Fate of phosphorus applied to soil in pig slurry under cropping in southern Brazil

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ABSTRACT

Strongly weathered soils (such as Oxisols), are inherently phosphorus (P) limiting and highly P-sorptive thus requiring continued P inputs for productive agriculture. Constant P inputs result in accumulation of soil P with increasing risk of eutrophication of waterways. The state of Santa Catarina is the largest pork producer in Brazil. Production is concentrated in confined systems, with large generation of nutrient rich waste, commonly utilised as fertiliser. The objective of this work was to investigate and quantify the impact of long-term P inputs in pig slurry to a high P-sorbing Oxisol under cropping in southern Brazil. Fifteen years of pig-slurry addition resulted in P accumulation and vertical movement down the soil profile in proportion to application rates, but significant effects were confined to the 0–20 cm soil layer. Phosphorus accumulated mainly in inorganic forms. Slurry input rates of 25, 50, 100, and 200 $m^3 ha^{-1} y^{-1}$ resulted in accumulations of 25, 57, 106, and 159 $kg P ha^{-1} y^{-1}$ (0–40 cm), of which only 8, 10, 23, and 28 $kg P ha^{-1} y^{-1}$ were organic P forms. Mass balance showed that between 62 and 94% of the P inputs in slurry were accounted for in grain exports (7–35%), soil storage (58–83%), minimal amounts were estimated in crop residues (< 1%), while the remainder (6–38%) was presumed to have been lost in drainage by overland flow.

1. Introduction

The state of Santa Catarina is the largest producer and exporter of pork in Brazil. Despite being the 7th smallest state, it is responsible for nearly 28% of total pork production and 35% of total Brazilian pork exports (ABPA, 2016). In Brazil, the vast majority of commercial pig (*Sus scrofa domesticus*) production is conducted in confined (housed) systems and the waste from these generated as a slurry. Given the size of the local pork sector, this waste is of particular significance to Santa Catarina, and can represent either an important fertiliser or a potential environmental hazard depending on how the resource is managed.

To meet dietary requirements, pigs in housed systems are commonly fed corn (*Zea mays*) and soybean (*Glycine* max) based feed formulations. The main form of phosphorus (P) in seeds/grains is *myo*-Inositol-1,2,3,4,5,6-hexa*kis*phosphate, which is also referred to as 'phytic acid' or 'inositol phosphate' (Raboy, 2003). In order to be utilised, the phosphate anion (PO_4^{-3}) needs to be cleaved from the organic complex (inositol), a process catalysed by the enzyme phytase (Shin et al., 2001).

Monogastric animals, including pigs, have low efficiency in utilising P present in grains (< 15% for swine) due to their insufficient production of extracellular phytase, therefore resulting in P-rich animal waste (Cromwell, 2005; Cunha, 2012).

Pig waste, containing substantial quantities of P (and other nutrients) is commonly applied to agricultural land (Cassol et al., 2001). This practice is regarded as an effective strategy to reduce or eliminate the dependency of mineral P fertiliser inputs to maintain crop/pasture productivity, and results in looped nutrient cycles and sustainable productive systems (Choudhary et al., 1996; Cassol et al., 2001; Pandolfo and Ceretta, 2008). However, the repeated application of pig-waste to agricultural fields may lead to significant accumulation of both inorganic and organic P in soils. This may increase the potential for enhanced P loss in drainage, resulting in contamination of aquatic ecosystems (Berwanger et al., 2008; Gatiboni et al., 2008; Pandolfo et al., 2008; Lourenzi et al., 2014; De Conti et al., 2015; Gatiboni et al., 2015). Moreover, long-term P input and accumulation (commonly referred to as 'legacy P', or 'residual P') are of global concern given the

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increasingly volatile supply and costs of phosphate rock resources (Cordell et al., 2011; Sattari et al., 2012; Haygarth et al., 2013; Ulrich and Frossard, 2014). Understanding the risk of repeated inputs of P-containing waste to soils is therefore important to facilitate sustainable management of animal waste in agroecosystems, and to remain resilient to variation in P-commodity prices and currency values on international markets.

Highly weathered soils dominate in tropical and subtropical parts of the globe (Cross and Schlesinger, 1995; Yang and Post, 2011). Oxisols cover > 60% of Brazil, are widely P limiting, and have an inherently high P adsorption capacity. Therefore, high inputs of P are normally required to support economically viable levels of agricultural production (Ker, 1997; Novais and Smyth, 1999; Motta et al., 2002; Almeida et al., 2003; Embrapa, 2013).

A field trial was established in Santa Catarina, Brazil in 2001 to assess agronomic responses of corn to different rates of pig slurry additions, together with changes in soil properties, and associated potential environmental impacts (Cassol et al., 2012; Mafra et al., 2015; Grohskopf et al., 2016). The objective of this study was to quantify the accumulation, distribution, and indicators of potentially adverse environmental impacts after the long-term pig slurry inputs to soils under cropping. Given the high P adsorption capacity of these soils, we hypothesised that the majority of P added via pig slurry was retained in the soil.

2. Materials and methods

2.1. Long-term field trial, Santa Catarina, Brazil

Soil properties and the agronomic responses of corn were determined in soil to which different rates of pig slurry additions had been applied. The trial was established in 2001 in Campos Novos, Santa Catarina, Brazil (27°23′ 34″ S, 51°21′ 47″ W) on an Oxisol formed from basalt rocks (Typic Hapludox [USDA]; Latossolo Vermelho Distroférrico [Embrapa, 2013]). The soil is naturally acidic (pH 4.5) and P limited (Mehlich-1 extractable $P < 3\,mg\,kg^{-1}$) (Almeida et al., 2003). The A horizon (0–20 cm depth) has 65% clay, 32% silt, and 3% sand. The clay fraction is predominantly kaolinite, 2:1 Al-hydroxy interlayer smectite and iron oxides (hematite and goethite) (Almeida et al., 2003). The climate at the location is classified as being humid mesothermal with mild summers (Cfb according to Köppen). The elevation is 863 m above sea level, the rainfall well distributed throughout the year (average = $1480\,mm\,year^{-1}$), and mean annual temperature is 16 °C (January 21 °C; June 12 °C) (Epagri/Ciram). Prior to the establishment of the trial, the area had been used for cropping (rotation of corn, soybean, wheat, and oats) under a no-tillage system for many years. The chemical properties of the soil to 20 cm at the trial establishment were: total carbon $25\,g\,kg^{-1}$, available P (Mehlich-1) $6\,mg\,kg^{-1}$, and pH (H$_2$O 1:1 v/v) 6.1. The approximate mean slope at the trial site is 3%, ranging from 2.5 to 3.5%. Further details of the site and trial set up are described in Cassol et al. (2012) and Mafra et al. (2015).

The five treatments investigated had received 15 annual additions (2001–2015) of pig slurry at rates of 0, 25, 50, 100, and $200\,m^3\,ha^{-1}\,y^{-1}$. Each treatment had four replicate plots, each 12 m × 6.3 m, randomly arranged in blocks (total of 20 plots). Pig slurry was applied to the soil surface in October of each year after the die-down of the winter cover-crop (generally this was black oat [*Avena strigosa*], but was radish [*Raphanus sativus*, in 2005 and 2008]). Corn (*Zea mays*) was planted annually (except in 2003 when black bean [*Phaseolus vulgaris*] was grown) as the summer (main) crop in rotation with winter crops (utilised as cover crop, i.e. not harvested). The area remained under no-tillage system during the period of experiment (Fig. S1, supplementary material).

The pig slurry originated from finishing pig barns that had been collected into open effluent ponds. Physicochemical properties (analysed each year) of the slurry were: pH 7.2 ± 0.3; dry matter

$44 \pm 17\,kg\,m^{-3}$; carbon (C) $22 \pm 7\,kg\,m^{-3}$; total P $1.37 \pm 0.6\,kg\,m^{-3}$; total nitrogen (N) $3.31 \pm 1.7\,kg\,m^{-3}$; C:N ratio 6.6 ± 1.8; total potassium $1.62 \pm 0.6\,kg\,m^{-3}$; total calcium $1.88 \pm 0.7\,kg\,m^{-3}$; and total magnesium $0.77 \pm 0.3\,kg\,m^{-3}$.

2.2. Soil sampling and analyses

In May 2016, soil samples were obtained by randomly collecting 8 subsamples per plot at the depths of 0–2.5, 2.5–5, 5–10, 10–20, and 20–40 cm. The composite soil samples were dried at 65 °C to constant weight and sieved (< 2 mm) prior to analyses. Soil bulk density was also assessed (Table S1, supplementary material) in order to correct the soil attributes and concentrations to units of mass per area in hectares. This involved collecting a known volume of soil in metal rings (5.8 cm diameter) at the respective soil layer, and weighing after drying at 105 °C to constant mass. Total soil C and N were analysed by an elemental analyser (LECO 2000 CNS Analyser). The quantities of total C and N (in units of $Mg\,ha^{-1}$ and $kg\,ha^{-1}$, respectively) for each soil layer were normalised to a constant depth increment and are expressed in units of $Mg\,ha^{-1}\,cm^{-1}$ and $kg\,ha^{-1}\,cm^{-1}$, respectively, to allow comparison between depths.

Soil P was characterized by chemical fractionation of a soil subsample with ammonium chloride (1 M NH$_4$Cl), sodium bicarbonate (0.5 M NaHCO$_3$, pH 8.5), sodium hydroxide (0.1 M NaOH), hydrochloric acid (1 M HCl), and a second extraction with 0.1 M NaOH (sonicated for 5 min) (Hedley et al., 1982; Condron et al., 1996; Condron and Newman, 2011). Total soil P was determined in a separate soil subsample after digestion with concentrated sulphuric acid (H$_2$SO$_4$) and hydrogen peroxide (H$_2$O$_2$ 30% v/v) according to Olsen and Sommers (1982). Total extracted organic P was determined as the sum of organic P extracted with NaHCO$_3$ and first and second extractions with NaOH, whereas total extracted inorganic P was calculated as the sum of inorganic P in all extracted fractions. The difference between total soil P and total extracted P (inorganic + organic) was regarded as non-extractable soil P. These multiple soil P fractions were grouped into four P pools according to their relative lability as follows: 'labile P' (sum of fractions NH$_4$Cl and NaHCO$_3$ [inorganic and organic]), 'moderately labile P' (first NaOH [inorganic and organic]); 'stable P' (HCl + second NaOH [inorganic and organic]); and 'residual P' ('non-extractable P') (Cross and Schlesinger, 1995). The quantities of total P, total inorganic P, total organic P, and inorganic and organic P fractions in the soil to 40 cm are expressed in units of $kg\,ha^{-1}$, while for each depth increment these P parameters are expressed in units of $kg\,ha^{-1}\,cm^{-1}$ to allow comparison between depths.

The degree of phosphate saturation (DPS) was determined as described by Pierzynski (2000). The DPS index relates the proportion of potential P adsorption sites occupied by P, and is an indicator of potential risks and P movement in the soil profile. In brief, composite samples (combined replicates) of the contrasting treatments receiving pig slurry at rates of 0 and $200\,m^3\,ha^{-1}\,y^{-1}$ were extracted with oxalate solution (0.114 M ammonium oxalate + 0.09 M oxalic acid, pH 3.0). Concentrations of P, iron (Fe) and aluminium (Al) in the extracts were determined by ICP-OES and followed by the calculations: (Eq. (1)) $PSI = P_{ox}/(Fe_{ox} + Al_{ox})$; and (Eq. (2)) $DPS = 200 \times PSI$; where PSI: phosphorus sorption index; P_{ox}, Fe_{ox} and Al_{ox} are the molar concentrations ($mmol\,kg^{-1}$) of the elements.

Potential for P release in drainage was assessed by plotting values of P concentration (in $mg\,P\,kg^{-1}$) present in the first extraction solution of the P fractionation scheme (NH$_4$Cl-P). Only the topmost soil layers (i.e. 0–2.5 and 2.5–5 cm) were considered following recommendations by McDowell et al. (2001) and Schroeder et al. (2004) for environmental assessment. Easily extractable P in soil is considered as an indicator of potential adverse effects resulting from soil erosion and surface runoff (McDowell and Sharpley, 2001; Sharpley et al., 2001; McDowell et al., 2002). A 'change-point' is reached when the soil can no longer adsorb P, and consequently, large amounts of weakly bound P are present (here