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Phosphorus mobility and degree of saturation in oxisol under no-tillage after long-term dairy liquid manure application

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ABSTRACT

The main way of manure use is its application to croplands near livestock farms as a nutrient source to enhance crop production. However, if incorrectly applied, the manure can become an environmental problem due to phosphorus losses to water bodies. This study aims: i) to assess the mobility of phosphorus downward in the soil profile; ii) to evaluate the long-term influence of dairy liquid manure (DLM) application under no-tillage on phosphorus adsorption; and iii) to suggest an environmental threshold for soil phosphorus. The experiments were conducted at two experimental stations of the ABC Foundation, Paraná state, Brazil. One site had a dystrophic red-yellow oxisol (sandy oxisol), sandy clay loam texture soil with 13% slope. The other site had a dystrophic oxisol (clayey oxisol), clayey texture soil with 10% slope. The experiments started in November 2005 and May 2006 in the sandy oxisol and clayey oxisol soils, respectively, in areas where the no-tillage system had been practiced for over 15 years. Treatments consisted of four rates of DLM (0, 60, 120, 180 m^3 ha^{-1} $year^{-1}$). Soil samples were collected in 2014 at six depths (0–10; 10–20; 20–30; 30–40; 40–50; 50–60 cm). The effect of DLM on downward phosphorus mobility in the soil profile was observed up to 50 cm in the sandy oxisol soil. In the clayey oxisol soil, the phosphorus in soil solution was affected by DLM application up to 20 cm. A reduction in the binding energy was observed in both soils with the application of DLM. The maximum phosphorus adsorption capacity decreased only in the sandy oxisol soil. It was possible to determine the change point only for the sandy oxisol soil at 62.2% of DPS_{Resin} (degree of phosphorus saturation with resin extraction) and 34.2% of $DPS_{Mehlich}$ (degree of phosphorus saturation with Mehlich extraction). This corresponds to 188 mg kg^{-1} of soil resin P and 103 mg kg^{-1} of soil Mehlich–1 P, at the soil surface (0–10 cm). These values for this type of soil, are recommended as an environmental threshold for phosphorus.

1. Introduction

Brazil is the fifth largest milk producer in the world, and Paraná state, Southern Brazil, is the major milk producer in Brazil (IBGE, 2014). Paraná state is the pioneer in adoption and diffusion of the no-tillage system in Brazil, with almost 50% of agricultural fields under this system (Motter and Almeida, 2015). The manure produced in this state is commonly applied to no-tillage croplands without incorporating into the soil, which promotes accumulation of P at the soil surface (Sharpley, 2003).

The long-term manure amendment has reduced costs of mineral fertilizers and improved the physical and chemical properties of the soil (Chang et al., 1991; Mellek et al., 2010; Sommerfeldt et al., 1998). However, in areas with large concentrations of confined animals, manure also plays an important role in nitrogen and phosphorus losses to water bodies (Carpenter et al., 1998). When applied without technical criteria, i.e., excessive applications, manure can turn into an environmental problem (Sharpley and Wang, 2014).

Nutrients from the application of manure in croplands can be transported from soil to water via the surface and subsurface, accelerating the process of eutrophication, which has become a common and growing problem in rivers, lakes, estuaries, and oceanic coasts (Smith et al., 1999). Phosphorus is considered the limiting element of the eutrophication process in freshwater bodies, it promotes the biological ability of some blue–green algae to fix atmospheric nitrogen, thus providing nitrogen to the aquatic system (Schindler et al., 2008).

The risk of phosphorus contamination in water bodies is mostly associated with its transport via surface runoff due to its great capacity for adsorption with iron and aluminium oxides, and clay minerals (Fontes and Weed, 1996; Novais and Smith, 1999). It is also known that

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Table 1
Particle size distribution and chemical properties of the soils investigated (0–20 cm).

Soils	Clay	Silt	Sand	pH $CaCl_2$	TOC	Al	H + Al	Ca	Mg	K	CEC	$P_{Mehlich}$
	$g\ kg^{-1}$				$g\ kg^{-1}$	$cmol_c\ kg^{-1}$						$mg\ kg^{-1}$
Sandy Oxisol	228	33	739	5.1	13.2	0	3.45	3.7	0.7	0.2	8.05	19
Clayey Oxisol	701	111	188	5.4	25.6	0	4.4	5	1.4	0.3	11.10	4

TOC = total organic carbon; CEC = cation exchange capacity.

the excessive input of organic and inorganic phosphorus can result in significant losses of phosphorus via both surface and subsurface flow (Pizzeghello et al., 2011; Sims et al., 1998).

The risk of phosphorus transport from soil to water bodies can be associated to its degree of saturation in the soil (Heckrath et al., 1995). The critical concentration in soil solution occurs before the complete saturation of phosphorus sorption sites in the soil (Breeuwsma and Silva, 1992), and represents the limit at which the soil is no longer a phosphorus sink and becomes a phosphorus source. This critical concentration is called by many authors a 'change point' or 'threshold', from which the risk of phosphorus loss to water bodies increases (Mcdowell and Sharpley, 2001; Nair et al., 2004). The change point is an excellent tool to estimate the vulnerability of phosphorus loss, however, to better estimate phosphorus environmental risk, several other factors should be considered (Sharpley and Wang, 2014).

The degree of phosphorus saturation (DPS) of the soil was initially used in the Netherlands as a tool to predict environmental limits of phosphorus in sandy soils. It was calculated as the ratio of [P] to [Fe + Al], extracted from the soil by oxalate, and related to water-soluble phosphorus (WSP) in soil (Breeuwsma and Silva, 1992). Studies involving the DPS have been extended to the entire world with modifications (Nair, 2014). Sims et al. (2002) calculated the DPS as [P] to [Fe + Al], extracted by Mehlich–3, and related it to dissolved reactive phosphorus obtained in a leaching column and runoff simulation. Nair et al. (2004) obtained the DPS as [P] to [Fe + Al], extracted by Mehlich–1 and related to WSP and 0.01 M $CaCl_2$–extractable P.

Some authors used the maximum phosphorus adsorption capacity (MPAC) of the soil estimated by the Langmuir adsorption isotherm to determine DPS (Abdala et al., 2012; Kleinman and Sharpley, 2002; Mcdowell and Sharpley, 2002; Pautler and Sims, 2000; Sharpley, 1995). According to Mcdowell and Sharpley (2002), the phosphorus in soil extracts used in the DPS calculation is usually specific for certain types of soils. Phosphorus adsorption isotherms also reflect the physico-chemical properties of soils through their parameters (MPAC and binding energy), which are fundamental in determining the phosphorus mobility potential of the soil (Holford et al., 1997; Mcdowell and Sharpley, 2002). Thus, it is recommended to use MPAC to obtain the DPS.

Phosphorus adsorption in soils is strongly affected by the texture (Fontes and Weed, 1996). Generally, sandy soils have a lower MPAC when compared to clay soils (Oliveira et al., 2014; Valladares et al., 2003). The continuous application of manure can alter the phosphorus-binding energy and MPAC (isotherm Langmuir parameters) due to occupation of the adsorption sites by organic matter where phosphorus could be sorbed, leading to greater phosphorus mobility and availability in the soil (Eghball et al., 1996; Guppy et al., 2005).

With dairy farming increasing worldwide, information on the impact of using dairy manure as an amendment on croplands that leads to pollution potential of water bodies is needed. This study aims (1) to evaluate the application of dairy liquid manure (DLM) over the long term (nine years) on phosphorus adsorption and mobility in oxisol soil of different textures (sandy and clayey) under no-tillage and (2) to suggest an environmental threshold for soil phosphorus.

2. Materials and methods

2.1. Experimental site

The experiments were conducted at two experimental stations of the ABC Foundation for Agricultural Assistance and Technical Divulgation, Paraná state, Brazil: one at Ponta Grossa (25°00′35″S, 50°09′16″W, 890 m altitude) on a dystrophic red-yellow oxisol (sandy oxisol), sandy clay loam texture soil with 13% slope, and the other at Castro (24°51′50″S, 49°56′25″W, 1027 m altitude) on a dystrophic oxisol (clayey oxisol), clayey texture soil with 10% slope. The regional climate is classified as Cfb − humid subtropical climate mesothermal (Köppen), with mild summers and an average annual rainfall of 1554 mm, without a dry season (Caviglione et al., 2000).

Experimental plots were installed in November 2005 and May 2006 at Ponta Grossa and Castro, respectively, where no-tillage system had been practiced for more than 15 years. Crop rotation involved black oat (*Avena strigosa* Schreb.) and wheat (*Triticum aestivum* L.) in the winter and soybean (*Glycine max* (L.) Merr.) and maize (*Zea mays* L.) in the summer. The no-tillage had been practiced at the two research sites prior to the first application of liquid dairy manure for more than 15 years, then, no-tillage practices continued to be applied along with annual applications of liquid dairy manure for the next 10 years. The soil properties before the beginning of the experiments are presented in Table 1.

Treatments consisted of four annual rates of DLM (0, 60, 120, 180 $m^3\ ha^{-1}\ year^{-1}$). The experiment was established as a randomized complete block design with four replications, and plots were 29.8 m^2 (3.5 m by 9 m). Each annual DLM rate was split into two applications: (i) half in the winter crop and (ii) half in the summer crop. The DLM was brought from a dairy farm near the experimental site and manually applied on the soil surface with a watering can. The chemical properties of the DLM applied since the beginning of the experiments (2005–2014) are provided in Tables 2 and 3. The amount of N, P, and K (annual average for winter plus summer crops) applied by DLM and by mineral fertilizers are in Table 4. Besides DLM, mineral fertilizers (NPK) were applied in the same amount for all treatments following the soil test and crop needs (Raij et al., 1997). Mineral fertilization without considering the quantity of nutrients applied by manure is a common practice among farmers, so the experiment was designed to simulate this condition and to investigate the environmental risk of this overfertilization.

2.2. Soil sampling and analyses

Soil samples were collected in July 2014 at Castro and in October 2014 at Ponta Grossa at six depths (0–10; 10–20; 20–30; 30–40; 40–50; 50–60 cm). All soil samples were air-dried and sieved through a 2-mm sieve. Soil phosphorus was extracted using an anion exchange resin (resin P) (Raij et al., 1997) and Mehlich–1 (Marques and Motta, 2003). Total soil phosphorus was extracted from soil samples using the USEPA 3051 method (USEPA, 2007) and determined by ICP-OES.

WSP extraction was performed in topsoil samples (0–10 cm), with deionised water at a 1:10 soil-to-water ratio, which were then shaken for one hour. After this, the samples were centrifuged and filtered through a cellulose membrane of 0.45 µm. The same procedure was used for extraction of phosphorus using a 0.01 mol L^{-1} $CaCl_2$ solution