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Changes in soil phosphorus lability promoted by phosphate sources and cover crops

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ABSTRACT

Crop rotation and soil management can promote expressive changes in accumulated (legacy) soil phosphorus (P) lability since cover crops can cycle more P into plant tissue, and have a beneficial effect on the subsequent cash crop. This study aimed to understand the P dynamics in soil under different P sources and cover crops over six consecutive cropped years, and also to track how changes over time can achieve more efficient use of soil P in a high P-fixing soil from south Brazil. It was used five cover crops (common vetch, white lupin, fodder radish, ryegrass, and black oat) plus fallow in winter, meanwhile the summer crops were treated with soluble P fertilizer (SSP- single superphosphate) or rock phosphate (RP) every year from 2009 to 2014, under a no-tillage system. Soil samples were taken after six years of cultivation (2014) and analyzed for P fractionation by the Hedley procedure. Next the results were compared to the results previously obtained at the beginning of this period (2009), and after the third summer cycle (2011). Cover crops affected P cycling under phosphate fertilizer when SSP was used and all cover crops were able to utilize more moderately labile (mod-labile) P and enhance the proportion of labile P fractions in the soil. In general, white lupin was the cover crop most effective in retaining the most P available for the subsequent crop in the soil and may be considered a P-mobilizing species, regardless of the source of the applied P. Rock phosphate promoted the highest proportion of inorganic P accumulated in the soil while the lowest one was recorded under SSP. Organic P fractions were depleted over the period, either with or without fertilizer, being the main source of plant extractable P in non-fertilized conditions over the period.

1. Introduction

Phosphate fertilizer sources when applied to tropical soils have promoted considerable phosphorus (P) adsorption to Fe and Al (hydr) oxides with substantial binding energy, making them unavailable for plant uptake (Pearse et al., 2007). In such cases, the amount of P applied to the soil is noticeably higher than the amount of P absorbed by plants (Dao et al., 2015), leading to a surplus of soil P over the time. Soluble P fertilizers, such as single superphosphate (SSP), release P easily to the soil solution and higher amounts of that P transform into unavailable forms over time compared to slow release P sources, such as rock phosphates (RP). It is important to search for mechanisms to make use of the high amounts of P retained in stable fractions, known as legacy P, which can reduce the use of limited and expensive P sources for crop cultivation.

The proportional distribution of soil P in pools with different lability depends on the amount of P applied, the P uptake by the harvested biomass, the soil type and management. In addition to management practices such as 4R nutrient stewardship (IFA, (2009)), inclusion of crop species with high P-uptake efficiency in crop rotation can help recycle more P for the subsequent crop and reduce the use of P fertilizer. Cover crops can also reduce P loss due to erosion, runoff or leaching by affecting the soil water dynamics and by taking up P and retaining this P within the system (Eichler-Löbermann et al., 2008; Maltais-Landry and Frossard, 2015). Crop rotation systems do not influence either maximum P adsorption capacity (Rheinheimer et al., 2003; Tiecher et al., 2012b) or the constant related to P binding energy (Rheinheimer et al., 2003), but they can be an effective soil P recycler over time.

Depending on the adaptation mechanisms of plants for acquiring

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soil P, access to soil P pools differ from one plant species to the next. These differences can even be observed in the various genotypes of a given species (Rengel and Marschner, 2005; Wissuwa, 2005). Certain plants like white lupin (*Lupinus albus*) and pigeon pea (*Cajanus cajan*) have the ability to use soil P fractions that are not readily available and store them in their shoots (Kamh et al., 1998; Wasaki et al., 2008). The succeeding crop can use this stored P after the crop residues have decomposed and increased the efficiency of this nutrient in the crop production system. Another beneficial effect is that organic acids released from the mineralization of residues can compete with orthophosphate for sorption sites in the soil and mobilize P for the following crop (Pypers et al., 2005). Franchini et al. (2004) tested the ability of cover crops to absorb P from soil surface layers and translocate it to the subsoil via the roots. They found that common vetch (*Vicia sativa*) was the most effective cover crop for this translocation. Pavinato et al. (2008) reported that radish (*Raphanus sativus*), with a higher root excretion of malic acid and higher P content in tissue, was the most efficient crop for increasing soil P availability out of many cover crops tested.

Phosphorus released by the decomposition of cover crops may remain plant available (STP– Soil Test P), be immobilized by microorganisms, transformed into organic P, or leached out from the soil (Alamgir et al., 2012; Ayaga et al., 2006; Damon et al., 2014; Oehl et al., 2001; Simpson et al., 2011). Cover crops with high P uptake and a substantial amount of P released in plant available forms normally have a positive effect on P cycling (Damon et al., 2014). In this way, it is believed that cover crops with a well-developed root system can be a good recycler and/or solubilizer of P in the soil when these crops are adequately used in a crop rotation system.

This study aimed to understand the P dynamics in soil under different P sources and cover crops over six consecutive cropped years, and also to track how changes over time can achieve more efficient use of soil P in a high P-fixing soil from south Brazil. Coming from this, we hypothesized that: i) cover crops with a higher P uptake are more effective in P cycling and can store more available P for the subsequent cash crop, ii) soil organic P is higher under cover crops compared to fallow as they take up P and release it to the soil according to their straw decomposition, (ii) rock phosphate is as effective as soluble phosphate in supplying P to crops over a long period, as well as retaining more legacy P in the soil.

2. Material and methods

2.1. Experimental design and management practices

A field experiment was conducted over six successive years (from 2009 to 2014) in a clayey Rhodic Hapludox soil (Soil Survey Staff, 1999) with low pH (5.2–5.4) and high organic matter content (~40 g dm^{-3}) in the topsoil layer (0–10 cm), located in Dois Vizinhos, in the state of Parana, south Brazil (25°44′05″S; 53°03′31″W; altitude: 509 m). This area had been cropped with commercial soybean, maize, and wheat since 2001 under a no-tillage system.

The experiment was established in 2009, in a randomized complete block split-plot design (considering three P treatments as the main plot and six cover crops as subplots) with three replicates. The subplot size was 5 × 5 m. Rock phosphate (RP) from Algeria (9% soluble P_2O_5 and 29% total P_2O_5) and single superphosphate (SSP: 18% soluble/total P_2O_5) were broadcasted over the whole surface area without incorporation before summer crop cultivation every year, in a dosage of 105 kg ha^{-1} yr^{-1} of soluble P_2O_5. A treatment without P addition was also considered as nil-P. Cover crop species tested were as follows: common vetch (*Vicia sativa*), white lupin (*Lupinus albus*), fodder radish (*Raphanus sativus*), ryegrass (*Lolium multiflorum*), black oat (*Avena strigosa*), and fallow. More details about experimental establishment, crop rotation and management, as well as the maximum P adsorption capacity, can be found in Pavinato et al. (2017) and Teles et al. (2017) (Supplemental Table S1 and Fig. S1).

For all six years, cover crops were established in the first half of May, right after the summer crop harvest. The amount of cover crop seeds used and the way they were cultivated are described by Pavinato et al. (2017). In the first half of September in all years, cover crop biomass was desiccated with glyphosate [*N*-(phosphonomethyl) glycine] (2 L a.i. ha^{-1}) and the residues remained in the soil surface. Maize was always established in spring/summer seasons, except in 2012/13 when soybean was established, being seeded in the second half of October and harvested manually in early April of each year.

2.2. Soil and plant sampling and analyses

The changes in soil P pools were evaluated in the 0–5 and 5–10 cm soil layers, collected after the sixth cover crop cycle, in September 2014. Four subsamples were collected and thoroughly mixed before being air-dried to get a composite sample of each subplot/depth layer. Then the soil samples were oven dried at 40 °C, sieved through a 2 mm mesh and analyzed for P pools by sequential fractionation as proposed by Hedley et al. (1982) and modified by Condron et al. (1985). Different extractors were added to 0.5 g of soil in the following sequential order: anion exchange resin (P_{AER}) and $NaHCO_3$ 0.5 mol L^{-1} (Pi_{BIC} and Po_{BIC}) – labile inorganic and organic P; NaOH 0.1 mol L^{-1} ($Pi_{HID-0.1}$ and $Po_{HID-0.1}$) and HCl 1.0 mol L^{-1} (Pi_{HCl}) - moderately labile inorganic and organic P; and NaOH 0.5 mol L^{-1} ($Pi_{HID-0.5}$ and $Po_{HID-0.5}$) - non-labile inorganic and organic P. At every step, the suspension was stirred for 16 h in an end-over-end shaker (33 rpm), centrifuged (20–30 min at 4000 rpm) and the supernatants were stored prior to colorimetric analysis, whereby the inorganic P in acidic extracts was determined according to the Murphy and Riley (1962) method and the P in alkali extracts was measured by the Dick and Tabatabai (1977) method. The organic P in alkaline extracts was estimated by the difference between total P, which was determined after digestion of the extracts with 7.5% (w/v) ammonium persulfate [$(NH_4)_2S_2O_8$] solution and 50% H_2SO_4 in an autoclave (103 kPa, 121 °C) for 2 h (USEPA - United States Environmental Protection Agency, 1971), and the inorganic P fraction. At the end of the sequential extraction, the remaining soil was dried in 50 °C, ground to homogenize, and digested with a mixture of concentrated H_2SO_4 + 30% H_2O_2 and saturated magnesium chloride to extract residual P ($P_{Residual}$) (Brookes and Powlson, 1981). More details about the procedure of extraction and P pools grouping can be obtained in Teles et al. (2017).

Accumulation of P in the cover crop tissue was determined by biomass sampling at the flowering stage (discussed in detail by Pavinato et al., 2017). Samples were oven dried at 65 °C for 72 h (or until constant weight), weighed, ground through a 2-mm sieve in a Wiley mill and stored for subsequent laboratory analysis. The concentration of P in the tissue was determined by acid digestion, according to Tedesco et al. (1995), and the nutrient uptake (kg ha^{-1}) was calculated based on total dry matter.

2.3. Data analysis

Variance homogeneity and normality of data distribution were tested for each parameter before carrying out an analysis of variance (ANOVA). Data were transformed using Box-Cox techniques Box and Cox (1964)) and outliers were removed when needed. Next, the data were submitted to ANOVA using PROC GLM to test the effect of phosphate fertilizer sources and cover crops on soil P fractions. When significant, means were compared using the t test (LSD) ($p < 0.05$). When the interaction phosphate fertilizer source × cover crop was significant, means were tested using LSD ($p < 0.05$). All the statistical analyses were carried out using the SAS 9.3 program (SAS Institute, Inc., Cary, NC, USA, 2008).