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Phosphorus fractions in different management systems in the Cerrado Goiano

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ABSTRACT

Phosphorus (P) is an essential macronutrient for plant development. Cerrado soils have a high P adsorption capacity, and conventional management can increase fixation, losses and reduce its availability in the soil. This study assesses the influence of different management practices on soil P fractions in cultivated areas in the Cerrado of Goiás. Deformed samples were collected at depths of 0-5 and 5-10 cm in two areas (Boa Vereda - BV and Mata do Lobo - ML). The total organic carbon content, pH, and phosphorus fractions (soluble, available, inorganic, organic, calcium-bound, occluded, and total) were quantified. The design was entirely randomized. Principal component analysis (PCA) was carried out. In BV, available and inorganic P levels were higher at 0-5 cm in the Cerrado area, while at 5-10 cm, available P was more prominent in soybean and Cerrado. The crop-livestock-forestry integration system showed high levels of occluded P. In ML, occluded P was predominant, except in the agroforestry system at 0-5 cm, where available, inorganic, calcium-bound, and total P levels were higher, while occluded and organic P levels were more prominent in soybean and pasture. At 5-10 cm, available P was lower in the cerrado, while occluded and total P levels were higher in soybean. The PCA confirmed the difference between the areas and management systems. Less intensive management systems promote higher levels of P fractions that are more available to plants.

Keywords: Cerrado crops, conservation systems, phosphorus lability, soil quality.

Frações de fósforo em diferentes sistemas de manejo no Cerrado Goiano

RESUMO

O fósforo (P) é um macronutriente essencial para o desenvolvimento das plantas. Os solos do Cerrado possuem alta capacidade de adsorção de P, e o manejo convencional pode aumentar a fixação, perdas e reduzindo sua disponibilidade no solo. O objetivo foi avaliar a influência de diferentes práticas de manejo sobre as frações de P do solo em áreas cultivadas no cerrado de Goiás. Foram coletadas amostras deformadas nas profundidades de 0-5 e 5-10 cm, em duas áreas (Boa Vereda – BV e Mata do Lobo - ML). Foi quantificado os teores de carbono orgânico total, pH, e as fracções de P (solúvel, disponível, inorgânico, orgânico, ligado ao cálcio, ocluso e total). O delineamento foi inteiramente casualizado. Foi realizada análise de componentes principais (ACP). Em BV, o P disponível, e inorgânico foram maiores a 0-5 cm na área de cerrado, enquanto a 5-10 cm, o disponível destacou-se em soja e cerrado. O sistema de integração lavoura-pecuária-floresta apresentou altos teores de P ocluso. Em ML, predominou P ocluso, exceto na agrofloresta a 0-5 cm, onde o disponível, inorgânico, ligado ao cálcio e total foram maiores, e o ocluso e orgânicos, em soja e pastagem. A 5-10 cm, o P disponível foi menor no cerrado, enquanto ocluso e total, maiores na soja. A ACP confirmou a diferença entre as áreas e sistemas de manejo. Os sistemas de manejo menos intensivos promovem maiores teores de frações de P mais disponíveis às plantas.

Palavras-chave: cultivo no Cerrado, labilidade do fósforo, qualidade do solo, sistemas conservacionistas.

1. INTRODUCTION

Phosphorus (P) is an essential macronutrient for plant development, playing a crucial role in metabolic and energy processes (El Jazouli *et al.*, 2024). However, the availability of P in soils formed in tropical climate conditions, such as those found in the Cerrado, is low (Cabral *et al.*, 2020; Alovise *et al.*, 2020; Du *et al.*, 2020). These soils are highly weathered and have high levels of iron and aluminum oxides, which results in a high capacity for fixing P, making it unavailable to plants (Cabral *et al.*, 2020; Gotz *et al.*, 2024).

This natural characteristic of most Cerrado soils is accentuated by conventional management practices, which intensify both the fixation and loss of P, reducing its availability (Rodrigues *et al.*, 2021). As an alternative, conservation management practices that preserve vegetation cover have been recommended as an effective strategy for improving P availability in the soil (Leite *et al.*, 2024). These management practices increase the efficiency of P use in the soil, indirectly reducing P fixation and promoting the gradual release of this nutrient through the decomposition of organic matter (Rigon *et al.*, 2024).

The release of P into the soil through the decomposition of plant residues depends on the forms of P accumulated (Oliveira *et al.*, 2017; Rigon *et al.*, 2022). In addition, organic acids released mainly during the decomposition of organic matter can play an important role in increasing the availability of P in the soil (Franco *et al.*, 2022). These acids act by blocking sites, reducing the fixation of P by soil minerals and facilitating its release to plants (Tirloni *et al.*, 2009; Braghiroli *et al.*, 2020).

P in the soil is bound and organized in different ways, and these characteristics affect the availability of this nutrient to plants (Chen *et al.*, 2024). P fractions can be classified into different categories based on their availability in the soil (Wang *et al.*, 2023). Among the phosphorus fractions there are those readily available to plants, which are considered more labile, the moderately labile fractions, and the fractions considered non-labile, which can have less than 10% potential availability and are therefore less accessible for plant absorption (Gatiboni and Condron, 2021). Therefore, understanding which fractions of P predominate in the soil is essential for understanding the dynamics of this nutrient, optimizing the use of fertilizers and thus improving plant nutrition.

The hypotheses of this study are that conventional management practices increase the loss of phosphorus in the soil, especially the more soluble and readily available fractions, due to greater exposure of the soil to erosive processes. Conversely, conservation practices tend to increase soil phosphorus levels. The aim of this study was to assess how different management practices influence the partitioning of phosphorus in the soil in cultivated areas in the Cerrado of Goiás.

2. MATERIAL AND METHODS

2.1. Study areas

The study was carried out in the Cerrado Goiano, in central-west Brazil. Area 1, Fazenda Boa Vereda (BV), is located in the municipality of Cachoeira Dourada - GO, with geographical coordinates of 18°31'54" S 49°42'72" O (Figure 1). While Area 2, Fazenda Mata do Lobo (ML), is located in the municipality of Rio Verde - GO, whose geographical coordinates are 18°08'17" S 50°42'24" O (Figure 1).

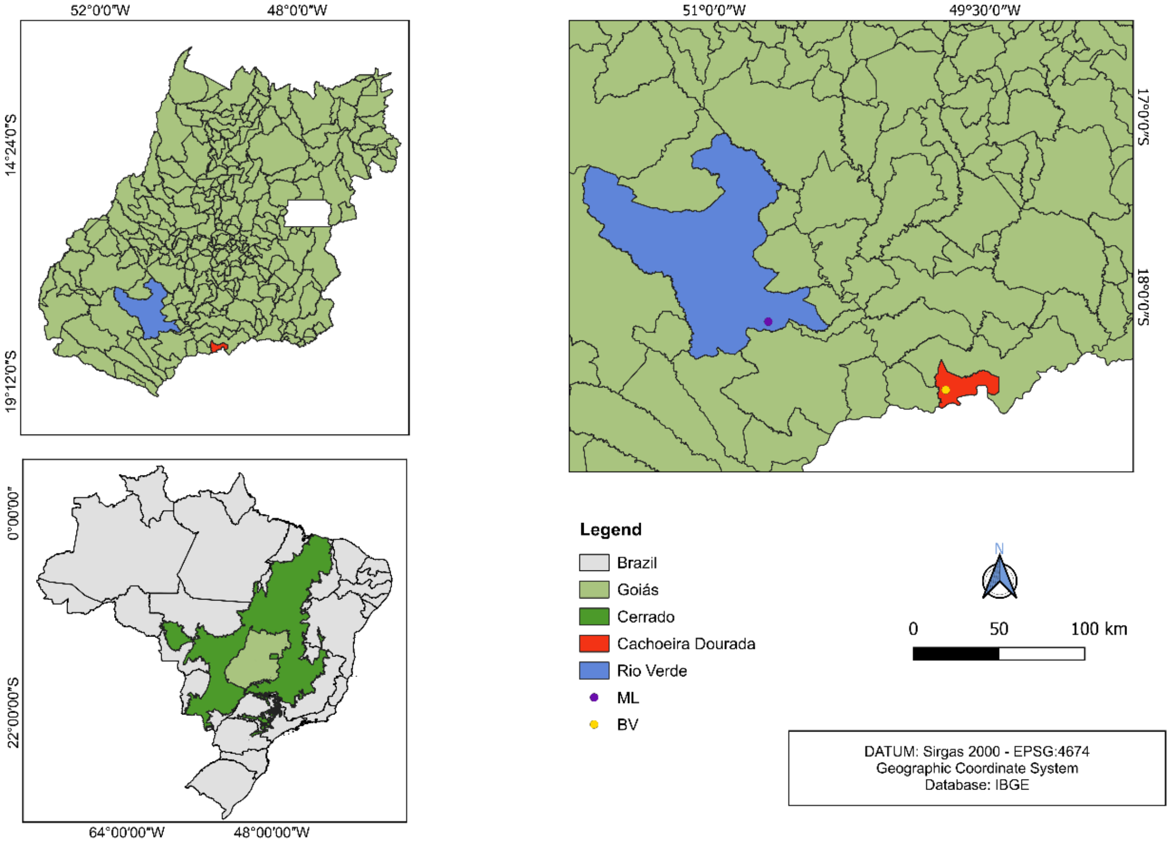

Figure 1. Location of the study areas (Mata do Lobo farm (ML) and Boa Vereda farm (BV)) in the municipalities of Cachoeira Dourada and Rio Verde - GO.

The climate of these areas is classified as Aw, according to the Köppen classification, and is characterized as tropical rainy, with two well-defined seasons: dry winter and rainy summer. The average annual rainfall is 1,700 mm year-1 and the average annual temperature is 24.2°C (Ribeiro *et al.*, 2022). The predominant soil class in both areas is Latossolo Vermelho-Amarelo distrófico (Ferralsol), with a clayey texture (clay ≥ 500 g kg-1) (Santos *et al.*, 2024).

2.2. Cover crops

In the BV area, the following types of management or vegetation cover were used: soybean monoculture, implemented in 2020; livestock-forest integration (IPF), with seven years of implementation; pasture and cerrado vegetation (cerrado). In the ML area, the following types of management or vegetation cover were used: monoculture with soybean succession, seven years ago; agroforestry; pasture and cerrado vegetation (cerrado).

2.3. History of the areas

2.3.1. Mata do Lobo Farm

The area currently used for agroforestry (AF) was previously used to grow soybeans and was converted to this system in 2017. This system uses a wide range of crops, including eucalyptus (*Eucalyptus globulus Labill.*), avocado (*Persea Americana Mill*), jatoba (*Hymenaea courbaril*), cedar (*Cedrela fissilis*), banana (*Musa sp.*), coffee (*Coffea sp.*), guapuruvu (*Schizolobium parahyba*), papaya (*Carica sp.*) and mombaça (*Panicum maximum*).

This system focuses on organic production, with a focus on the production of specialty coffees. The pasture area is located next to the AF area, shows no signs of degradation, has ample animal support capacity and was heavily fertilized. The area where soybeans are grown is a semi-organic system, in which herbicides were used and mineral and organic fertilizers were combined. The fragment of native cerrado has no human intervention, and at the time of collection, high biomass production was observed.

2.3.2. Boa Vereda Farm

At the time of sampling, the area was under soybean cultivation (*Glycine max L.*). The area was previously degraded pasture. When preparing the area for soybean cultivation, 2 Mg of lime ($CaCO_3$) was applied to correct the acidity of the soil, as well as base fertilization with 350 kg ha^{-1} of the 08-28-16 formulation at sowing.

In the IPF system area, which was also previously a degraded pasture area, soybean cultivation was carried out using more conservationist practices, namely: desiccation of the pasture followed by planting soybeans without disturbing the soil. After harvesting the soybeans, eucalyptus (*Eucalyptus globulus Labill*) was introduced and then planted in consortium with the soybean crop. In the second cycle, crop rotation was adopted between soybeans and Piatã grass (*Urochloa brizantha cv.*). In addition, samples were collected in an area of pasture that remains degraded and untreated and in an intact fragment of typical cerrado, without anthropogenic action.

2.4. Sample collection in the study areas

In the GO study areas, four subplots were marked out at each site, with an area of 300 m^2. Single samples were collected from these subplots, which, when combined, resulted in a composite sample. The samples were collected using an auger, at depths of 0-5 cm and 5-10 cm, totaling 64 sampling units (2 areas x 4 forms of land use x 4 pseudo repetitions x 2 soil layers) (Figure 2).

After collection, the samples were taken to the laboratory, air-dried, crumbled and passed through a 2 mm sieve to obtain the fine air-dried soil (FADS) used for subsequent analysis.

2.5. pH and total organic carbon

From the FADS samples, the pH in water was determined at a ratio of 1:2.5 soil:water, leaving the soil in contact with distilled water for approximately one hour. After this period, measurements were taken using a bench pH meter (Teixeira *et al.*, 2017).

Total organic carbon (TOC) was determined using the method of oxidizing organic matter with potassium dichromate ($K_2Cr_2O_7$) at a concentration of 0.2 mol L^{-1} in a sulphuric medium, followed by titration with ammoniacal ferrous sulphate at 0.1 mol L^{-1}, as described by Yeomans and Bremner (1988), at both sampling depths.

2.6. Fractionation of organic and inorganic phosphorus

The The P fractions were extracted from the MT and GO areas according to the method proposed by Gatiboni and Condron (2021). Five P fractions with different degrees of lability and bioavailability potential were extracted sequentially from 1.0 g of FADS, as follows:

Soluble P with 0.01 mol L^{-1} $CaCl_2$ solution (Psol) (soluble phosphorus); available P with Mehlich3 extractant solution (Mehlich, 1984) (PM3) (available phosphorus); Inorganic P and autoclaved P extracted with 0.5 mol L^{-1} NaOH solution (PiOH and Pautoclave, respectively) (inorganic and organic phosphorus); and P extracted with 1 mol L^{-1} HCl (PHCl) (calcium-bound phosphorus) (Figure 2).

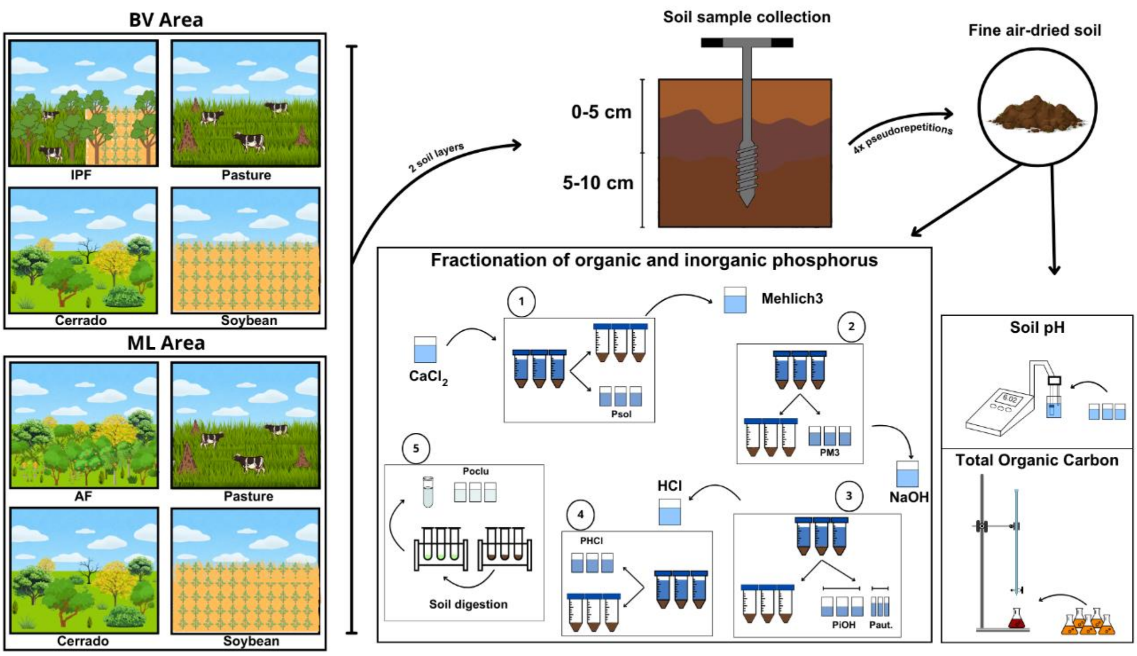

Figure 2. Scheme of soil sample collection in the experimental areas and analyses performed. Legend: BV Area: Boa Vereda Farm; ML Area: Mata do Lobo Farm; Soybean: soybean monocrop; IPF: integrated livestock and forest system; AF: agroforestry; Cerrado; Pasture: pasture; Soil pH (Teixeira *et al.*, 2017); Total Organic Carbon (Yeomans and Bremner, 1988); $CaCl_2$: calcium chloride extractor (0.01 mol L^{-1}); Mehlich3: Mehlich3 extractor; NaOH: sodium hydroxide extractor (0.5 mol L^{-1}); HCl: hydrochloric acid extractor (1.0 mol L^{-1}); Psol: soluble phosphorus; PM3: available phosphorus; PiOH: inorganic phosphorus; Paut.: fósforo autoclave; PiOH - Paut. = PoOH: organic phosphorus; PHCl: calcium-bound phosphorus; Poclu: occluded phosphorus; and Psol + PM3 + PiOH + PoOH + Poclu = PT: total phosphorus (Gatiboni and Condron, 2021).

P concentrations in each fraction were determined by colorimetry (Murphy and Riley, 1962). Organic P extracted with NaOH (PoOH) was obtained by the difference between Pautoclave and PiOH. Occluded P (Poclu) (occluded phosphorus) was also quantified, consisting of the highly recalcitrant Pi and Po forms that were not extracted by the previous extractants (CaCl2 0.01 mol L^{-1}, Mehlich 3, NaOH 0.5 mol L^{-1} and HCl 1 mol L^{-1}). Poclu was obtained by subtracting the P content of the Psol, PM3, PiOH, PoOH and PHCl fractions from the PT (Figure 2).

2.7. Data analysis

The results were analyzed in a completely randomized design and submitted to multivariate ANOVA analysis. The average values were compared using the Tukey test at 5% significance. As a complementary analysis, a similarity method was carried out in order to identify the relationship between the management systems as a function of the variables obtained. In addition, a principal component analysis (PCA) was carried out, based on Pearson's correlation matrix, also with 5% significance, to provide a better explanation of the variables as a function of the different systems evaluated. All statistical analyses were carried out using the R Core Team program (2020).

3. RESULTS E DISCUSSION

3.1. BV Area

The pH, Psol, PM3, PiOH, PoOH, PHCl, Poclu, PT and TOC values for the Fazenda Boa Vereda (BV) area in the different land use and management systems are shown in Table 1.

Table 1. Phosphorus fraction content of the soil at Boa Vereda Farm in the different land use and management systems, Cerrado biome region.

Syst.	pH	Psol	PM3	PiOH	PoOH	PHCl	Poclu	PT	TOC
		mg kg^{-1}							g kg^{-1}
				0-5 cm					
Soybean	4.76 b	0.63 a	99.03 ab	75.92 b	26.31 a	10.70 a	152.26 ab	357.84 bc	21.99 a
IPF	5.78 a	0.76 a	79.89 ab	67.50 b	32.85 a	10.62 a	225.46 a	413.49 ab	22.11 a
Cerrado	6.12 a	0.31 a	162.28 a	98.20 a	34.51 a	47.75 a	225.82 a	564.92 a	36.01 a
Pasture	6.02 a	0.41 a	51.90 b	62.92 b	24.6 a	19.03 a	83.98 b	239.43 c	20.94 a
CV%	3.55	44.49	41.85	12.97	32.8	46.57	33.07	20.29	29.72
				5-10 cm					
Soybean	4.66 c	0.64 a	86.21 a	66.37 b	22.78 a	12.61 a	75.18 ab	262.33 ab	14.56 b
IPF	5.66 ab	0.56 ab	38.13 ab	53.02 b	26.19 a	19.04 a	145.57 a	281.61 ab	17.81 ab
Cerrado	5.53 b	0.23 b	123.58 a	124.93 a	18.13 a	30.47 a	133.96 ab	411.04 a	30.00 a
Pasture	5.94 a	0.20 b	23.13 b	37.18 c	27.76 a	26.78 a	57.23 b	178.40 b	18.82 ab
CV%	2.83	44.85	6.47	10.66	41.61	67.14	38.59	32.68	34.37

Legend: Averages followed by equal lowercase letters for management systems, these by the Tukey test, with 5% probability. Depths (0-5 and 5-10 cm); Soybean: soybean monoculture; IPF: integrated livestock and forest system; Psol: soluble phosphorus; PM3: available phosphorus; PiOH: inorganic phosphorus; PoOH: organic phosphorus; PHCl: calcium-bound phosphorus; Poclu: occluded phosphorus; and PT: total phosphorus.

The pH values ranged from 4.9 to 6.38 at all depths (Table 1). In the 0-5 cm depth, the lowest pH values were observed in the soybean-growing areas, while in the 5-10 cm depth of this same area, the pH values were significantly higher in the pasture area, with the lowest values of this attribute being observed in the soybean area (Table 1). The lower pH values in the BV area in the soybean monoculture system may be associated with inadequate management practices or the application of inputs, such as soil acidity correction, either through the application of insufficient doses of lime or the lack of reapplication between crops. These practices are essential, as their implementation can contribute to improving soil fertility, promoting a better balance and availability of nutrients and increasing pH (Yakuwa *et al.*, 2020).

The TOC values ranged from 9.85 to 52.32 g kg^{-1} at the 0-5 and 5-10 cm depths, respectively, with no significant difference between the systems at the 0-5 cm depth. On the other hand, at a depth of 5-10 cm, TOC levels were significantly higher in the cerrado area (Table 1). The higher TOC levels, especially in the cerrado area, can be attributed to the absence of agricultural practices, such as row planting and the transit of machinery and cattle, which help to preserve a layer of plant residues on the soil. At a depth of 0-5 cm, no significant differences were observed between the systems, which may be related to the management practices adopted, such as in the IPF and soybean areas, which use crops with high biomass production. On the other hand, the lack of significant differences in the pasture system may be associated with the absence of management practices, such as soil turning, which contributes to a reduction in the mineralization of organic residues.

Psol levels in the BV area ranged from 0.19 to 0.78 mg kg^{-1} at both depths. At a depth of 0-5 cm, there were no significant differences between the systems (Table 1). However, at a depth of 5-10 cm, Psol levels were significantly higher in the system with soybean monoculture (Table 1). The average proportion of P in the soil in the different management systems at Fazenda Boa Vereda (BV) is shown in Figure 3. The proportion of Psol ranged from 0.01 to 0.40% at depths of 0-5 cm and 5-10 cm. In the first layer, the variation was from 0.01% to 0.40%, while in the second, these values ranged from 0.04% to 0.38% (Figure 3).

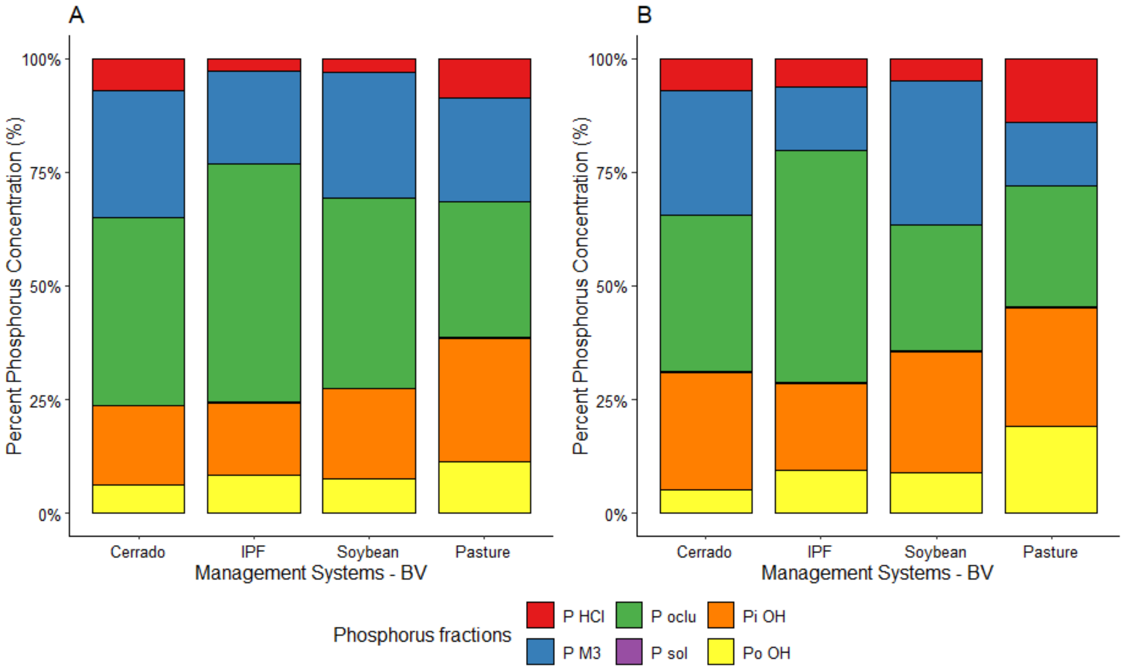

Figure 3. Average proportion of P in the soil of different management systems at Boa Vereda farm (BV) - GO.
Legend: A: 0-5 cm; B: 5-10 cm; Soybean: soybean monocrop; IPF: integrated livestock and forest system; Cerrado; Pasture: pasture; Psol: soluble phosphorus; PM3: available phosphorus; PiOH: inorganic phosphorus; PoOH: organic phosphorus; PHCl: calcium-bound phosphorus; Poclu: occluded phosphorus; and PT: total phosphorus.

According to Gatiboni and Condron (2021), Psol and PM3 are the fractions most available to plants. The Psol content at a depth of 5-10 cm, although low, was significantly higher in the soybean-growing area. This pattern may be due to the low mobility of P in the soil and the management practices adopted in this system, in which turning the soil over homogenizes the layers, leaving no P concentrated in the surface layer (Carneiro *et al.*, 2009; Oliveira *et al.*, 2020). This fraction of P is highly labile and is more susceptible to loss through erosion and surface runoff (Kalkhajeh *et al.*, 2021). However, it can be seen that this fraction represents less than 1% in both areas and depths in these cultivation systems, due to its high lability, which facilitates rapid solubilization, absorption by plants and loss in the soil. Corroborating this study, Gatiboni and Condron (2021) obtained similar results in soils from Santa Catarina - Brazil, with low proportions of Psol.

PM3 levels ranged from 11.38 to 209.30 mg kg^{-1} at both depths. At a depth of 0-5 cm, the levels were significantly higher in the cerrado area, while at a depth of 5-10 cm, the values were significantly higher in both the cerrado area and the soybean monoculture system (Table 1). The values for the proportion of PM3 at a depth of 0-5 cm ranged from 14.56% to 41.00%, while at 5-10 cm from 9.86% to 45.10% (Figure 3). The lowest proportions of PM3 were observed in the IPF and pasture areas, in the two layers evaluated.

The highest levels of the PM3 fraction in the 5-10 cm layer in the soybean area of the BV area, levels that may be associated with soil turning, which in addition to promoting its homogenization, accelerates the decomposition of OM and may release P into the soil, a practice that is absent in other systems (Khadka *et al.*, 2017). The high proportion of the PM3 fraction in the soybean system and cerrado area can be explained by the dynamics of each system: soybean cultivation, with intensive management practices, tends to accelerate processes of OM mineralization and P loss (Chen *et al.*, 2024), while in the cerrado area, the absence of disturbance promotes greater accumulation of P in the soil (Aleixo *et al.*, 2020). This shows that systems with intensive management, such as soybean cultivation, can increase P availability in the short term, but compromise its stock in the long term.

The PiOH content ranged from 34.87 to 137.93 mg kg^{-1} at the 0-5 and 5-10 cm depths, being significantly higher in the cerrado area at both depths (Table 1). The proportion of PiOH varied from 12.82% to 32.93% in the two depths, respectively. In the 0-5 cm depth, values ranged from 12.82% to 32.84%, while in the 5-10 cm depth, these values ranged from 16.61% to 32.93% (Figure 3). The higher levels of the PiOH fraction may be associated with the absence of intensive agricultural practices, which reduces the exposure of P to solubilization (Oliveira *et al.*, 2020). In terms of proportion, the PiOH fraction is the third most abundant, and at a depth of 0-5 cm this proportion is higher in the pasture area. According to Gotz *et al.* (2024), grasses have the ability to improve the efficiency of P use and enzymatic activity, due to the action of the root system and the release of organic exudates, which may explain the higher proportions of PiOH in the pasture areas in this study.

The PoOH content in this area ranged from 2.47 to 64.76 mg kg^{-1} at all depths. However, there were no significant differences between the systems at these depths (Table 1). As for the proportion of PoOH, these percentages ranged from 2.96 to 15.03% at the 0-5 cm depth, while at the 5-10 cm depth this proportion ranged from 0.88% to 29.84% (Figure 3). Thus, the highest proportions of PoOH were observed in the pasture system at both depths. In terms of proportion, the PoOH fraction was higher in the pasture, possibly due to the greater nutrient cycling provided by the grass roots, as well as the lower intensity of agricultural activities. The constant addition of organic matter, such as feces and plant residues, can favor the formation and maintenance of this P fraction (Bünemann, 2015). In addition, the mineralization of organic P tends to be slower in less intensive systems, where the decomposition of waste occurs gradually (Bai *et al.*, 2020). This environment, because it is less stable compared to the cerrado area, shows more active and rapid decomposition, contributing to a greater release of P in organic form.

The PHCl content ranged from 7.94 to 62.16 mg kg^{-1} at both depths (Table 1). There were no significant differences between the systems in the content of this fraction at both depths (Table 1). The variation in the percentage values of the proportion of PHCl was from 2.18% to 13.27% in the 0-5 cm depth, and in the 5-10 cm depth from 3.32 to 29.67% (Figure 3). The low PHCl levels and the lack of significant differences between the management systems at both depths may be related to the nature of the binding of this fraction, which is predominantly associated with calcium. The levels of this fraction may be associated with the natural condition of the soil, with low calcium levels (Pavinato *et al.*, 2009; Gatiboni and Condron, 2021). The highest proportions of this fraction were observed in the pasture and cerrado areas, at both depths, which may be associated with a better balance and equilibrium of nutrients in these systems, and this fraction may also be made available by plants that have the ability to acidify the rhizosphere (Cabeza *et al.*, 2017).

The Poclu content ranged from 14.99 to 299.37 mg kg^{-1} at both depths, being significantly higher at 0-5 cm in the IPF and cerrado areas, while at 0-10 cm there was only a difference in the IPF system (Table 1). The proportion of Poclu in the 0-5 cm depth ranged from 20.11 to 62.36%, and in the 5-10 cm depth from 7.30 to 55.21%, with higher proportions of Poclu being observed in the IPF system at both depths (Figure 3). The Poclu fraction has an availability potential of around 10%, and its absorption by plants is low (Gatiboni and Condron, 2021). The highest levels of this fraction are associated with the IPF system, as the adoption of less intensive agricultural practices promotes the gradual accumulation of P over time. The permanence of the soil's vegetation cover and crop rotation favors the immobilization of P in stable organo-mineral complexes. In addition, the nature of the source material and the high degree of weathering can favor the fixation of P, which tends to be strongly bound to iron and aluminum oxides, resulting in an increase in the contents of this fraction and affecting its proportion.

3.2. ML Area

Similarly, the pH, Psol, PM3, PiOH, PoOH, PHCl, Poclu, PT and TOC values for the Mato do Lobo Farm (ML) area in the different land use and management systems are described in Table 2.

Table 2. Soil phosphorus fractions in the area of Mato do Lobo Farm in the different land use and management systems, Cerrado biome region.

Syst.	pH	Psol	PM3	PiOH	PoOH	PHCl	Poclu	PT	TOC
		mg kg^{-1}							g kg^{-1}
					0-5 cm				
Soybean	7.10 a	0.39 a	63.93 b	32.74 b	20.08 a	21.42 ab	441.92 a	575.91 b	33.60 a
AF	6.77 a	0.59 a	1201.08 a	50.93 a	13.84 ab	32.94 a	235.32 b	1527.14 a	22.83 a
Cerrado	4.29 b	0.29 a	9.28 c	8.88 c	9.01 b	6.64 b	248.70 b	283.40 c	23.05 a
Pasture	6.60 a	0.52 a	64.20 b	34.26 b	21.57 a	15.70 ab	277.55 a	417.64 bc	30.10 a
CV%	4.38	44.49	41.85	12.97	32.8	46.57	33.07	20.29	33.16
					5-10 cm				
Soybean	6.71 a	0.49 a	31.54 a	22.64 a	15.60 a	15.57 a	395.1 a	480.28 a	23.44 a
AF	6.31 a	0.48 a	51.12 a	23.65 a	16.65 a	6.72 a	222.65 b	327.08 b	15.01 a
Cerrado	4.61 b	0.23 a	5.17 a	7.59 b	7.83 a	7.66 a	284.24 b	314.07 b	17.79 a
Pasture	6.04 a	0.55 a	37.11 a	26.11 a	13.01 a	6.62 a	263.47 b	351.99 b	16.13 a
CV%	5.75	44.85	6.47	10.66	41.61	67.14	38.59	32.68	41.67

Legend: Averages followed by the same lowercase letters for management systems are the same according to the Tukey test at 5% probability. Depths (0-5 and 5-10 cm); Soybean: soybean monoculture; AF: agroforestry; Psol: soluble phosphorus; PM3: available phosphorus; PiOH: inorganic phosphorus; PoOH: organic phosphorus; PHCl: calcium-bound phosphorus; Poclu: occluded phosphorus; and PT: total phosphorus.

The pH values ranged from 3.85 to 7.23 in the 0-5 and 5-10 cm depths, with lower values being observed in the cerrado area in both layers. The lower pH values observed in the cerrado vegetation area can be attributed to the natural characteristics of Brazil's tropical regions, where soils are typically acidic, highly weathered and of low natural fertility (Matias *et al.*, 2019). The high acidity is related to the absence of agricultural practices, such as acidity correction through liming. In addition, the recurrence of fires in the cerrado, whether due to natural causes or human action, accelerates the process of soil degradation by removing the vegetation cover, favoring the leaching of nutrients and promoting acidification. In addition, burning also leads to a reduction in organic matter levels (Santos *et al.*, 2024).

The TOC values in this area ranged from 5.76 to 48.83 g kg^{-1}, with no significant differences between the systems for these contents at the two depths studied. Regarding TOC levels, there were no significant differences between the management areas, which can be explained by the natural conditions of the biome, which is subject to long periods of drought associated with high temperatures during the rainy season. This condition favours the rapid mineralization of organic matter, making it difficult for it to stabilize in the soil (Ribeiro *et al.*, 2022). Despite the greater density of vegetation in the AF area, there was no significant increase in TOC levels compared to the other areas, suggesting that the time taken to adopt the management system has not yet been sufficient to bring about major changes.

Psol levels ranged from 0.24 to 0.68 mg kg^{-1}, with no significant differences between the systems and depths evaluated. As for Psol levels, the results also showed no significant differences between the management areas. The proportion of Psol ranged from 0.03 to 0.40%, and at a depth of 0-5 cm, these percentages ranged from 0.03 to 0.40%, while at 5-10 cm, the values were between 0.03 and 0.26% (Figure 4).

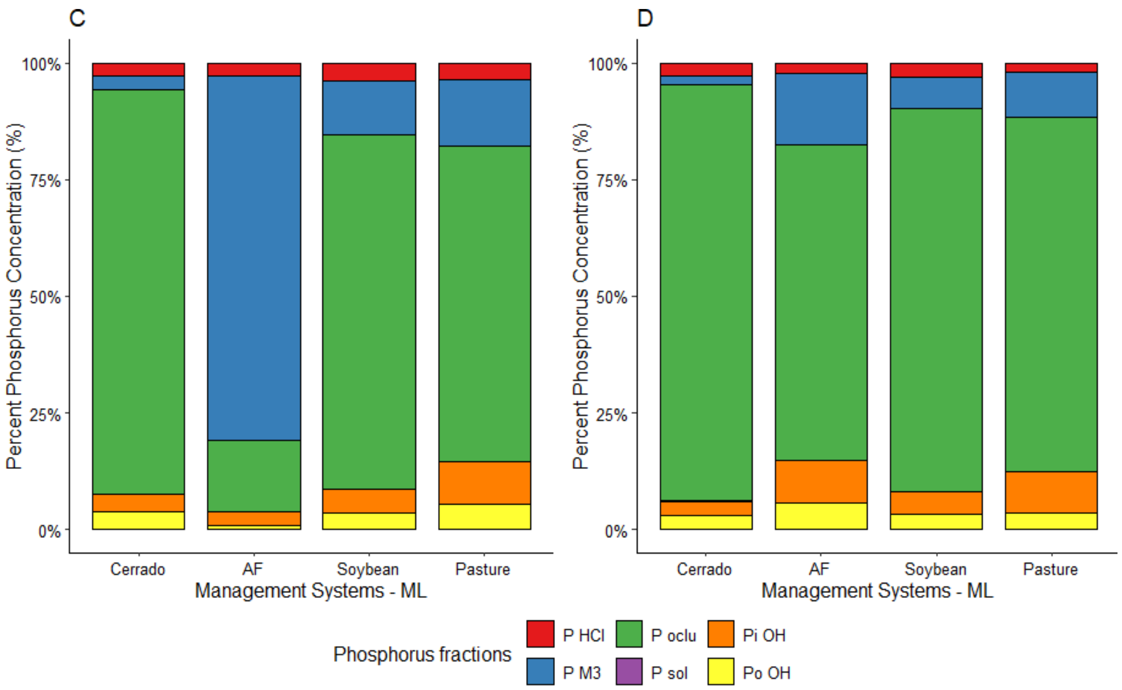

Figure 4. Average proportion of P in the soil of different management systems at Mata do Lobo farm (ML) - GO.
Legend: C: 0-5 cm; D: 5-10 cm; Soybean: soybean monoculture; AF: agroforestry; Cerrado; Pasto: pasture; Psol: Soluble Phosphorus; PM3: Available Phosphorus; PiOH: Inorganic Phosphorus; PoOH: Organic Phosphorus; PHCl: Phosphorus bound to calcium; Poclu: Phosphorus occluded; and PT: Total Phosphorus.

This pattern may be related to the nature of the region's soils, which are highly weathered and have high levels of iron oxides, which contribute to the fixation of P in less soluble forms available to plants (Tiecher *et al.*, 2023). Tropical soils, such as those in the cerrado, have a high capacity for retaining P, especially in conditions of high acidity, and Psol is rapidly absorbed by plants, which may explain the lack of significant accumulation of this fraction in the soil (Gatiboni and Condron, 2021).

The PM3 content ranged from 1.58 to 1,449.39 mg kg^{-1}, being significantly higher in the agroforestry area (AF) at a depth of 0-5 cm, while in the 5-10 cm layer, no significant differences were observed between the systems. The proportion of PM3 varied from 0.61% to 80.44%. At a depth of 0-5 cm, the variation was from 0.90 to 80.44%, while at a depth of 5-10 cm, the values ranged from 0.61% to 20.02%. The highest proportions of PM3 were observed in AF at both depths (Figure 4). For the PM3 fraction, the highest levels were observed in the 0-5 cm layer in the AF area, which can be attributed to the greater diversity of plants and the application of organic fertilizer, promoting nutrient cycling and the mobilization of P, particularly in the surface layer (Pradhan *et al.*, 2021; Silva *et al.*, 2024). The AF system, characterized by the absence of soil disturbance and less intensive agricultural practices, favors the accumulation of P from the decomposition of organic matter. In addition, the presence of tree species with deep root systems contributes to the gradual mineralization of OM (Sokol *et al.*, 2019), releasing P in forms that are more available to plants (Mandi *et al.*, 2024). The poorly mobile nature of P explains the lower PM3 levels observed at a depth of 5-10 cm (Silva *et al.*, 2024).

PiOH levels ranged from 6.71 to 63.50 mg kg^{-1}. In the 0-5 cm depth, these levels were significantly higher in AF. On the other hand, at a depth of 5-10 cm, these values were significantly lower in the cerrado area compared to the other systems. The proportion of PiOH ranged from 2.07 to 12.37%. In the 0-5 cm depth, these percentages were between 2.32% and 12.37%, while in the 5-10 cm depth, this variation was between 2.07% and 10.39% (Figure 4). The higher levels of the PiOH fraction at the 0-5 cm depth in PA may be associated with less soil disturbance and the maintenance of vegetation cover. Conservation management practices favor the accumulation of P and the reduction of losses of this nutrient (Kaur *et al.*, 2024). Systems with a greater diversity of plants tend to have a more active microbial community, which promotes the decomposition of organic matter and the conversion of P from organic to inorganic forms (Roohi *et al.*, 2020; Rigon *et al.*, 2022). According to Tiecher *et al.* (2023) the accumulation of P in cerrado soils forms a strong gradient in depth, which explains the lower levels of PiOH in the 5-10 cm depth due to its mobility.

The results for PoOH content at a depth of 0-5 cm were significant in the soybean/maize monoculture area and in the pasture, while at 5-10 cm there was no statistical difference between the systems. The values for this degree of lability ranged from 3.60 to 33.89 mg kg^{-1} at both depths. The variation for the proportion of PoOH was between 0.31% and 12.37% for both depths. For the 0-5 cm depth, the values ranged from 0.31 to 6.68%, while for the 5-10 cm depth, they varied from 1.66 to 12.37% (Figure 4). In the PoOH fraction, the higher levels found in the soybean and pasture areas may be due to the lower intensity of agricultural management, favoring the maintenance of continuous vegetation cover and providing a stable environment for microbial activity. According to Gatiboni and Condron (2021), PoOH levels are higher in soils with higher M.O. levels, so the higher levels observed may be associated with the maintenance of vegetation cover and the formation of organo-mineral complexes, which protect P, since this fraction is moderately labile. Average TOC levels of over 30% were also observed in these areas, which reinforces the greater cycling of nutrients and the decomposition of organic matter, promoting the release of P (Allan *et al.*, 2021).

Similarly, PHCl levels showed a significant difference in the 0-5 cm depth, with higher levels in the AF area, and for the second depth, there was no significant difference between the systems. The values for this degree of lability ranged from 4.51 to 39.47 mg kg^{-1} at both depths. For PHCl levels, significant differences were only observed in the 0-5 cm depth, with the highest levels quantified in the AF area. For the PHCl ratio, there was a variation of 1.15 to 5.59% for the two depths, with the first layer 0-5 varying from 1.15 to 5.59% and the 5-10 cm layer from 1.51 to 5.46% (Figure 4). These results can be attributed to conservation practices, which include the application of organic and mineral fertilization, introducing sources of P linked to calcium (Jonczak, 2021). Although the system is still in the early stages of consolidation, it is hoped that, over time, there will be greater efficiency in the use of nutrients, reducing the need for inputs.

As for the Poclu content, there was a significant difference only in the two layers in the soybean/maize monoculture area and in the pasture. The values for this degree of lability ranged from 172.67 to 614.72 mg kg^{-1}. For the proportion of Poclu, this variation ranged from 13.67% to 93.33% at both depths. For the 0-5 cm depth, the variation was from 13.67% to 88.64%, and for the 5-10 cm depth from 62.37% to 93.33% (Figure 4). The highest proportions of Poclu were observed in the cerrado, at both depths (Figure 4). The higher Poclu levels in the soybean areas, at both depths, may be associated with the maintenance of vegetation cover, less soil disturbance and the use of organic fertilizers, which promote the accumulation of P over time, favouring its immobilization in less available forms. The high capacity for fixing P, characteristic of these soils due to the high proportion of iron and aluminum oxides, also contributes to this behavior (Gatiboni and Condron, 2021; Vasconcelos *et al.*, 2022). The lower proportions of Poclu in the AF area may be related to the greater bioavailability of P in other forms.

The different fractions of P, depending on the management adopted and the depths analyzed, reveal the complexity of the dynamics of this nutrient in tropical environments. The results suggest that conservation practices favor the accumulation of P in the most available forms, especially in the surface layers, while in areas with less anthropogenic interference, such as the cerrado, they have a greater capacity to fix P. Understanding the specificities of these fractions is fundamental to guiding agricultural practices that ensure the maintenance of productivity and soil conservation in these environments.

3.3. Principal Component Analysis (PCA)

The Principal Component Analysis (PCA) considered the first two principal components, Dim1 and Dim2, which together explain approximately 54.2% of the total variability of the data. The Dim1 axis represents 31.1% of the variation and the Dim2 axis explains 23.1%, representing the relationships between the management systems, areas and variables evaluated (Figure 5).

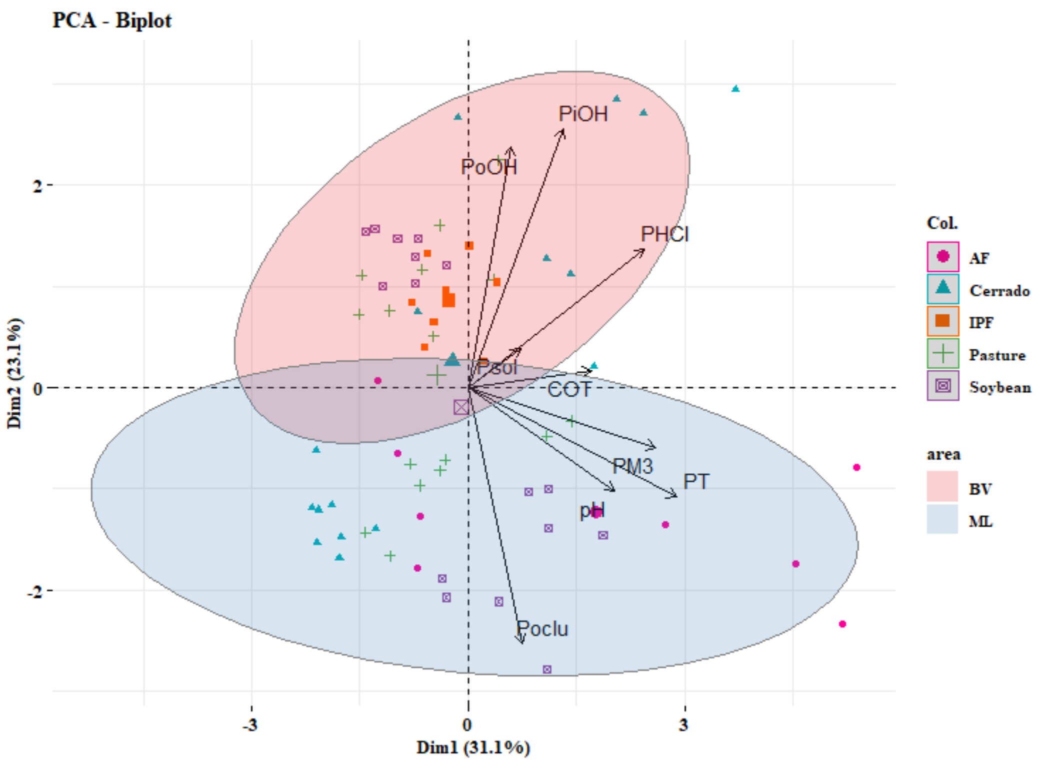

Figure 5. Principal component analysis (PCA) of areas under different management systems in the state of Goiás.
Legend: BV: Boa Vereda farm; ML: Mata do Lobo farm; Soybean: soybean monoculture; IPF: integrated livestock and forest system; AF: agroforestry; Pasture: pasture; Psol: soluble phosphorus; PM3: available phosphorus; PiOH: inorganic phosphorus; PoOH: organic phosphorus; PHCl: calcium-bound phosphorus; Poclu: occluded phosphorus; and PT: total phosphorus.

The ellipses represent the distribution of observations in each area, and their overlap indicates a slight similarity between the areas based on the variables analyzed, while the separation by the Y axis (Dim2) highlights the difference between the areas (Figure 5). The fractions of P, pH and TOC are positioned on the positive side of the X axis (Dim1), and these attributes were separated by the Y axis (Dim2), showing that the variables that are most correlated with the BV area are PiOH, PoOH, Psol, and PHCl, while pH, TOC, Poclu, PM3 and PT seem to be more associated with the ML area (Figure 5).

The pasture and soybean areas show a distribution of points along both the X and Y axes in the four quadrants, suggesting that these systems do not have such a clear correlation with the variables evaluated (Figure 6). The IPF area has no direct association with the variables evaluated (Figure 6).

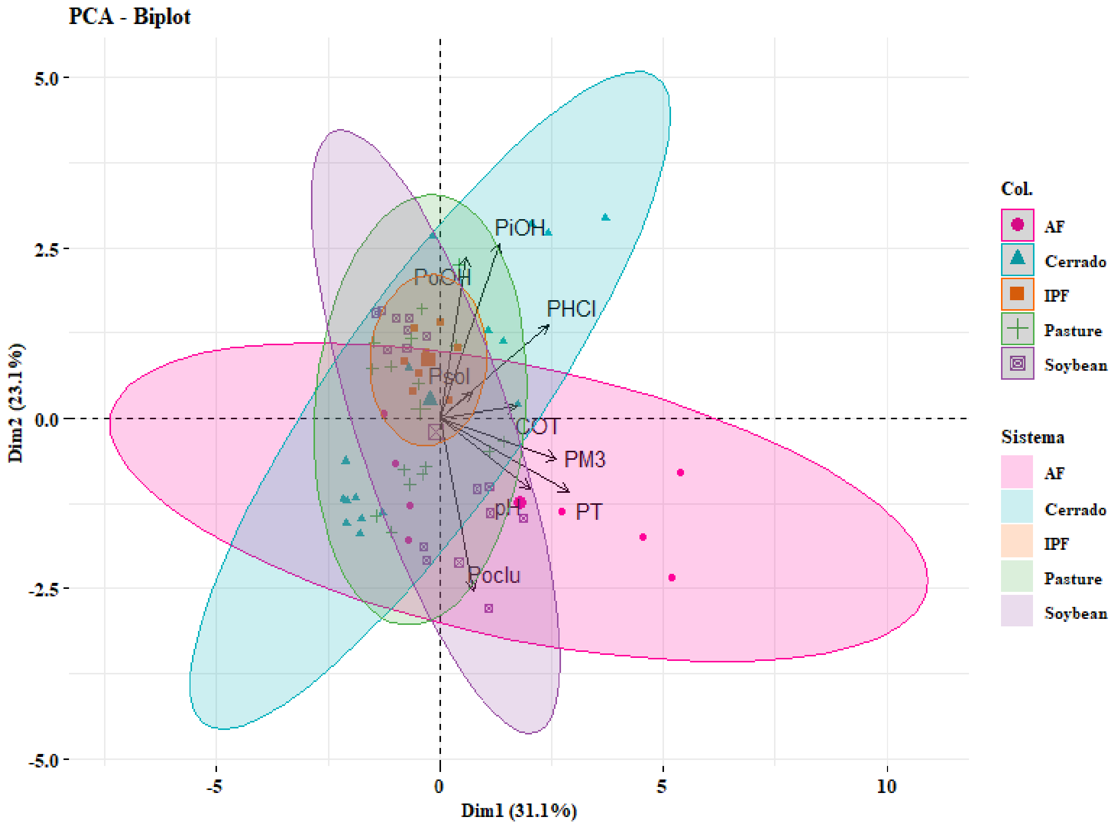

Figure 6. Principal component analysis (PCA) of areas under different management systems in the state of Goiás.

Legend: BV: Boa Vereda farm; ML: Mata do Lobo farm; Soybean: soybean monoculture; IPF: integrated livestock and forest system; AF: agroforestry; Pasture: pasture; Psol: soluble phosphorus; PM3: available phosphorus; PiOH: inorganic phosphorus; PoOH: organic phosphorus; PHCl: calcium-bound phosphorus; Poclu: occluded phosphorus; and PT: total phosphorus.

The PT and PM3 variables, located on the positive side of Dim1 and the negative side of Dim2, are more correlated with the AF area, while the PiOH and PHCl variables, located on the positive side of Dim1 and the positive side of Dim2, are more correlated with the cerrado area (Figure 6). The other variables showed no correlation with any other area, due to the overlapping of the ellipses.

The PCA confirmed the difference between the different cultivation areas (BV and ML), in which each is correlated to different P fractions, in which the PoOH and PiOH fractions are correlated to the BV area, as well as the PHCL fraction. While the ML area is more diverse, being correlated to both the PM3 fraction, which is available for plant absorption, and the Poclu fraction, which is less available to plants, as well as being correlated to pH and TOC. These results illustrate that although the areas are in the same biome and have similar cultivation systems, the responses differ, highlighting the importance of management practices adapted to the specific characteristics of each area.

4. CONCLUSION

The pH values, TOC contents and phosphorus fractions in the different management systems showed a different pattern between the areas (BV and ML) and depths (0-5 and 5-10 cm).

In the BV area, the available phosphorus, inorganic phosphorus and occluded phosphorus fractions predominated, with higher levels in the cerrado area (0-5 cm) and in the soybean cultivation area (5-10 cm). The livestock-forest integration system stood out for having higher occluded phosphorus levels.

In ML, occluded phosphorus was dominant, except in the agroforestry system (0-5 cm), where the highest levels were available, inorganic, calcium-bound and total phosphorus. At 5-10 cm, available phosphorus was lower in the cerrado, while occluded and total phosphorus reached the highest values in the soybean monoculture.

PCA confirmed the difference between the areas, associating BV with calcium-bound phosphorus, inorganic phosphorus and organic phosphorus, and ML with pH, TOC, available phosphorus, total phosphorus and occluded phosphorus. Additionally, variations among management systems were evident, with the cerrado being correlated with inorganic and calcium-bound phosphorus fractions, whereas the agroforestry system was associated with total and available phosphorus.

The management system used in each area of the Cerrado affected the availability of phosphorus in the soil. In management systems with less soil disturbance and greater maintenance of vegetation cover, the highest levels of the phosphorus fractions most available to plants were observed.

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