12.6	86.0					90	52	286
40	8.29	218.0	22.2	132.2	10.70	118.7	16.8	114.8					63	38	183
80	13.51	416.8	41.2	258.2	12.12	159.3	21.6	168.3					75	39	229
F test	*	*	**	**	*	**	**	**							
	Fifth growing season (2004/2005)														
	Black oat + Common vetch				Maize										
	Mg ha^{-1}	kg ha^{-1}			Mg ha^{-1}	kg ha^{-1}							%		
0	2.40	29.1	5.4	40.5	5.13	46.6	7.9	53.6					-	-	-
20	3.48	61.8	8.9	67.5	8.04	74.4	13.5	95.1					70	10	177
40	3.68	65.4	10.8	69.5	10.92	109.2	24.0	142.1					58	12	152
80	4.48	96.9	15.4	102.3	15.08	172.5	37.8	190.8					56	11	129
F test	*	*	**	**	*	*	**	**							
	Sixth growing season (2005/2006)														
	Black oat				Black bean				Sunn hemp						
	Mg ha^{-1}	kg ha^{-1}			Mg ha^{-1}	kg ha^{-1}			Mg ha^{-1}	kg ha^{-1}			%		
0	2.59	34.4	4.7	38.5	1.37	32.7	3.3	26.5	1.75	39.3	5.2	11.2	-	-	-
20	4.78	59.0	11.0	76.2	3.03	71.5	8.0	73.8	2.97	58.4	11.2	28.3	61	5	146
40	5.15	70.2	16.0	81.4	3.11	74.1	11.5	70.2	2.87	68.4	13.2	26.3	37	5	73
80	6.23	104.7	21.8	114.0	4.69	110.6	16.7	115.5	2.93	66.0	15.0	43.5	36	4	70
F test	**	**	**	**	**	**	**	**	*	*	**	*			
	Seventh growing season (2006/2007)														
	Mg ha^{-1}	kg ha^{-1}			Mg ha^{-1}	kg ha^{-1}			Mg ha^{-1}	kg ha^{-1}			%		
0	4.04	73.1	10.1	38.5	3.66	22.8	8.8	37.6	3.01	42.5	5.9	30.9	-	-	-
20	5.89	136.0	19.6	70.2	6.60	48.7	21.8	62.9	4.11	78.5	12.6	52.7	108	18	104
40	6.96	202.8	23.5	70.2	7.19	72.0	24.1	69.8	4.80	118.1	15.2	52.8	110	11	57
80	7.54	218.9	23.0	120.3	8.78	87.2	34.9	131.9	5.52	160.5	18.4	73.9	71	8	72
F test	**	**	**	**	**	**	**	**	**	**	**	*			

(1) Apparent recovery = [(nutrient quantity taken up at the application rate - nutrient quantity taken up in the treatment without manure)/nutrient quantity applied in manure]×100; (2) * and ** indicates that the coefficients of determination were significant by the F test at 5 and 1 %, respectively, for the quadratic regression equations.

addition, because of the amounts of DM produced with the PS fertilization in this study, it was possible to maintain the plant cover on the soil, with all benefits in terms of soil conservation, greater water infiltration and higher C quantity stored in the soil, resulting in greater microbial activity.

CONCLUSIONS

1. The increase in the pig slurry rates applied over the years led to an increase in nutrient availability, especially of phosphorus, but also of elements potentially toxic to plants, e.g., of copper and zinc.

Table 4. Mathematical equations of best fit for dry matter (DM) and nutrient accumulation for different crops and growing seasons

Variable	Fitted quadratic polynomial equation					
	Third growing season (2002/2003)					
	Black oat	R^2	Pearl millet	R^2	Black bean	R^2
DM	$\hat{y} = 3.7142 + 0.2184 x - 0.0018 x^2$	0.99	$\hat{y} = 5.2014 + 0.1495 x - 0.0002 x^2$	0.91	$\hat{y} = 0.6306 + 0.0478 x - 0.0002 x^2$	0.99
N	$\hat{y} = 68.095 + 3.8121 x - 0.0316 x^2$	0.99	$\hat{y} = 44.965 + 0.9344 x + 0.0087 x^2$	0.94	$\hat{y} = 21.122 + 1.9815 x - 0.0123 x^2$	0.96
P	$\hat{y} = 8.7273 + 0.5443 x - 0.0037 x^2$	0.99	$\hat{y} = 8.7627 + 0.4554 x + 0.0016 x^2$	0.99	$\hat{y} = 1.930 + 0.2183 x - 0.0012 x^2$	0.98
K	$\hat{y} = 60.654 + 3.3907 x - 0.0221 x^2$	0.99	$\hat{y} = 81.571 + 3.1022 x - 0.0033 x^2$	0.97	$\hat{y} = 12.994 + 0.8292 x - 0.0005 x^2$	0.99
	Fourth growing season (2003/2004)					
	Black oat + Common vetch	R^2	Maize	R^2		
DM	$\hat{y} = 5.0689 + 0.0929 x + 0.0001 x^2$	0.96	$\hat{y} = 6.5626 + 0.1366 x - 0.0008 x^2$	0.99		
N	$\hat{y} = 120.90 + 2.4794 x + 0.0146 x^2$	0.96	$\hat{y} = 55.395 + 1.5846 x - 0.0034 x^2$	0.99		
P	$\hat{y} = 8.8682 + 0.3633 x + 0.0005 x^2$	0.98	$\hat{y} = 8.0264 + 0.2613 x - 0.0011 x^2$	0.99		
K	$\hat{y} = 78.157 + 1.3951 x + 0.0102 x^2$	0.95	$\hat{y} = 57.672 + 1.4562 x - 0.0009 x^2$	0.99		
	Fifth growing season (2004/2005)					
	Black oat + Common vetch	R^2	Maize	R^2		
DM	$\hat{y} = 2.4829 + 0.0435 x - 0.0002 x^2$	0.96	$\hat{y} = 5.0888 + 0.1624 x - 0.0005 x^2$	0.99		
N	$\hat{y} = 32.144 + 1.1704 x - 0.0047 x^2$	0.95	$\hat{y} = 45.855 + 1.5066 x + 0.001 x^2$	0.99		
P	$\hat{y} = 5.5527 + 0.1552 x - 0.0004 x^2$	0.99	$\hat{y} = 7.3027 + 0.3914 x - 0.0001 x^2$	0.99		
K	$\hat{y} = 43.331 + 0.8662 x - 0.0018 x^2$	0.95	$\hat{y} = 51.915 + 2.5976 x - 0.0107 x^2$	0.99		
	Sixth growing season (2005/2006)					
	Black oat	R^2	Black bean	R^2	Sunn hemp	R^2
DM	$\hat{y} = 2.7482 + 0.093 x - 0.0006 x^2$	0.96	$\hat{y} = 1.538 + 0.0567 x - 0.0002 x^2$	0.94	$\hat{y} = 1.8651 + 0.0489 x - 0.0005 x^2$	0.84
N	$\hat{y} = 35.826 + 1.0063 x - 0.0019 x^2$	0.99	$\hat{y} = 36.515 + 1.3506 x - 0.0055 x^2$	0.94	$\hat{y} = 39.434 + 1.1302 x - 0.01 x^2$	0.99
P	$\hat{y} = 4.6918 + 0.3507 x - 0.0017 x^2$	0.99	$\hat{y} = 3.3491 + 0.2458 x - 0.001 x^2$	0.99	$\hat{y} = 5.4673 + 0.2953 x - 0.0022 x^2$	0.98
K	$\hat{y} = 41.765 + 1.4189 x - 0.0066 x^2$	0.95	$\hat{y} = 32.096 + 1.4456 x - 0.0053 x^2$	0.90	$\hat{y} = 13.341 + 0.494 x - 0.0016 x^2$	0.89
	Seventh growing season (2006/2007)					
	Black oat	R^2	Maize	R^2	Black oat	R^2
DM	$\hat{y} = 4.0613 + 0.1037 x - 0.0008 x^2$	0.99	$\hat{y} = 3.8635 + 0.1261 x - 0.0008 x^2$	0.96	$\hat{y} = 3.0255 + 0.0592 x - 0.0004 x^2$	0.99
N	$\hat{y} = 69.576 + 4.4276 x - 0.0318 x^2$	0.99	$\hat{y} = 22.156 + 1.6121 x - 0.010 x^2$	0.99	$\hat{y} = 41.202 + 2.2185 x - 0.009 x^2$	0.99
P	$\hat{y} = 10.332 + 0.5242 x - 0.0046 x^2$	0.99	$\hat{y} = 9.8445 + 0.5084 x - 0.0025 x^2$	0.96	$\hat{y} = 6.1809 + 0.3275 x - 0.0022 x^2$	0.99
K	$\hat{y} = 42.46 + 0.8265 x + 0.0016 x^2$	0.94	$\hat{y} = 40.423 + 0.6194 x + 0.0064 x^2$	0.98	$\hat{y} = 33.245 + 0.7139 x - 0.0027 x^2$	0.93

2. The apparent recovery of nutrients by the commercial grain and cover crops decreased with the increasing number of pig slurry applications to the soil.

3. Accumulated dry matter production of the crops and the maize grain yield were highest at an annual application rate of 80 m^3 ha^{-1} of pig slurry. However, common bean grain yield increased up to 20 m^3 ha^{-1} yr^{-1} of pig slurry, showing that the crop to be grown should be taken into consideration when defining the application rate.

ACKNOWLEDGEMENTS

The authors wish to thank the National Council for Scientific and Technological Development (CNPq) and FAPERGS (Fundação de Amparo a Pesquisa do Estado do Rio Grande do Sul) for funding this research.

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