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Soil phosphorus compounds in integrated crop-livestock systems of subtropical Brazil

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ABSTRACT

Soil phosphorus (P) utilization may be affected by agricultural complexity, in particular when combining annual crops and livestock grazing on the same land area and at overlapping times. Our objectives were to qualify and quantify soil organic and inorganic P compounds using sodium hydroxide-ethylenediaminetetraacetic acid (NaOH-EDTA) extraction and ^{31}P nuclear magnetic resonance spectroscopy (^{31}P NMR) in response to increasing complexity with integrated crop-livestock systems (ICLS) in subtropical Brazil. Soil at a depth of 0–5 cm was collected from three long-term (7 to 12 years) cropping studies with and without ruminant grazing of cover crops. All sites were managed under no tillage, and treatments with livestock were managed with moderate grazing intensity. In these agro-ecosystems, grazing compared with no-grazing had greater soil P content as total and bioavailable orthophosphate and lower soil organic P and fewer monoesters, including inositol phosphates. Grazing increased P bioavailability and reduced recalcitrant organic P concentration in soil; therefore, cropping systems that integrate livestock (ICLS) can be a sustainable alternative to improve P use in farming systems of subtropical Brazil.

1. Introduction

Phosphorus (P) is a key component of agricultural production and has become a global security issue due to rapidly dwindling and limited ore reserves amidst a rapidly expanding human population. Inefficient use and recovery by animals and plants and high losses to the environment in agricultural systems contribute to this reality (Elser and Bennett, 2011; Cordell and White, 2013). These issues are intertwined and require strategies of sustainable intensification to somehow balance demands (Godfray and Garnett, 2014).

One approach to sustainably intensify agriculture and increase P cycling may be through integrated crop-livestock systems (ICLS), which can be developed using a variety of approaches (Bell and Moore, 2012; Moraes et al., 2014; Sulc and Franzluebbers, 2014). In subtropical Brazil (south of 23° S), agriculture is purposely intensified with moderate stocking of livestock grazing on annual and perennial forages in crop sequences under no-tillage. Ruminant livestock can alter agro-ecosystem properties through their impacts on forage and soil characteristics via spatial and temporal distribution of grazing (i.e. consumption of forage), trafficking, and excretion. Litter decomposition can be accelerated via exposure to rumen microbes (Haynes and Williams, 1993; Acosta-Martínez et al., 2010a, 2010b; Davinic et al., 2013).

In the soil, P is distributed into organic and inorganic forms and these are subdivided into functional groups. The functional groups of organic P are orthophosphate monoester, orthophosphate diester, phosphonate and polyphosphate (Condron et al., 2005) and of inorganic P are orthophosphate, polyphosphate and pyrophosphate (Cade-Menun and Preston, 1996). To break down diesters, plants and microorganisms require hydrolysis by both phosphodiesterases and phosphomonoesterases to release free phosphate, whereas monoesters require only the latter (Turner, 2008a). However, although inositol phosphates are classified as monoesters, they require both solubilization and hydrolysis by phytase to release a free phosphate and they can be strongly bound to metal oxides, clays, and organic matter (Turner, 2008a).

Inorganic P in soils can be sorbed to clays and Al and Fe oxyhydroxides, which depends on sorption and desorption processes to release orthophosphate to soil solution. Moreover, inorganic P can also be present as secondary (e.g., Ca, Fe and Al phosphates) and

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primary P minerals (e.g., apatites), depending on dissolution processes to release orthophosphate, and precipitation as a way to fix P in the case of secondary minerals (Shen et al., 2011).

We hypothesized that livestock grazing with ICLS would enable greater P utilization due to the cycling of P in the soil-plant-animal continuum, thereby increasing availability of P in soil.

Our objective was to determine soil P composition from agro-ecosystems with and without livestock grazing. Specifically, we wanted to qualify and quantify soil organic and inorganic P compounds using NaOH-EDTA extraction and nuclear magnetic resonance (NMR) spectroscopy to characterize soil P composition in response to increasing agricultural complexity with ICLS in subtropical Brazil.

2. Materials and methods

2.1. Study sites

Three long-term experiments (7 to 12 years) investigating various aspects of ICLS were established in Rio Grande do Sul and Parana states of southern Brazil (Table 1). Each experiment had treatments selected to compare low and high agricultural complexity, i.e. without and with grazing of cover crops. Baseline cropping system was summer grain crop followed by winter cover crop at all locations. The same cover crop was used whether grazed or not. All experiments used no-till soil management, and moderate grazing intensity if livestock was part of the treatment. When grazed, a target forage height was achieved using a put-and-take stocking technique (Mott and Lucas, 1952). At each location, each treatment was sampled three times. All grazed experimental units (~0.2 ha for sheep and ~2.5 ha for cattle) had at least three plots within a paddock for continuous stocking. Ungrazed plots were not always replicated in the design (i.e., São Miguel das Missões and Eldorado do Sul), but plots were subdivided for sampling purposes.

Table 1
Climate and agronomic history of experiments at Guarapuava, São Miguel das Missões and Eldorado do Sul with no-grazing (sole-cropping system) or grazing of winter cover crops as an integrated crop-livestock system in subtropical Brazil.

Sites	Guarapuava	São Miguel das Missões	Eldorado do Sul
Coordinates	25° 33′ S 51° 29′ W	29° 03′ S 53° 50′ W	30° 05′ S 51° 39′ W
Climate (Köppen system)[a]	Cfb	Cfa	Cfa
Altitude above sea level (m)	1100	465	46
Soil classification[b]	Oxisol	Oxisol	Ultisol
Clay content (%)	61.4[c]	54.0[d]	15.5[e]
Mean precipitation (mm $year^{-1}$)	1900	1850	1440
Mean annual temperature (°C)	17.5	19.0	19.6
Experiment establishment (year)	2006	2001	2003
Fertilizer input (kg ha^{-1} $year^{-1}$)[f]			
N	285	56	161
P	70	9	27
K	170	24	47
Grazing P output: crops/animals (kg ha^{-1} $year^{-1}$)	34.5/3.2	12.8/3.9	13.1/3.4
No-grazing P output: crops (kg ha^{-1} $year^{-1}$)	32.6	13.4	11.4
Grazing P budget (kg P ha^{-1})	32.1	−8.0	10.5
No-grazing P budget (kg P ha^{-1})	37.2	−4.7	15.6

[a] Cfa: subtropical with humid and hot summer and Cfb: temperate with no definite dry season.
[b] Soil Survey Staff (2010).
[c] Sandini et al. (2011).
[d] Costa et al. (2014).
[e] Barth-Neto et al. (2014).
[f] Since the experiment establishment.

The field trial at São Miguel das Missões was the oldest. Prior to the current experiment that started in 2001, land was in no-till soybean (*Glycine* max) in summer rotated with *Avena strigosa* for seed production in winter. This experiment had four cattle grazing intensities of the winter forage, *Lolium multiflorum* and *A. strigosa* mixture (forage maintained at 10, 20, 30, or 40 cm height). Soybean was grown in summer. The moderate grazing intensity (20-cm height) had adequate grazing intensity to promote sustainability of ICLS (Chávez et al., 2011; Assmann et al., 2014; Costa et al., 2014; Martins et al., 2014a, 2014b), and therefore, was selected to compare with an ungrazed soybean/cover crop mixture. Grazing was with 1-year-old beef calves starting in mid-July and ending in early November. On average, four animals ha^{-1} were needed to maintain a sward height of 20 cm. Soybean was seeded between late November and early December. Nitrogen fertilization as urea (46% N) was applied at 45 to 90 kg N ha^{-1} (lower level during first 10 years) approximately 45 days after cover crop seeding (Anghinoni et al., 2013). Soybean was fertilized with an average of 3 kg N ha^{-1}, 27 kg P ha^{-1} and 69 kg K ha^{-1} to achieve a target of 4.0 Mg ha^{-1} yield, as recommended by the Local Soil Fertility Committee (CQFS-RS/SC, 2004). Lime (62% calcium carbonate equivalent) was applied to the surface of the entire area at 4.5 Mg ha^{-1} in November 2001 (Martins et al., 2014a, 2014b).

The experiment at Eldorado do Sul was initiated in 2003 comparing continuous and rotational stocking of sheep under low and moderate grazing intensity (i.e. 5.0 and 2.5% consumption, NRC, 1985), as well as an ungrazed winter cover crop of *L. multiflorum*. Soybean only and soybean-maize (*Zea mays*) were grown in the summer. From 1999 to 2003, land was under no-till production of *Pennisetum glaucum* in summer and *L. multiflorum* in winter (Carassai et al., 2011). We selected the continuous, moderate grazing intensity of winter cover crop in soybean-maize rotation and no grazing of the same crop sequence as treatments for analysis in this study. Mean sward height of the grazed treatment was 22.5 cm. The previous crop prior to soil sampling was soybean. Texel and Ile de France cross-bred lambs (initial average weight of 21.9 kg) or single-bearing lactating ewes (initial average weight of 63.5 kg) and lambs (initial average weight of 9.6 kg) of the same breed were used for grazing for approximately 120 days (for more details see Barth-Neto et al., 2014).

The experiment in Guarapuava was established in 2006. Prior to that time, the land was managed for 8 years with no-till summer crops. The experimental design was four N fertilizer levels (0, 75, 150, and 225 kg N ha^{-1}) applied to a winter cover crop mixture (*L. multiflorum* + *A. strigosa*), which was either grazed by sheep or not grazed. Summer cropping was a common bean (*Phaseolus vulgaris*)-maize rotation (fertilized with 120 and 150 kg N ha^{-1}, respectively). We selected an intermediate winter N level (150 kg N ha^{-1}) for both grazed and ungrazed cover crops, which was considered adequate to optimize a residual N effect for rotated crops in ICLS (Sandini et al., 2011). The previous crop before soil sampling was common bean. At least six tester lambs (2 months old, initial average weight of 25 kg) and a variable number of put-and-take lambs were stocked to maintain sward height of ~15 cm. Since experimental initiation, lime was only applied in April 2013 at a rate of 4.0 Mg ha^{-1}. Liming was performed according to the Local Soil Fertility Committee (CQFS-RS/SC, 2004).

The P budget was determined according to the balance method proposed by Syers et al. (2008), which considered the yield and P uptake relative to the amount of P applied. Crop and animal yield data were collected from Martins et al. (2015) for São Miguel das Missões, from Sandini (2009); Pellegrini et al. (2010); Sandini et al. (2011); Sartor (2012), Andreolla (2010), and Andreolla et al. (2014) for Guarapuava, and Lunardi et al. (2008); Barth-Neto (2015), and Macari et al. (2011) for Eldorado do Sul. To determine P uptake relative to crop yield, 5 kg P Mg^{-1} grain yield for soybean (Borkert et al., 1994) and 4.67 kg P Mg^{-1} grain yield for common bean (Rosolem and