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Soils and Surface Waters as Affected by Long-Term Swine Slurry Application in Oxisols of Southern Brazil*[1]

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ABSTRACT

The accelerated expansion of swine production in Brazil has increased the generation of liquid wastes, which are usually applied to agricultural soils after a simplified treatment and pose potential environmental impacts. The objective of this study was to assess the agronomic and environmental impacts of long-term application of swine slurry (SS) on soil and stream water properties in watersheds dominated by Oxisols in Quinze de Novembro of Southern Brazil. Soil samples (0–30 cm) were collected from farms with continuous application of SS since 1990 at low (40–80 m^3 SS ha^{-1} $year^{-1}$) and high (120–300 m^3 SS ha^{-1} $year^{-1}$) rates of SS. Surface water samples were collected from streams adjacent to the farm fields. Long-term SS application did not change total organic C and particulate organic C compared to cropland and woodland soils without SS application. The high rates of SS increased total N, P, Cu, and Zn and available P and Cu in the topsoil (0–10 cm) compared to woodland and cropland soils without SS application. Surface water analyses showed that fecal coliform bacteria and biological oxygen demand exceeded the legal limits for high quality water (Class 1). Other water parameters (such as NO_3^-, phosphate and total suspended solids) were within the acceptable limits. Long-term disposal of SS in cropland under no-tillage had impaired water quality in Quinze de Novembro, especially biological parameters. Some best management practices should be adopted, including more rigorous control of SS application to cropland as well as requiring edge-of-field and riparian vegetative buffers.

Key Words: no-tillage, nutrient balance, swine farm, water quality, watershed

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INTRODUCTION

The global production of pork, the chief source of animal protein for human consumption, increased by 12% from 2003 to 2011. Brazil is a key player in the global pork market, supplying major international buyers in the European Union, Japan, Russia and China (USDA, 2012), with potential for further expansion because of its large territory and increasing grain production.

Recent trends in the pork trade have lead to specialization and intensification of swine production. In Brazil, disposal of the liquid effluent from confined swine feeding facilities, also known as swine slurry (SS), is government regulated and must follow environmental licensing protocols. As in other swine producing countries (*e.g.*, USA and Canada), application on cropland is considered by environmental agencies as an adequate disposal strategy for Brazilian SS. This is because SS has substantial nutrient contents and can be readily decomposed by soil microorganisms (Pote *et al.*, 2001; Burkholder *et al.*, 2007; Kunz *et al.*, 2009). However, there is a risk of significant environmental impact if best management practices are not strictly followed (Sharpley *et al.*, 1997; Unc and Goss, 2004; Williams, 2008; Scherer *et al.*, 2010). This risk is exacerbated if logistical constraints that govern modern pork production lead to concentration of swine farms in certain regions or watersheds (Kunz *et al.*, 2009).

Long-term application of high rates of SS to cropland results in accumulation of nutrients, especially P, Zn and Cu that are common supplements in swine feed, and can lead to crop nutrient imbalance and even plant toxicity (Redding, 2001; Redding *et al.*, 2002; Gräber *et al.*, 2005). Moreover, there is a risk of surface water contamination when SS is spread on the soil surface, caused by transport of SS or its decomposition products with runoff, especially in high rainfall areas (Red-

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ding, 2001; Allen and Mallarino, 2008; Anami *et al.*, 2008). Subsurface waters can also be affected if excess nutrients or organic pollutants leach to subsurface soil layers (Burkholder *et al.*, 2007).

The aim of this study was to assess changes in soil and stream water properties in agricultural catchments with long-term application of SS, based on the premise that application of SS in agricultural soils is compatible with maintenance of soil and surface water quality.

MATERIALS AND METHODS

Study area

This research was conducted from 2010 to 2012 in 6 swine farms located in 4 agricultural catchments of Quinze de Novembro Municipality in the state of Rio Grande do Sul (RS), Brazil (Fig. 1). These farms are finishing operations, with the number of animals per operation ranging from 450 to 1 000 pigs. Quinze de Novembro has been a major swine production area since the early 1900s, with an important share of the Brazilian pork production. The climate is subtropical (Cfa—humid temperate climate with hot summer, according to Köppen climate classification), with a mean annual temperature of 18.8 °C and a mean annual rainfall of 1 750 mm. Altitudes vary from 380 to 440 m above sea level and the topography is gently sloping, with steeper slopes occurring near rivers. According to Soil Taxonomy (Soil Survey Staff, 2014), soils are predominantly Oxisols (Typic Hapludox covers approximately 80% of the region), developed from basaltic rocks that dominate the geology of South-central Brazil. Other soils with minor occurrence are Entisols, Inceptisols and Ultisols.

The most usual cropping system comprises summer crops of soybean (*Glycine max*) and corn (*Zea mays*), the latter grown for grain and silage, and winter crops of black oats (*Avena sativa*) and wheat (*Triticum aestivum*), grown as cover and grain crops, respectively. Soil management is almost exclusively no-tillage (NT). Perennial pasture, especially *Cynodon* sp. cv. Tifton 85 (Tifton), is also grown for dairy cattle grazing and/or hay production.

Experiment

The study addressed only Oxisols that had been receiving SS for approximately 20 years. Farm fields, located in 4 agricultural catchments, were selected after interviewing swine farmers and local extension agents. After anaerobic fermentation in earth-banked lagoons with impervious polyethylene liners, SS was spread on Tifton fields and from fall to early spring on fields cultivated with cover crops (oat and ryegrass) or wheat on a monthly basis. As farmers do not keep systematic records on the exact amount of SS applied to farm fields, two rate ranges of SS application were established: high rate ranging from 120 to 300 m^3 SS ha^{-1} year^{-1}, usually applied in perennial pasture fields, and low rate ranging from 40 to 80 m^3 SS ha^{-1} year^{-1}, used in annual cropland. Because fields with both high and low rates of SS application were not available in all

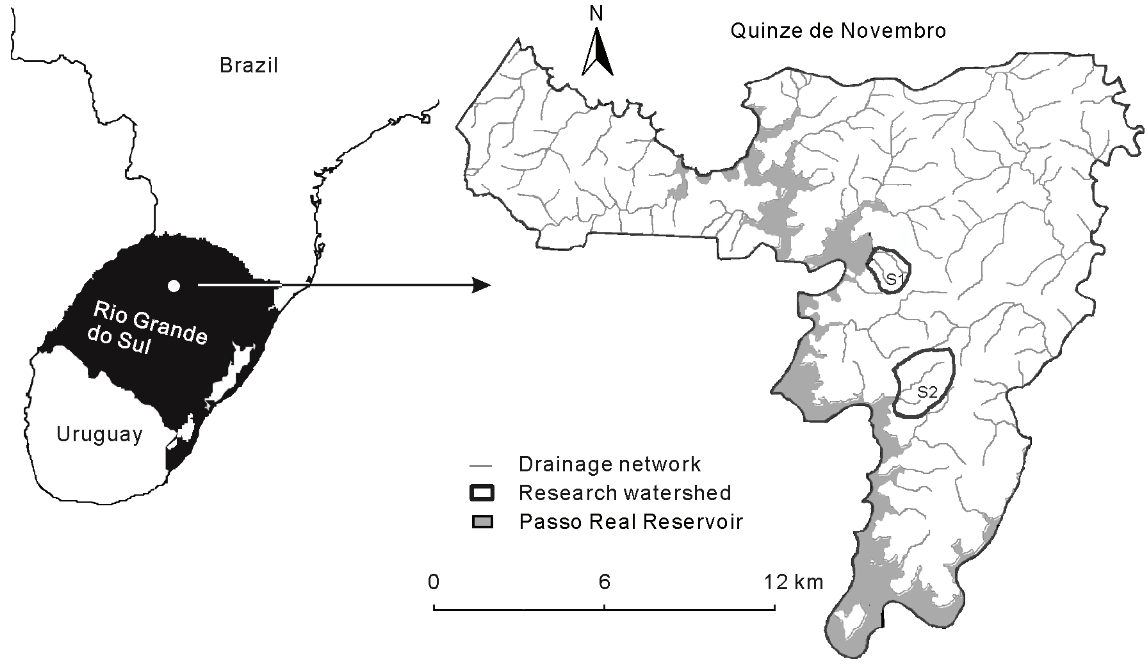

Fig. 1 Geographic location of Quinze de Novembro Municipality in Rio Grande do Sul State, Southern Brazil. Surface water samples were collected from two first-order streams (S1 and S2) in selected watersheds.

farms, additional high-rate fields were sampled in one of the farms studied. Care was taken to selected farm fields that were similar with respect to all crop inputs (*e.g.*, liming, chemical fertilizers and other farm chemicals) within each SS application level. Additionally, croplands with no record of SS (*i.e.*, receiving only mineral fertilizers at usual rates in the region) and woodlands (undisturbed fragments of subtropical forests), adjacent to the fields receiving SS, were chosen as the controls.

SS sampling and analysis

To obtain an estimate of SS composition used by farmers, SS was collected from anaerobic lagoons (the number of lagoons = 9) at various dates throughout the duration of the study. For each lagoon and sampling date, the collected SS was mixed and four samples were randomly collected with 10 L buckets from different positions (borders and centers). These samples were composited, thoroughly mixed and an aliquot (about 3 L) transported in a refrigerated container for analysis of the following parameters: water content by gravimetric analysis, pH by potentiometry, organic C by wet combustion, total N, NH_4^+ and NO_3^- by Kjeldahl, and total P, Cu and Zn by nitric-perchloric acid digestion followed by inductively coupled plasma spectroscopy, as discussed in detail by Tedesco *et al.* (1995).

Soil sampling and analysis

Soil samples were collected at three depths (0–10, 10–20 and 20–30 cm) from freshly dug pits (25 cm wide × 30 cm long × 40 cm deep) at two sampling points randomly assigned to each cropland or woodland site with at least 150 m separation. The samples were air-dried and sieved by a 2-mm mesh before analysis. After pretreatment with H_2O_2 (10%, v/v) for the removal of organic matter, particle size distribution was determined with the pipette method (Gee and Bauder, 1986). Particulate organic C (POC) was obtained as the method described in Cambardella and Elliot (1992) and determined by the dry combustion method in a Shimadzu C analyzer. Total organic C (TOC) and total N were determined by the dry combustion and Kjeldahl methods, respectively. Plant-available Cu and Zn were extracted with 0.1 mol L^{-1} HCl and determined by atomic absorption spectroscopy (AAS). Available P was determined by the Mehlich-1 method. Total P, Cu and Zn were determined by AAS following nitric-perchloric acid digestion. The analytical methods are described in Sparks *et al.* (1996), with the modifications for routine analysis proposed by Tedesco *et al.* (1995).

Sampling of stream water

Surface water samples were collected from two first-order streams (S1 and S2) (Fig. 1) in selected watersheds where croplands has been receiving high rates of SS (120 to 300 m^3 ha^{-1} $year^{-1}$) applied by tractor-pulled slurry spreaders or fertigation (spray rigs). The catchment where stream S1 is located covers approximately 76 ha with a length of 875 m, while that where S2 is located covers 46.7 ha with a length of 1 000 m. The outlets of streams into the Passo Real Reservoir are located at 53°6′43.584″ W, 28°45′18.931″ S for S1 and 53°6′17.148″ W, 28°47′55.34″ S for S2. Sampling points were established at somewhat random intervals in S1 (source, midpoint and outlet) and S2 (source and outlet). The riparian zones in these catchments are typically fenced-off and covered with woods or shrubs, however, farmers do not regard these areas as buffer zones with respect to cropland runoff.

Grab samples (about 2 L) were collected from stream S1 in Jul. 2010–Jun. 2011 and from stream S2 in Apr. 2011–Mar. 2012, from which 300 mL aliquots were obtained and kept in polyethylene flasks and refrigerated at about 4 °C until analysis. This sampling approach of surface water quality monitoring was consistent with the Resolution No. 357/2005 (RES357) of the Brazilian National Environmental Council (CONAMA, 2005) and international protocols (Bartram and Ballance, 1996). It is necessary to avoid water sampling after rainfall events, which could produce streamflow peaks and potentially dilute contaminants. Monthly rainfalls in stream S1 and stream S2 are shown in Fig. 2 throughout the duration of the study. Selected water quality parameters, such as pH, electrical conductivity (EC), apparent color, turbidity, total N, total P, biochemical oxygen demand (BOD_5), NH_4^+, NO_3^-, total suspended solids (TS) and fecal coliform bacteria (FCB), were analyzed according to American Public Health Association (APHA) standard methods (Clescerl *et al.*, 1998).

Statistical analysis

Statistical analyses were conducted in SAS version 9.0 (SAS Institute, 2004). Data were initially tested for normality with the Kolmogorov-Smirnov test and homogeneity of variances using the Levene's test. If necessary, data were log-transformed. Analysis of variance (ANOVA) was applied to the data considering a completely random design. Tukey's test was applied when significant differences ($P < 0.05$) were observed. No statistical tests were applied to surface water data be-

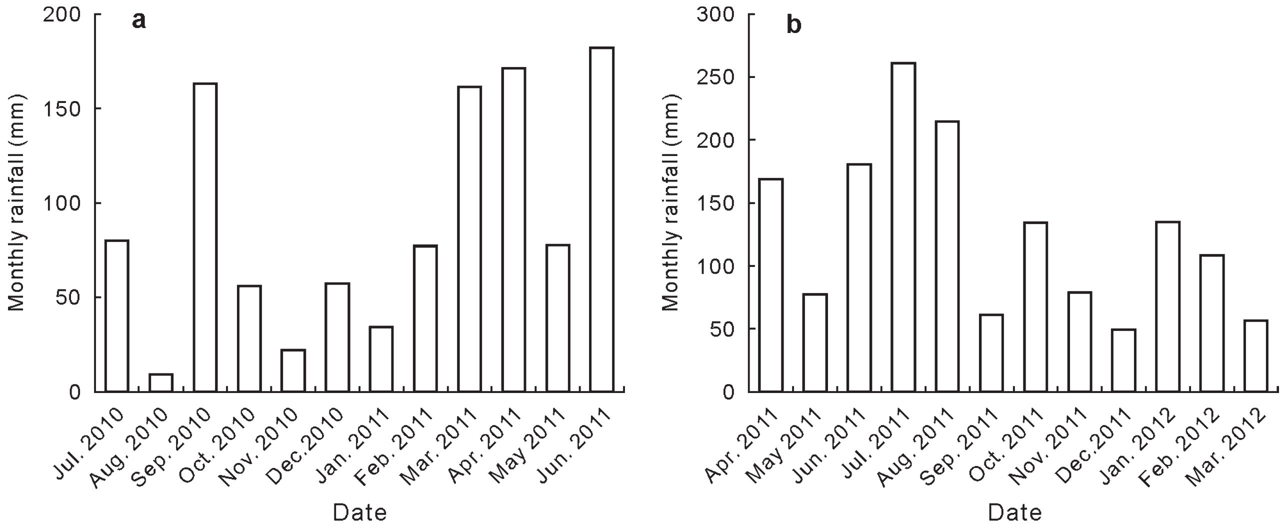

Fig. 2 Monthly rainfalls in stream S1 (a) and stream S2 (b) throughout the duration of the study.

TABLE I

Some physical and chemical characteristics[a] of swine slurry samples ($n = 9$) collected from each anaerobic lagoon of swine farms in Quinze de Novembro

Statistics	Water content	pH	TOC[a]	Total N	NH_4^+	Total P	NO_3^-	Total Cu	Total Zn
	g kg^{-1}		kg m^{-3}				g m^{-3}		
Mean	988.0	7.6	4.5	1.6	1.4	0.3	9.3	1.9	12.0
Median	997.0	7.6	1.4	1.1	1.0	0.1	2.0	0.6	4.6
CV[b] (%)	1.7	4.1	171.4	79.4	34.3	149.6	155.4	139.9	142.9

[a] TOC = total organic C. TOC, total N, P, Cu and Zn data were reported on a wet basis.

[b] Coefficient of variation.

cause only one sample was measured for each date and sampling location.

RESULTS AND DISCUSSION

SS composition and nutrient balance

Analyses of SS collected throughout the duration of this study from lagoons in farms showed nutrient compositions (Table I), which were similar to those reported in other studies (Pote *et al.*, 2001; Gräber *et al.*, 2005; Miranda, 2007; Kunz *et al.*, 2009; Scherer *et al.*, 2010). Although these wastes are highly diluted, long-term SS application introduces large quantities of nutrients to these soils (notably N, P, Zn and Cu).

Brazilian and international environmental quality standards for confined animal production wastes and effluents usually treat N and P as key elements of concern. SS management regulations require that SS application rates should be determined by the N content of the residue and target crop N requirements. The low rate of 80 m SS ha^{-1} year^{-1} already met the N requirement of a corn crop with a target yield of 9.0 Mg grain ha^{-1} (Table II), which is 60% higher than the regional average yield of 5.0 Mg grain ha^{-1} year^{-1}. The high rate (300 m^3 SS ha^{-1} year^{-1}) commonly applied to Tifton pastures would add approximately 500 kg N ha^{-1} year^{-1}. Alvim *et al.* (1999) noted that Tifton 85 responded to N fertilizer in doses up to 600 kg ha^{-1} year^{-1}, whereas Brink *et al.* (2003) found that Tifton pastures extract up to 462 kg N ha^{-1} year^{-1}. These results suggest that most N applied with the high rate of SS could be taken up by Tifton pastures.

TABLE II

Estimated nutrient quantity (input and export) of cropland cultivated with Tifton 85 and corn under long-term swine slurry (SS) application in Quinze de Novembro, considering the upper limit of application rate ranges

Item	N	P	Cu	Zn
	kg ha^{-1} year^{-1}			
Input by SS application				
80 m^3 SS ha^{-1} year^{-1}	128	24	0.15	0.96
300 m^3 SS ha^{-1} year^{-1}	480	90	0.57	3.60
Export[a] with crop product				
Tifton 85 (20 Mg DM[b] ha^{-1})	385	43	0.11	0.28
Corn grain (9 Mg ha^{-1})	187	34	0.11	0.40
Corn silage (18 Mg DM ha^{-1})	223	25	-	-

[a] Nutrient quantity was estimated based on data by Brink *et al.* (2003) for Tifton 85 and Murrell (2008) for corn.

[b] Dry matter.

The 80 m^3 SS ha^{-1} year^{-1} application rate, which was commonly used by farmers in Quinze de Novembro, could potentially meet the P requirements for high yielding corn crops as grown in this region. At the same time, P added with the high rate considered in this study would be two to three times greater than that needed to produce 24 Mg dry matter (DM) ha^{-1} year^{-1} of Tifton (SBCS-NRS, 2004). Additionally, using nutrient extraction estimates for Tifton pastures reported by Brink *et al.* (2003), a high rate of SS, noted in well-managed Tifton pastures of Quinze de Novembro, provided more than 100% of P required to produce 20 Mg DM ha^{-1} year^{-1}.

Other nutrients in SS may pose environmental risks, such as Cu and Zn, which are also added to soils in large quantities (Table II). This was especially true at the high rate of SS (0.57 kg Cu ha^{-1} year^{-1} and 3.60 kg Zn ha^{-1} year^{-1}), which added 4 to 10 times more than the estimated extraction of Cu and Zn by the crops grown (Brink *et al.*, 2003). Moreover, fertilization of annual crops and pastures with micronutrients is generally not recommended for annual crops in the Oxisols in Southern Brazil because these soils are generally well supplied with these nutrients (SBCS-NRS, 2004). Therefore, while agronomic benefits from large inputs of these two micronutrients are not expected, the risk of phytotoxicity needs to be further elucidated (Borkert *et al.*, 1998).

In summary, a low rate (up to 80 m^3 SS ha^{-1} year^{-1}) to the cropping system (summer corn/winter black oats) under NT is compatible with the crops' requirements if managed for high yields. The crops will take up most of the nutrients introduced by SS and a large part thereof exported with the harvest products (grain and biomass). On the other hand, high SS application rates (up to 300 m ha^{-1} year^{-1}) in Tifton pastures represent a risk to environmental quality because the nutrients added to soils exceed that of crop uptake. These observations are supported by other nutrient balance studies at the watershed-scale that have reported impaired stream and ground water quality following continuous application of high rates of SS (Stone *et al.*, 1998; Burkholder *et al.*, 2007).

Soil organic C, particulate organic C, and total N

Soil TOC, POC and the POC/TOC ratio did not significantly differ among various soil managements and land uses (Table III). This was consistent with other cropland SS disposal studies in similar soils of Southern Brazil and has been attributed to the lability and rapid decomposition of soil organic matter (SOM) in SS (Aita *et al.*, 2006a; Scherer *et al.*, 2010). However, a significant increase (albeit of only 15%) in TOC content was observed after applying 120 m^3 SS ha^{-1} year^{-1} for 3 years by Balota *et al.* (2010), who conducted a field experiment in a clayey Hapludox similar to soils of this study. It should be noted that the SS used in the study of Balota *et al.* (2010) was more concentrated (209 g DM kg^{-1}), leading to an annual C input four-fold greater than the low rates applied in Quinze de Novembro (Table I). Concurrently, Lourenzi *et al.* (2011) reported higher TOC in a Hapludult (sandy loam in the topsoil) after 80 m^{-3} SS ha^{-1} year^{-1} applied continuously (8 years). While most stu-

TABLE III

Total organic C (TOC), particulate organic C (POC), total N, POC/TOC ratio, and C to N ratio (C/N) of the soils at three depths under various swine slurry (SS) application rates and land uses in Quinze de Novembro

Soil depth	Land use	SS rate	n	TOC	POC	Total N	POC/TOC	C/N
				g kg^{-1}			%	
0–10 cm	Woodland	Zero	9	23.6±8.1[a)]a[b)]	1.6±1.3a	2.2±0.6a	6±3.0a	10.4±1.5a
	Cropland	Zero	8	19.5±5.1a	1.0±0.7a	1.7±0.4b	5±2.3a	11.5±1.2a
		Low	8	22.0±1.6a	1.0±0.4a	1.8±0.1ab	5±1.7a	10.6±0.6a
		High	12	18.7±5.8a	1.9±1.4a	2.2±0.5a	8±4.2a	10.2±0.8a
10–20 cm	Woodland	Zero	9	15.7±4.4a	0.7±0.4a	1.5±0.2a[c)]	4±1.6a	9.9±1.3b
	Cropland	Zero	8	14.8±3.1a	0.5±0.3a	1.3±0.3ab	3±0.9a	11.6±1.9a
		Low	8	13.9±1.7a	0.4±0.2a	1.3±0.1ab	3±1.3a	10.6±1.5ab
		High	12	12.7±2.5a	0.5±0.3a	1.2±0.2b	4±2.0a	10.4±0.7ab
20–30 cm	Woodland	Zero	9	12.7±3.3a	0.4±0.2a	1.2±0.2a	3±1.3a	10.7±1.7a
	Cropland	Zero	8	12.1±2.0a	0.3±0.2a	1.0±0.1a	3±1.2a	11.8±1.5a
		Low	8	11.5±2.7a	0.4±0.2a	1.1±0.3a	3±1.1a	10.4±1.1a
		High	12	11.4±3.3a	0.6±0.6a	1.0±0.2a	5±5.6a	10.9±1.3a

[a)] Means±standard deviations.

[b)] Means followed by the same letter(s) within the same column and soil layer are not significantly different at $P < 0.05$, according to Tukey's honestly significant difference test.

[c)] $n = 8$.

dies focus on surface soil changes, Angers *et al.* (2010) observed a decrease of TOC in soil subsurface layers, which was attributed to a priming effect from the large input of labile C in SS on decomposer microorganisms. This effect was not observed in our study.

SS impact on total N was significant only in the surface layers (0–10 and 10–20 cm) (Table III). Cropland without SS application had the lowest total N contents in the surface layer (0–10 cm) in comparison with soils under woodland or high rates of SS. In contrast, total N was significantly higher in the 10–20 cm layer in woodland soil and lower under high rates of SS. This latter observation could be attributed to enhanced crop growth responding to higher SS rates, and consequently, greater N removal, thus reducing the likelihood of N leaching to subsurface. Approximately 50% of N added with SS is readily available to plants and microorganisms (Aita *et al.*, 2006b). Furthermore, Tifton pastures in this study have high potential response to N (Alvim *et al.*, 1999; Brink *et al.*, 2003), and other soil properties, management and climatic conditions are generally favorable to high primary productivity and yields.

The values of C/N ratio were lower in cropland with high SS application rates (Table III), consistent with the results in comparable Hapludox reported by Balota *et al.* (2010). Large quantities of SS with high N content lead to some N buildup in soils, whereas most C added is labile and lost by enhanced decomposer activity. The low C/N ratio observed in woodland soils could indicate a major presence of N_2-fixing trees which are known to increase N content in soils (Fisher, 1995), but an assessment of woodland species inventory was beyond the scope of this study.

Soil P, Cu and Zn

Cropland receiving high rates of SS had significantly higher total P, whereas total Cu and Zn in the surface layer (0–10 cm) were unaffected by treatments (Table IV). Accumulation of Zn and Cu, which are added to feedstuffs in excess of the absorption capacity of swine, occurs in the soil surface layers under long-term continuous SS application (Basso *et al.*, 2012; Legros *et al.*, 2013). For example, SS application of 300 m ha^{-1} year^{-1} with a mean P content of 0.3 kg m^{-3} added approximately 90 kg P ha^{-1} year^{-1} (about 200 kg P_2O_5 ha^{-1} year^{-1}), most of which was highly labile, exceeding crop growth requirements (Table II). Favorable conditions to the accumulation of nutrients in these soils are augmented by very low erosion rates due to widespread adoption of NT and high biomass crops, especially perennial pasture like Tifton.

Higher contents of available P and Zn were observed under high SS application rates relative to other treatments, whereas available Cu was significantly higher only in the 0–10 cm surface layer (Table IV). The observed increase of available P across treatments and depths is in agreement with the suggestion that available P pools in soil are constantly replenished through reactions of dissolution or desorption of more stable inorganic P and the mineralization of organic P, followed by movement of this nutrient in the soil profile

TABLE IV

Total and available nutrients (P, Cu and Zn) of the soils studied in Quinze de Novembro as affected by various swine slurry (SS) application rates and land uses

Soil depth	Land use	SS rate	n	Total P	Available P	Total Zn	Available Zn	Total Cu	Available Cu
				mg kg^{-1}					
0–10 cm	Woodland	Zero	9	701.2±191.4[a]b[b]	7.0±4.0c	104.3±26.4a	5.4±3.2bc	179.2±52.7a	8.4±3.6b
	Cropland	Zero	8	739.2±192.8b	15.2±8.6bc	84.0±11.5a	3.3±2.2c	129.4±24.3a	8.0±4.8b
		Low	8	771.8±156.1ab	21.0±12.9b	102.2±12.7a	9.1±4.6b	196.1±46.0a	12.6±4.9b
		High	12	1 051.8±251.1a	63.1±30.4a	116.8±29.3a	28.6±14.5a	169.6±61.7a	16.2±7.6a
10–20 cm	Woodland	Zero	9	625.1±197.7a	4.5±1.5 b	105.7±24.7a	4.1±2.9ab	180.1±54.1ab	12.1±4.6a
	Cropland	Zero	8	551.6±123.4a	6.0±2.0 b	85.8±19.5a	1.9±2.2b	125.8±20.4b	8.5±4.4a
		Low	8	648.1±80.4a	5.9±3.5b	97.1±7.4a	2.5±1.3ab	202.6±43.8a	13.3±3.6a
		High	12	690.0±200.5a	16.9±10.8a	87.6±20.6a	6.0±3.7a	161.4±59.4ab	12.8±5.2a
20–30 cm	Woodland	Zero	9	602.1±166.3a	4.8±2.2b	109.2±26.6a	2.6±2.5a[c]	178.7±57.1ab	14.6±4.2a
	Cropland	Zero	8	515.6±113.0a	5.2±0.9b	79.5±15.0b	1.4±1.8a	128.5±21.1b	9.5±5.4a
		Low	8	599.7±70.7a	4.1±2.0b	93.6±10.1ab	1.5±0.8a	205.5±43.6a	13.4±4.1a
		High	12	583.3±166.8a	10.8±7.0a[d]	81.4±16.4b	3.2±2.1a	161.0±58.2ab	12.4±5.3a

[a] Means±standard deviations.

[b] Means followed by the same letter(s) within the same column and soil layer are not significantly different at $P < 0.05$, according to Tukey's honestly significant difference test.

[c] $n = 8$.

[d] $n = 11$.

to subsurface layers (Hountin *et al.*, 2000). In soils of Southern Brazil, it has been observed that continued use of SS in the soil increases labile forms of adsorbed P (Gatiboni *et al.*, 2008), which can leach to the soil subsurface layers (Ceretta *et al.*, 2010). Higher available Zn across depths in soils with high SS application rates indicated that Zn also leached to subsurface layers. Zn is found in soils mainly as free ions or complexes with low binding energy (Citeau *et al.*, 2003), and the high rainfall in the region (1 750 mm) favors leaching.

Conversely, Cu has a high affinity and forms stable complexes with SOM (Croué *et al.*, 2003), thus accumulation of available Cu in the surface layer of cropland receiving SS application (Table IV) was enhanced by generally higher TOC observed. Gräber *et al.* (2005) noted that available Cu accumulation in the surface layers of loamy soils in Denmark receiving up to 120 m^3 SS ha^{-1} $year^{-1}$ for 12 years. In addition, Legros *et al.* (2013) recently proposed that CuS_2, a low solubility compound present in SS, could contribute to Cu accumulation in the soil surface layers.

Two watershed-scale studies, evaluating trace elements in Oxisols receiving SS in similar climatic conditions of Southern Brazil, reported increases of available Zn and Cu in soil surface layers. In the surface layer (0–20 cm) of soils receiving 144 m^3 SS ha^{-1} $year^{-1}$ for only 4 years, Mattias *et al.* (2010) observed 2.5 times higher available Zn and 4 times higher available Cu in comparison to those in this study. By assessing effects of SS application rates (30 and 60 m^3 SS ha^{-1}, comparable to the low rate in this study) after approximately 20 years, Scherer *et al.* (2010) observed available P and Zn concentrations similar to our observations, and nutrient stratification in the top soil layers.

Stream water quality

This study employed the guidelines for surface water quality presented in the Resolution No. 357/2005 of the Brazilian National Environmental Council (CONAMA, 2005), which establishes a 5-class system ranging from class "special" (pristine waters) to class 4 (less stringent quality requirements). This scheme is similar to other widely recognized monitoring protocols such as the Water Quality Index developed by United States National Sanitation Foundation (NSF). Most physicochemical parameters measured (pH, EC, color, turbidity, N, P, NH_4^+, NO_3^- and TS) were within acceptable limits for inclusion in the "Class 1" category, which corresponded to freshwater in populated regions that required minimal treatment (such as filtration) for human and animal consumption. Only parameters of FCB and BOD_5 were discussed here because these were the two water parameters that precluded classification of these streams in "Class 1". The value of FCB exceeded 200 MPN (most probable number) 100 mL^{-1} in 80% of 6 samples collected bimonthly within one year. BOD_5 surpassed the threshold of 3 mg O_2 L^{-1} in several samples.

Stream surface water analyses showed the FCB content above 200 MPN 100 mL^{-1} during the sampling campaigns, especially at S1 (Fig. 3) and S2 (Fig. 4) outlets. A quarter of samples in S1 near the source of this stream exceeded the limit of Class 1. Stream S2 showed showed greater parameter variability, and the contents of FCB and BOD_5 exceeded the limits of Class 1 and Class 2 in more than 50% of the samples (Fig. 4). These high contents of FCB in streams could be attributed to runoff from cropland receiving up to 300 m^3 SS ha^{-1} $year^{-1}$ in this watershed. However, occasional access of dairy cattle to S2 near the outlet of this stream into Passo Real Reservoir, which confounded the assessment of the source of SS contamination, could be ruled out. Downgrading S2 waters to "Class 3" would require more rigorous water treatment for human con-

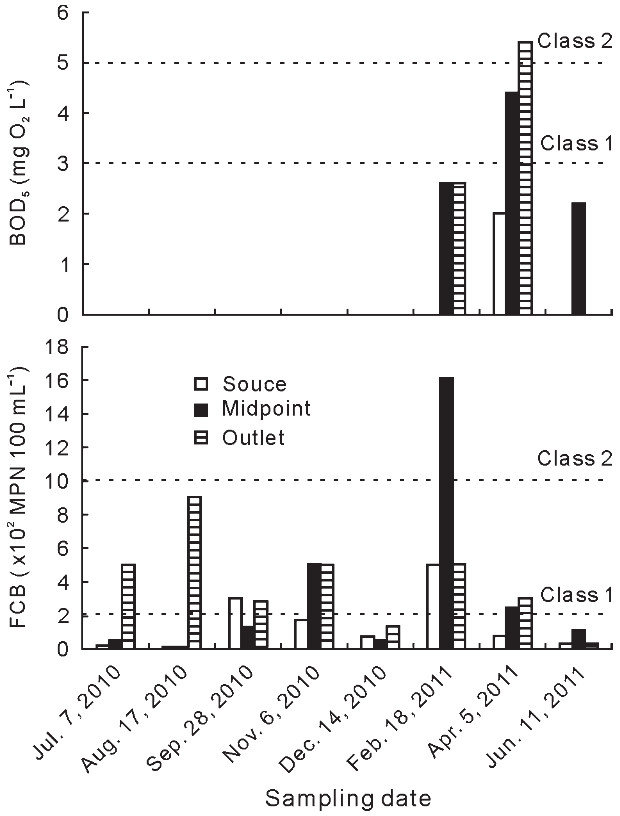

Fig. 3 Biochemical oxygen demand (BOD_5) and fecal coliform bacteria (FCB) measured from Jul. 2010 to Jun. 2011 at various sampling points (source, midpoint and outlet) of stream S1. Dotted horizontal lines indicate Class 1 and 2 limits according to the Resolution No. 357/2005 of the Brazilian National Environmental Council (CONAMA, 2005). No columns indicate data below the detection limit. MPN = most probable number.

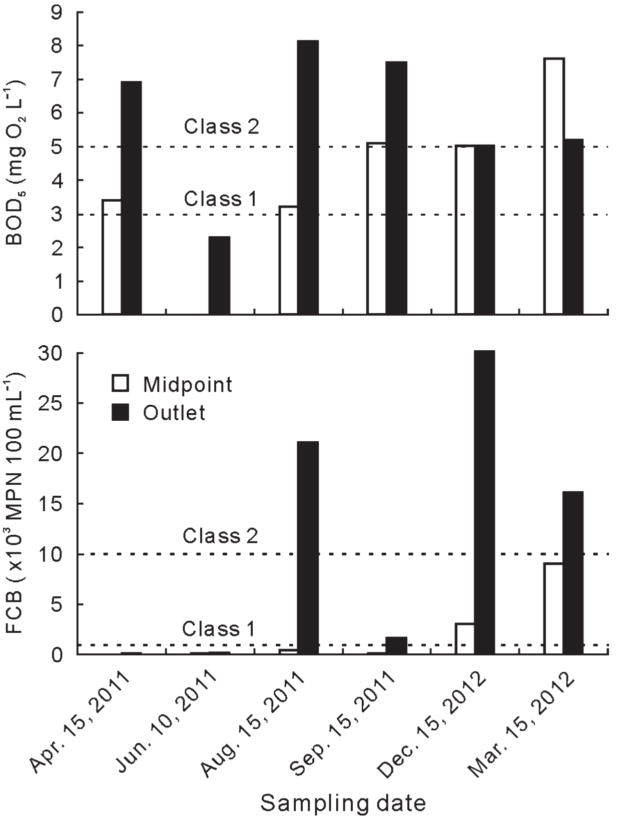

Fig. 4 Biochemical oxygen demand (BOD$_5$) and fecal coliform bacteria (FCB) measured from Apr. 2011 to Mar. 2012 at various sampling points (midpoint and outlet) of stream S2. Dotted horizontal lines indicate Class 1 and 2 limits according to the Resolution No. 357/2005 of the Brazilian National Environmental Council (CONAMA, 2005). No columns indicate data below the detection limit. MPN = most probable number.

sumption and irrigation of horticultural crops. The above observations were in accordance with Rodrigues and Binotto (2006), who detected the highest contamination near stream outlets in a water quality assessment of a major swine producing region in Northwestern RS, Brazil.

Surface spreading SS prior to intense rainfall events favor transport of surface-applied SS to these drainages. NT management, generally adopted by farmers in Quinze de Novembro and throughout Southern Brazil, has been shown to increase runoff and enhance loss of surface-spread SS (Cogo *et al.*, 2003; Bertol *et al.*, 2007, 2010). Kim *et al.* (2005) reported that the diffuse pollution from agricultural sources, especially pathogens, has a marked relationship with rainfall and runoff. In this study, contents of FCB and BOD$_5$ were not correlated with rainfall (data not shown). As an accurate record of SS application dates and quantities by farmers in Quinze de Novembro is not available, establishing clearer relationships between SS application, rainfall, runoff and surface water quality are precluded in this study.

CONCLUSIONS

Long-term, continuous application of SS in intensively cropped Oxisols in Southern Brazil has added large quantities of nutrients and contaminants. The buildup of total and plant-available nutrients was evident especially under high application rates, but intensive cropping systems and high yields could partially offset this imbalance to the extent that no detrimental effects on crops were observed. It could be cautiously stated that plant uptake followed by export with crop products largely mitigated the environmental impact of nutrients present in SS. However, because of reported increase of contaminant concentration in runoff under NT management, there was heightened potential for surface water contamination in these watersheds. In fact, a pattern of biological contamination was evidenced by microbial pathogens and labile organic matter contents. It is apparent that SS application to cropland in Quinze de Novembro has often exceeded the capacity of these soils to attenuate contaminant loads, leading to biological water contamination. Therefore, continuous application of high rates of SS to cropland, as currently practiced in the study region and other municipalities with similar edaphoclimatic conditions, poses environmental and health risks. We propose that improved SS disposal management and edge-of-field conservation practices that have been successful elsewhere should now be incorporated in the Brazilian production system. Research is currently under way to elucidate the relationships between stream water quality and SS application by addressing both in-field and edge-of-field aspects.

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