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# Soil phosphorus fractions in response to cropping system, liming, and phosphate fertilization in an expanding sugarcane plantation area

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**ABSTRACT.** The forms of phosphorus (P) present in soil are not stable and permanent. The sequential fractionation of soil P allows us to understand the dynamics of this nutrient in the soil. This study identifies alterations in P forms within the soil, induced by the processes of liming, phosphating, and cover crop cultivation preceding the planting of sugarcane, within an environment marked by constraints on sugarcane expansion. Employing a randomized block experimental design with sub-split plots and three replications, two lime doses (6 Mg ha$^{-1}$ and 12 Mg ha$^{-1}$) were assessed in the primary plots. Subsequently, the impact of three distinct species-*Glycine max, Crotalaria spectabilis*, and *Crotalaria juncea* remnant-cultivated following the *Urochloa brizanta* cultivar Xaraés, was evaluated in the subplots, preceding the introduction of *Saccharum officinarum*. Further refinement involved the examination of three Phosfaz calcined thermophosphate doses (0, 380, and 760 kg ha$^{-1}$) administered on the spot in the sub-subplots and incorporated with limestone and gypsum. The experiment unfolded under field conditions, and soil samples were collected at depths of 0 to 0.1 m, 0.1 to 0.2 m, and 0.2 to 0.4 m for the purpose of conducting phosphorus fractionation. Liming, phosphating, and antecedent crops to sugarcane cultivation exhibited varying impacts on the forms of P in the assessed soil layers. Generally, the application of limestone at a dosage exceeding that required for soil acidity correction (12 Mg ha$^{-1}$), coupled with corrective fertilization involving 380 kg ha$^{-1}$ of thermophosphate and the cultivation of *Crotalaria juncea*, resulted in an augmented content of labile phosphorus up to the 0.4 m soil layer. These findings suggest that liming, phosphating, and cultural practices-particularly involving *Crotalaria juncea* cultivation-have the potential to enhance phosphorus availability during the renewal of sugarcane fields.

**Keywords:** limestone; crotalaria; labile phosphorus; moderately labile P; non-labile P.

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## Introduction

Phosphorus (P) plays a crucial role in agricultural production, directly influencing biological processes essential for plant growth. Its deficiency significantly impacts the entire food production chain. Phosphorus exists in various organic and inorganic forms in the soil, exhibiting different labilities (Tiecher et al., 2018; Guo et al., 2022). These forms are neither stable nor permanent (Guo et al., 2022) and are subject to influence by soil physicochemical properties, plant-related factors, microbiological activity, and fertilization practices (Rheinheimer et al., 2019).

Plants facing low P availability often adopt strategies to enhance P absorption, such as releasing root exudates and enzymes into the rhizosphere (Zhu et al., 2020; Guo et al., 2022). These exudates can directly solubilize and mineralize P from less labile fractions or indirectly enhance microbial activity, thereby increasing P reservoirs accessible to plants (Amadou et al., 2021). Addressing P acquisition and utilization strategies is imperative to maximize the world's P reserves. Consequently, the implementation of novel strategies is warranted, encompassing adjustments in fertilizer recommendations, adoption of improved management practices, and incorporation of crop rotation.

Improving agricultural operations is paramount, as they constitute the foundation of the production process and significantly impact plant development and productivity (Horii, 2004). The cultivation of cover crops, particularly legumes like *Crotalaria juncea* and *Crotalaria spectabilis*, prior to the main crops, enhances soil quality, increases organic matter content, and contributes to plant nutrition through nutrient cycling (Abranches et al., 2021).

In managing soil acidity, the application of limestone, supplemented by gypsum, is a common practice in sugarcane cultivation, with recent trends emphasizing deep limestone incorporation at higher doses for acidic sandy soils (Yang et al., 2022). This approach ensures an environment conducive to root system growth throughout the entire sugarcane cultivation cycle, obviating the need for supplementation during the ratoon.

Exploring the contribution of various P forms in the soil to plant nutrition is imperative. Understanding the forms of P in the soil is fundamental for determining which fractions influence nutrient availability and predicting nutrient dynamics under different management systems, offering strategies to enhance P utilization.

Soil use and management practices alter P dynamics, especially in sandy soils (Rheinheimer, 2000). Sequential fractionation of P is a valuable methodology for comprehending P dynamics in the soil. This method employs chemical extractors sequentially applied to the same sample, wherein substances with increasing extraction capacities transfer P from the soil, estimating from labile to recalcitrant forms (Hedley et al., 1982).

Therefore, this study aims to identify changes in P forms in the soil induced by liming, phosphate applications, and cover crop cultivation before planting sugarcane in an area characterized by a restrictive environment where sugarcane plantations are expanding.

## Material and methods

The study was conducted at the SOEBE Farm in the municipality of Juti, Mato Grosso do Sul State, Brazil (22°41′11.6″ S, 54°32′30.0″ W), at an average altitude of 375 m (Figure 1). According to the Köppen classification, the climate is designated as Cwa, characterized by a humid mesothermal climate with hot summers and dry winters (Fietz et al., 2017). The soil at the site is classified as psammitic dystrophic red latosol (Santos et al., 2018).

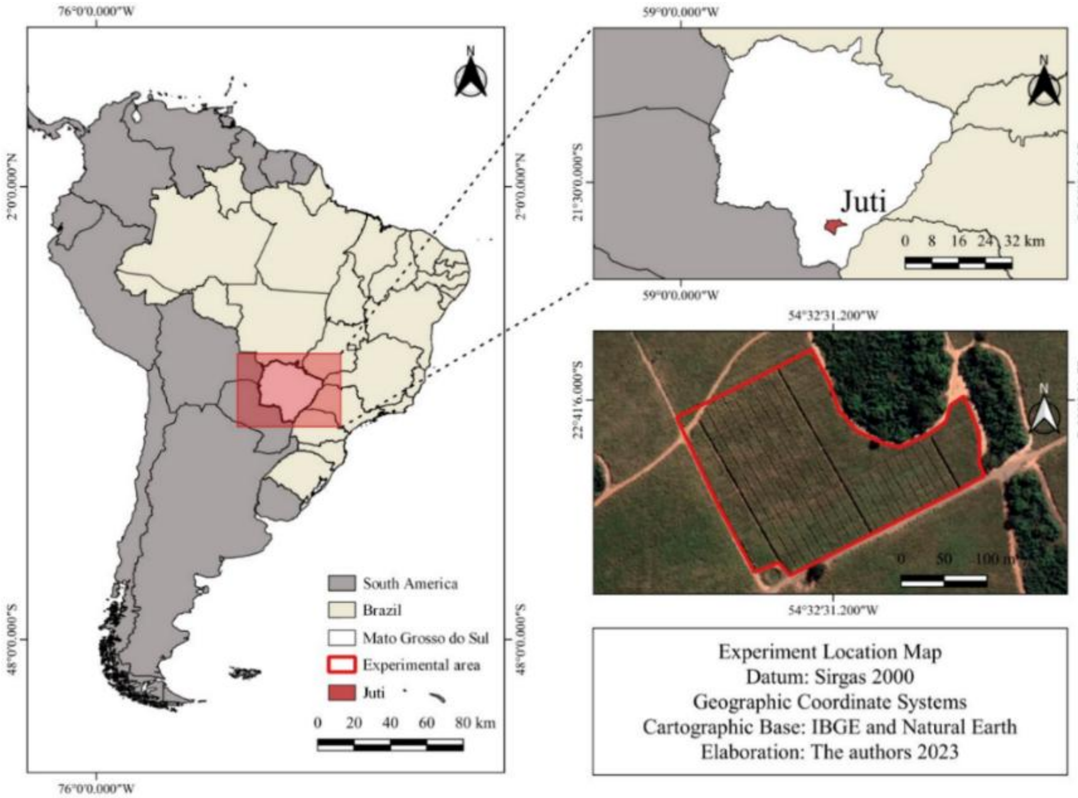


**Figure 1.** Location of the experimental area.

Soil samples were extracted at depths of 0 to 0.1, 0.1 to 0.2, and 0.2 to 0.4 m for subsequent chemical and physical characterization. The physicochemical analyses encompassed determinations of sand, silt, and clay content using the densimeter method, pH in both water and $CaCl_2$, H+Al, aluminum (Al), phosphorus (P) extracted by the Mehlich-1 method, potassium (K), calcium (Ca), and magnesium (Mg). These analyses were performed following the methodology outlined by Teixeira et al. (2017) (Table 1).

**Table 1.1** Chemical and granulometric characterization of the soil at depths of 0 to 0.1, 0.1 to 0.2, and 0.2 to 0.4 m before Experiment Setup.

| Depth | pH water | pH $CaCl_2$ | $Al^{3+}$ | Ca | Mg | K | P[1] | V | Sand | Silt | Clay |
|---|---|---|---|---|---|---|---|---|---|---|---|
| m | | | -------- $cmol_c\ dm^{-3}$ -------- | | | | mg $m^{-3}$ | % | ------- g $kg^{-1}$ -------- | | |
| 0-0.1 | 5.16 | 4.36 | 0.30 | 0.41 | 0.35 | 0.06 | 3.67 | 26.5 | 856 | 57 | 87 |
| 0.1-0.2 | 5.18 | 4.39 | 0.30 | 0.42 | 0.17 | 0.04 | 1.30 | 16.1 | 857 | 51 | 92 |
| 0.2-0.4 | 4.93 | 4.10 | 0.50 | 0.43 | 0.11 | 0.03 | 0.63 | 14.4 | 842 | 50 | 108 |

[1]Available phosphorus content determined by the Mehlich-1 method. Al = aluminum; Ca = calcium; Mg = magnesium; K = potassium; P = phosphorus; V = base saturation.

The experimental design employed a randomized block design within sub-subdivided plots, each with three replicates. Two doses of limestone (38.0% CaO and 11.2% MgO, PRNT = 74.9%) at 6 Mg $ha^{-1}$ and 12 Mg $ha^{-1}$ were assessed in the plots. The 6 Mg $ha^{-1}$ dose aimed at correcting soil acidity in the 0 to 0.5 m layer, while the 12 Mg $ha^{-1}$ dose targeted soil fertility profile construction (twice the initial dose). In the subplots, the study evaluated the impact of three species (*Glycine max*, *Crotalaria spectabilis*, and *Crotalaria juncea*) grown after the *Urochloa brizanta* Xaraés cultivar before planting *Saccharum officinarum*. Additionally, three Phosfaz calcined thermophosphate doses (0, 380, and 760 kg $ha^{-1}$, equivalent to 0, 87.4, and 174.8 kg $ha^{-1}$ of $P_2O_5$) were assessed, applied through casting and incorporated with limestone and gypsum in the subplots.

In the plots, liming involved the application of 3 or 6 Mg $ha^{-1}$ of limestone, incorporated using a moldboard plow (a 2.5 m wide implement with four moldboards). Subsequently, an additional 3 or 6 Mg $ha^{-1}$ of limestone and 2 Mg $ha^{-1}$ of gypsum were applied, followed by incorporation using an intermediate harrow (a 4.2 m wide implement with 70 cm diameter toothed discs), subsoiling, and leveling with a disk harrow. Subsequently, the *Brachiaria brizantha* cultivar Xaraés was cultivated for nine months, followed by *Glycine max*, *Crotalaria spectabilis*, or *Crotalaria juncea* in the subplots before *Saccharum officinarum*.

The area of each sub-subplot (treatment of thermophosphate doses) was 105 $m^2$, comprising seven rows of cane spaced 1.50 m apart and 10 m long. The sub-plot (treatment of the previous crop) covered 345 $m^2$ (10.0 m x 34.5 m), and the plot (treatment of the fertility management system and liming practice) spanned 1,173 $m^2$ (34 x 34.5 m).

The *Urochloa brizantha* Xaraés cultivar was sown in the plots with a seeding rate of 80%. The grass was desiccated using 5 L $ha^{-1}$ of glyphosate herbicide + 1 L $ha^{-1}$ of 2,4D herbicide. Subsequently, *Glycine max*, *C. spectabilis* (90% purity, minimum germination of 80%), and *C. juncea* (90% purity, minimum germination of 80%) were sown in the subplots. In subplots with *Glycine max*, 267 kg $ha^{-1}$ of 07-34-12 fertilizer was applied at planting, and 160 kg $ha^{-1}$ of potassium chloride fertilizer was top-dressed 27 days after emergence.

After soybean harvesting and crotalaria management using a knife roller, sugarcane (variety SP 832847) was mechanically planted at a spacing of 1.50 m. In the sugarcane planting furrow, 500 kg $ha^{-1}$ of 10-25-25 fertilizer was applied. At 113 days after planting sugarcane, a trench was opened in each experimental unit, and soil samples were taken from the 0 to 0.1, 0.1 to 0.2, and 0.2 to 0.4 m layers using a PVC gutter and a stainless-steel spatula, cutting a soil slice about 0.01 m thick, 0.60 m long, and corresponding to the sampling depth for P forms fractionation.

Inorganic and organic P fractions were extracted from the soil following the method of Hedley et al. (1982), with modifications by Condron and Goh (1989). For each sample, 0.5 g of soil was used to extract organic phosphorus (Po) and inorganic phosphorus (Pi) sequentially using anion exchanger resin (Pi) (AMI-7001 plates), sodium bicarbonate ($NaHCO_3$) 0.5 mol $L^{-1}$ at pH 8.5 (Pi + Po), sodium hydroxide (NaOH) 0.1 mol $L^{-1}$ (Pi and Po), hydrochloric acid (HCl) 1.0 mol $L^{-1}$ (Pi), sodium hydroxide (NaOH) 0.5 mol $L^{-1}$ (Pi and Po), and digestion with $H_2SO_4$ + $H_2O_2$ + $MgCl_2$ (residual P). Acidification was conducted for the Pi of the alkaline extracts of $NaHCO_3$ 0.5 mol $L^{-1}$ and NaOH 0.1 and 0.5 mol $L^{-1}$. The P content of the acid extracts was determined using Murphy and Riley's method (1962). The obtained P fractions were categorized based on lability according to Rotta (2015) classification: Labile phosphorus (Labile), Moderately Labile P (M Labile P), and Non-Labile P (N Labile P), expressed as g $kg^{-1}$.

Data underwent Deviance Analysis, and the F-statistic was computed. In case of significant treatment effects ($p < 0.05$) in the Deviance Analysis, means were compared using the Tukey test with the "emmeans" package (Lenth et al., 2025). Plot and subplot effects were incorporated into the model as random effects. All models were fitted using the gamlss package in the R statistical software (Rigby & Stasinopoulos, 2005; R Core Team, 2022).

## Results and discussion

An interaction was observed among the study factors (liming and phosphate applications; crop and phosphate applications) concerning the labile P variable and the liming and crop factors in the moderately labile P variable (%). Phosphate applications alone significantly influenced the labile P variable. There was an isolated significant difference for the crop factor only for labile P (%) (Table 2).

**Table 2.** Results of the F-statistic from the deviance analysis followed by the p-value from the normality test (pno) and the Coefficient of Variation (CV) when considering the 0-0.1 m depth for the labile, moderately labile (M Labile P), and non-labile (N Labile P) forms of P in the soil.

| Treatment | Labile P | M Labile P | N Labile P | Total | Labile P | M Labile P | N Labile P |
|---|---|---|---|---|---|---|---|
| | ------------------- mg kg$^{-1}$ ------------------- | | | | ---------------- % ---------------- | | |
| Liming (Ca) | 1.836 | 0.959 | 7.586 | 3.84 | 1.218 | 0.904 | 1.063 |
| Culture (C) | 0.276 | 2.638 | 1.862 | 3.812 | 17.53** | 3.754 | 3.258 |
| Phosphate applications (F) | 4.336** | 0.425 | 1.316 | 1.062 | 0.22 | 0.312 | 0.545 |
| Ca:C | 1.480 | 3.727 | 1.703 | 1.828 | 4.063 | 4.798** | 2.509 |
| Ca:F | 3.812** | 0.904 | 2.397 | 1.075 | 0.33 | 0.709 | 0.813 |
| C:F | 6.073** | 0.183 | 0.718 | 0.235 | 0.669 | 0.013 | 0.118 |
| Ca:C:F | 2.595 | 1.259 | 0.944 | 1.316 | 0.682 | 1.381 | 1.494 |
| Pno | 0.236 | 0.102 | 0.001 | 0.219 | 0.745 | 0.097 | 0.086 |
| CV (%) | 23.45% | 33.98% | 3.99% | 12.23% | 22.43% | 22.71% | 9.62% |

**Significant by the F test in the Deviance analysis. M Labile P: moderately labile phosphorus, N Labile P: non-labile phosphorus.

Concerning liming management, the application of 12 Mg ha$^{-1}$ associated with a dose of 380 kg ha$^{-1}$ of thermophosphate resulted in a higher labile P content (Table 3). This outcome emphasizes the significance of correcting soil acidity combined with the dose of P for efficient phosphate fertilization. The anticipated positive impact of liming, neutralizing aluminum effects and reducing P retention reactions, might not have been evident at doses of 0 and 760 kg ha$^{-1}$ of thermophosphate due to elevated Ca and P levels in the soil solution resulting from limestone and fertilizer applications, respectively.

**Table 3.** Labile P content in the soil as a function of the dose of limestone and calcined thermophosphate at a depth of 0 to 0.1 m.

| Limestone dose (Mg ha$^{-1}$) | Thermophosphate dose (kg ha$^{-1}$) | | | Mean |
|---|---|---|---|---|
| | 0 | 380 | 760 | |
| | -------------------------------- mg kg$^{-1}$ -------------------------------- | | | |
| 6 | 24.74 Aa | 25.00 Ba | 26.58 Aa | 25.61 |
| 12 | 26.49 Aa | 37.13 Aa | 25.93 Aa | 31.07 |
| Mean | 25.61 | 31.07 | 26.26 | 27.64 |
| CV (%) | 23.45 | | | |

Averages followed by the same uppercase letter in the columns and lowercase letter in the rows do not differ significantly (Tukey, 5%).

When analyzing the effect of P doses and the previous crop, where no P was added and at a dose of 760 kg ha$^{-1}$ of thermophosphate, both crotalaria species were statistically similar. *They* differed from soybeans, exhibiting a lower fraction of labile P (Table 4). As stated by Calegari (2016), Barbosa et al. (2020), and Carvalho et al. (2022), crotalaria produces more biomass than soybeans, potentially making more P available to the soil after the mineralization of plant residues. *C. juncea* and *C. spectabilis* can provide the shoots with 27.0 to 37.5 kg ha$^{-1}$ of P (61.9 to 85.9 kg ha$^{-1}$ of $P_2O_5$) and 13.0 to 16.6 kg ha$^{-1}$ of P (29.8 to 38.0 kg ha$^{-1}$ of $P_2O_5$) to the soil, respectively, while soybeans provide 11 kg ha$^{-1}$ of P (25.2 kg ha$^{-1}$ of $P_2O_5$). This suggests that the supply of 90.8 kg ha$^{-1}$ of $P_2O_5$ at soybean planting (267 kg ha$^{-1}$ of 07-34-12 fertilizer) was insufficient to compensate for the P supplied by crotalaria plant residues through nutrient recycling. Moreover, the increase in soil organic matter levels may decrease P fixation by releasing low molecular weight organic acids, competing with P for adsorption sites (Bortoluzzi et al., 2015).

**Table 4.** Labile P content in the soil depending on the previous crop and calcined thermophosphate at a depth of 0 to 0.1 m.

| Previous crop | Thermophosphate dose (kg ha$^{-1}$) | | | Mean |
|---|---|---|---|---|
| | 0 | 380 | 760 | |
| | ------------------ mg kg$^{-1}$ ------------------ | | | |
| *Crotalaria juncea* | 30.41 Aa | 31.43 Aa | 32.56 Aa | 31.47 |
| Soybean | 19.54 Ba | 33.64 Aa | 16.58 Ba | 23.25 |
| *Crotalaria spectabilis* | 26.88 Aa | 28.13 Aa | 29.63 Aa | 28.21 |
| Mean | 25.61 | 31.07 | 26.25 | 27.64 |
| CV (%) | | 23.45 | | |

Averages followed by the same uppercase letter in the columns and lowercase letter in the rows do not differ significantly (Tukey, 5%).

Crotalaria contributed more labile phosphorus to the soil than soybeans (Table 5). These results suggest that cultivating crotalaria as a crop before sugarcane is more efficient, providing readily available phosphorus. According to Collier et al. (2018), the root system of crotalaria releases organic acids that occupy sites that would otherwise retain phosphorus. This facilitates higher content of labile forms of P and represents a significant alteration in the dynamics and use efficiency of applied P.

**Table 5.** Labile P (%) in the soil depending on the previous crop at a depth of 0 to 0.1 m.

| Previous crop | Labile phosphorus (%) |
|---|---|
| *Crotalaria juncea* | 7.30 A |
| Soybean | 5.60 B |
| *Crotalaria spectabilis* | 7.69 A |
| Mean | 6.86 |
| CV | 22.43 |

Averages followed by the same uppercase letter in the columns and lowercase letter in the rows do not differ significantly (Tukey, 5%).

Regarding the moderately labile form of P, liming at a dose of 6 Mg ha$^{-1}$ favored greater accumulation of this form of P when the previous crops were *Crotalaria juncea* and soybeans. For the 12 Mg ha$^{-1}$ dose of limestone, the highest levels of M labile P occurred in the *Crotalaria juncea* treatments (Table 6). The increase in the moderately labile form with crotalaria cultivation must also be associated with greater biomass production and P cycling compared to soybeans (Calegari, 2016; Carvalho et al., 2022).

When comparing the labile and moderately labile forms, the results reveal a certain interdependence between them, indicating that the moderately labile fraction contributes to buffering the labile form. When the labile form becomes saturated with $H_2PO_4^-$, P ions undergo adsorption onto Fe and Al oxyhydroxides or become associated with organic complexes, constituting an intermediate class of nutrient availability. This replenishes the labile fraction when P availability in the soil is low (Leite et al., 2016).

**Table 6.** Moderately labile P (%) in the soil depending on the dose of limestone and the previous crop at a depth of 0 to 0.1 m.

| Previous crop | Limestone dose (Mg ha$^{-1}$) | | Mean |
|---|---|---|---|
| | 6 | 12 | |
| | ------------------ % ------------------ | | |
| *Crotalaria juncea* | 32.44 Aa | 36.38 Aa | 34.41 |
| Soybean | 33.24 Aa | 26.02 Bb | 29.63 |
| *Crotalaria spectabilis* | 19.42 Bb | 31.52 ABa | 25.47 |
| Mean | 28.37 | 31.31 | 29.84 |
| CV (%) | | 22.71 | |

Averages followed by the same uppercase letter in the columns and the same lowercase letter in the row do not differ significantly (Tukey, 5%).

An interaction was observed between the study factors (liming, crop, and phosphate applications), and an isolated effect of the factors was found only for the labile P variable (Table 7).

The application of 12 Mg ha$^{-1}$ of limestone tended to provide greater availability of phosphorus in the most accessible form when sugarcane was planted successively to *Crotalaria juncea* and soybeans, regardless of the applied thermophosphate dose (Table 8).

Similar to what was observed in the 0 to 0.1 m layer, crotalaria contributed a higher percentage of labile phosphorus to the soil, especially at the lowest lime dose when compared to soybeans (Table 9). Thus, the beneficial effect of using crotalaria on P availability for plants in the 0 to 0.2 m layer is inferred. As a result, there will be a greater supply of P to the surface of the roots and, consequently, greater root development and greater absorption of P by the plant roots.

**Table 7.** Results of the F-statistic of the deviance analysis followed by the p-value of the normality test (pno) and the Coefficient of Variation (CV) when considering the 0.1 to 0.2 m depth of the forms of P in the soil.

| Treatment | Labile P | M Labile P | N Labile P | Total | Labile P | M Labile P | N Labile P |
|---|---|---|---|---|---|---|---|
| | ------------------- mg kg$^{-1}$ ------------------- | | | | ---------------- % ---------------- | | |
| Liming (Ca) | 2.820 | 0.048 | 6.766 | 0.86 | 0.587 | 0.011 | 0.014 |
| Culture (C) | 18.651** | 1.476 | 1.524 | 2.066 | 20.233** | 1.979 | 1.669 |
| Phosphate applications (F) | 0.495 | 0.013 | 0.514 | 0.098 | 0.655 | 0.023 | 0.091 |
| Ca:C | 6.313** | 2.629 | 0.293 | 1.733 | 15.657** | 4.296 | 2.332 |
| Ca:F | 2.600 | 1.532 | 0.385 | 1.009 | 3.474** | 0.583 | 0.676 |
| C:F | 4.344** | 0.514 | 0.656 | 0.948 | 2.267 | 0.568 | 0.74 |
| Ca:C:F | 4.707** | 1.104 | 0.656 | 1.392 | 1.425 | 0.718 | 1.079 |
| Pno | 0.691 | 0.741 | 0.003 | 0.545 | 0.116 | 0.574 | 0.513 |
| CV (%) | 8.67% | 38.15% | 2.42% | 11.60% | 14.03% | 28.93% | 10.02% |

**Significant by the F test in the Deviance analysis. M Labile P: moderately labile phosphorus, N Labile P: non-labile phosphorus.

**Table 8.** Labile P content in the soil as a function of the dose of limestone and calcined thermophosphate and the previous crop at a depth of 0.1 to 0.2 m.

| Previous crop | Limestone dose (Mg ha$^{-1}$) | | Mean |
|---|---|---|---|
| | 6 | 12 | |
| | ----------------------------- mg kg$^{-1}$ ----------------------------- | | |
| | 0 kg ha$^{-1}$ of thermophosphate | | |
| *Crotalaria juncea* | 19.02 Bb | 24.69 Aa | 21.86 |
| Soybean | 12.61 Cb | 19.02 Ba | 15.82 |
| *Crotalaria spectabilis* | 26.12 Aa | 16.87 Bb | 21.50 |
| Mean | 19.25 | 20.19 | 19.73 |
| | 380 kg ha$^{-1}$ of thermophosphate | | |
| *Crotalaria juncea* | 21.24 Ab | 27.14 Aa | 24.19 |
| Soybean | 9.01 Bb | 17.57 Ba | 13.29 |
| *Crotalaria spectabilis* | 22.64 Aa | 20.91 Ba | 21.78 |
| Mean | 17.63 | 21.87 | 19.75 |
| | 760 kg ha$^{-1}$ of thermophosphate | | |
| *Crotalaria juncea* | 19.74 Ab | 24.64 Aa | 22.19 |
| Soybean | 12.10 Ba | 12.40 Ba | 12.25 |
| *Crotalaria spectabilis* | 24.34 Aa | 21.93 Aa | 23.14 |
| Mean | 18.73 | 19.66 | 19.19 |
| CV (%) | 8.67 | | |

Averages followed by the same uppercase letter in the columns and the same lowercase letter in the row do not differ significantly (Tukey, 5%).

**Table 9.** Labile P (%) in the soil depending on the dose of limestone and the previous crop at a depth of 0.1 to 0.2 m.

| Previous crop | Limestone dose (Mg ha$^{-1}$) | | Mean |
|---|---|---|---|
| | 6 | 12 | |
| | -------------------------------- % -------------------------------- | | |
| *Crotalaria juncea* | 5.28 Bb | 6.51 Aa | 5.90 |
| Soybean | 3.07 Cb | 5.99 Ba | 4.53 |
| *Crotalaria spectabilis* | 7.78 Aa | 5.42 ABb | 6.60 |
| Mean | 5.38 | 5.97 | 5.67 |
| CV (%) | 14.03 | | |

Averages followed by the same uppercase letter in the columns and the same lowercase letter in the row do not differ significantly (Tukey, 5%).

The highest percentage of labile P was observed in the treatment in which 12 Mg ha$^{-1}$ of limestone was applied combined with a dose of 380 kg ha$^{-1}$ of thermophosphate (Table 10). The literature reports gains in productivity with the presence of available P in subsurface layers (Hansel et al., 2017; Lu et al., 2019; Oliveira et al., 2020).

**Table 10.** Labile P (%) in the soil as a function of the dose of limestone and calcined thermophosphate at a depth of 0.1 to 0.2 m.

| Limestone dose (Mg ha$^{-1}$) | Thermophosphate dose (kg ha$^{-1}$) | | | Mean |
|---|---|---|---|---|
| | 0 | 380 | 760 | |
| | ------------------------------- % ------------------------------- | | | |
| 6 | 5.74 Aa | 5.05 Ba | 5.34 Aa | 5.38 |
| 12 | 5.54 Aa | 6.12 Aa | 5.37 Aa | 5.67 |
| Mean | 5.74 | 5.05 | 5.34 | 5.38 |
| CV (%) | 14.03 | | | |

Averages followed by the same uppercase letter in the columns and lowercase letter in the rows do not differ significantly (Tukey, 5%).

An interaction was identified between the study factors (crop and phosphate applications), with an isolated effect of the factors observed for the labile and moderately labile P variables (Table 11).

**Table 11.** Results of the F-statistic from the deviance analysis followed by the p-value from the normality test (pno) when considering the 0.2 to 0.4 m depth of the forms of P in the soil.

| Treatment | Labile P | M Labile P | N Labile P | Total | Labile P | M Labile P | N Labile P |
|---|---|---|---|---|---|---|---|
| | ------------------- mg kg$^{-1}$ ------------------- | | | | ---------------- % ---------------- | | |
| Liming (Ca) | 3.52 | 0.381 | 2.538 | 1.548 | 1.668 | 0.152 | 0.38 |
| Culture (C) | 8.087** | 1.538 | 2.963 | 3.851 | 12.949** | 4.015 | 3.032 |
| Phosphate applications (F) | 0.351 | 3.424** | 2.287 | 2.361 | 0.054 | 3.108 | 3.267 |
| Ca:C | 2.346 | 1.782 | 0.478 | 1.218 | 5.324** | 3.098 | 1.544 |
| Ca:F | 3.167 | 0.404 | 0.99 | 0.495 | 2.261 | 0.181 | 0.161 |
| C:F | 3.284** | 1.185 | 0.528 | 1.048 | 2.148 | 0.846 | 0.89 |
| Ca:C:F | 1.403 | 1.744 | 5.07** | 1.994 | 2.127 | 1.345 | 1.684 |
| Pno | 0.928 | 0.226 | 0.039 | 0.489 | 0.447 | 0.160 | 0.424 |
| CV (%) | 13.12% | 36.19% | 1.59% | 9.59% | 15.35% | 28.89% | 8.33% |

**Significant by the F test in the Deviance analysis. M Labile P: moderately labile phosphorus, N Labile P: non-labile phosphorus.

In general, crotalaria outperformed soybeans in increasing labile P in the soil profile, particularly when associated with the highest dose of thermophosphate (Table 12). The presence of P throughout the soil profile and water close to the roots favors P absorption by plants (Sousa et al., 2016). Furthermore, it is worth noting that the main mechanism plant roots use to obtain P is diffusion, which occurs over short distances. In these cases, a larger volume of soil with P will favor nutrient absorption by the root system and, consequently, increase productivity.

**Table 12.** Labile P in the soil as a function of the dose of calcined thermophosphate and the previous crop at a depth of 0.2 to 0.4 m.

| Previous crop | Thermophosphate dose (kg ha$^{-1}$) | | | Mean |
|---|---|---|---|---|
| | 0 | 380 | 760 | |
| | --------------------------------- mg kg$^{-1}$ --------------------------------- | | | |
| *Crotalaria juncea* | 17.52 Aa | 22.11 Aa | 19.82 Aa | 17.52 |
| Soybean | 10.10 Aa | 20.02 Ba | 15.06 Ba | 10.10 |
| *Crotalaria spectabilis* | 19.85 Aa | 18.77 Aba | 19.31 Aa | 19.85 |
| Mean | 15.82 | 20.30 | 18.06 | 15.82 |
| CV (%) | | 13.12 | | |

Averages followed by the same uppercase letter in the columns and lowercase letter in the rows do not differ significantly (Tukey, 5%).

Concerning the percentage of labile P, crotalaria tended to stand out in increasing labile P at depth, regardless of the limestone doses (Table 13). For the previous crops of *C. juncea* and soybeans, there was a greater increase in labile P at the dose of 12 Mg ha$^{-1}$ of limestone. On the other hand, for the *C. spectabilis* residue, there was a greater increase in labile P when 6 Mg ha$^{-1}$ of limestone was applied (Table 13). This result allows us to infer that the cultivation of *C. spectabilis* is more advantageous when the amount of limestone indicated by the base saturation method is applied to raise it to 60%. Meanwhile, the cultivation of *C. juncea* has greater potential to raise the levels of labile phosphorus in the 0.2 to 0.4 m layer of the soil when a greater amount of limestone is applied.

**Table 13.** Labile P (%) in the soil depending on the dose of limestone and the previous crop at a depth of 0.2 to 0.4 m.

| Previous crop | Limestone dose (Mg ha$^{-1}$) | | Mean |
|---|---|---|---|
| | 6 | 12 | |
| | -------------------------------- % -------------------------------- | | |
| *Crotalaria juncea* | 4.86 Bb | 6.06 Aa | 5.46 |
| Soybean | 3.02 Cb | 5.42 Ba | 4.22 |
| *Crotalaria spectabilis* | 6.85 Aa | 5.59 ABb | 6.22 |
| Mean | 4.91 | 5.69 | 5.30 |
| CV (%) | 15.35 | | |

Averages followed by the same uppercase letter in the columns and the same lowercase letter in the row do not differ significantly (Tukey, 5%).

The decrease in moderately labile P content with the addition of doses of thermophosphate was linear (Figure 2). The small accumulation of P in this form occurs due to the smaller number of adsorption sites and the lower binding energy of phosphate with the soil colloids, which gives sandy soils their greater resilience.

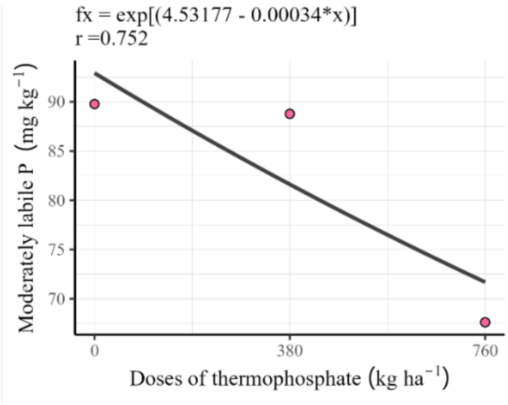


**Figure 2.** Moderately labile P content in the soil as a function of the doses of calcined thermophosphate at a depth of 0.2 to 0.4 m.

For a fraction of low phosphorus availability (non-labile P), overall, *C. juncea* and soybeans provided the highest content of non-labile P, where 6 Mg ha$^{-1}$ of limestone was added. With the application of 12 Mg ha$^{-1}$ of limestone, crotalaria provided the highest content of this form (Table 14). However, in general terms, the previous crops, liming, and phosphate applications had little influence on the higher recalcitrant P levels. It suggests that the system maintains a constant P buffering status for the solution in equilibrium with the labile fraction. Specifically for the treatment relating to the previous crops, the low influence on this fraction of P is also associated with handling the plants with the knife roller. Thus, a limited effect of the mineralization of the phytomass on the dynamics of this nutrient is expected at the depth of 0.2 to 0.4 m.

**Table 14.** Non-labile P content in the soil as a function of the dose of limestone and calcined thermophosphate and the previous crop at a depth of 0.2 to 0.4 m.

| Previous crop | Limestone dose (Mg ha$^{-1}$) 6 | 12 | Mean |
|---|---|---|---|
| | ------------------------------ mg kg$^{-1}$ ------------------------------ | | |
| | 0 kg ha$^{-1}$ of calcined thermophosphate | | |
| *Crotalaria juncea* | 242.94 Aa | 246.33 Aa | 244.63 |
| Soybean | 240.42 Aa | 243.17 ABa | 241.80 |
| *Crotalaria spectabilis* | 238.90 Aa | 236.27 Ba | 237.59 |
| Mean | 240.75 | 241.92 | 241.34 |
| | 380 kg ha$^{-1}$ of calcined thermophosphate | | |
| *Crotalaria juncea* | 243.09 Aa | 245.13 Aa | 244.11 |
| Soybean | 242.99 Aa | 238.94 Aa | 240.97 |
| *Crotalaria spectabilis* | 226.15 Bb | 244.26 Aa | 235.20 |
| Mean | 237.41 | 242.78 | 240.09 |
| | 760 kg ha$^{-1}$ of calcined thermophosphate | | |
| *Crotalaria juncea* | 241.92 Ab | 249.66 Aa | 245.79 |
| Soybean | 241.12 Aa | 244.15 Aa | 242.63 |
| *Crotalaria spectabilis* | 240.78 Aa | 242.44 Aa | 241.61 |
| Mean | 241.27 | 245.41 | 243.34 |
| CV (%) | 1.59 | | |

Averages followed by the same uppercase letter in the columns and the same lowercase letter in the row do not differ significantly (Tukey, 5%).

## Conclusion

Liming, phosphate applications, and previous crops affected the forms of phosphorus (P) in the soil of the sugarcane crop to varying degrees in the evaluated soil layers. Overall, the application of limestone at a higher dose than needed to correct the soil acidity (12 Mg ha$^{-1}$), combined with corrective fertilization using 380 kg ha$^{-1}$ of thermophosphate and the cultivation of *Crotalaria juncea*, resulted in a higher content of phosphorus in the labile form up to the 0.4 m soil layer.

## References

Abraches, M. O., Silva, G. A. M., Santos, L. C., Pereira, L. F., & Freitas, G. B. (2021). Contribuição da adubação verde nas características químicas, físicas e biológicas do solo e sua influência na nutrição de hortaliças. *Research, Society and Development*, *10*(7), 1-17. https://doi.org/10.33448/rsd-v10i7.16351

Amadou, I., Houben, D., & Faucon, M. P. (2021). Unravelling the role of rhizosphere microbiome and root traits in organic phosphorus mobilization for sustainable phosphorus fertilization. A review. *Agronomy*, *11*(11), 1-28. https://doi.org/10.3390/agronomy11112267

Barbosa, I. R., Santana, R. S., Mauad, M., & Garcia, R. A. (2020). Dry matter production and nitrogen, phosphorus and potassium uptake in *crotalaria juncea* and *crotalaria spectabilis*. *Pesquisa Agropecuária Tropical*, *50*, 1-10. https://doi.org/10.1590/1983-40632020v5061011

Bortoluzzi, E. C., Pérez, C., Ardisson, J. D., Tiecher, C., & Carner, L. (2015). Occurrence of iron and aluminum sesquioxides and their implications for the P sorption in subtropical soils. *Applied Clay Science, 104*, 196-204. https://doi.org/10.1016/j.clay.2014.11.032

Calegari, A. (2016). *Manual técnico de plantas de cobertura* (2. ed.). IAPAR.

Carvalho, M. L., Vanolli, B. S., Schiebelbein, B. E., Borba, D. A., Luz, F. B., Cardoso, G. M., Bortolo, L. S., Marostica, M. E. M., & Souza, V. S. (2022). *Guia prático de plantas de cobertura: aspectos filotécnicos e impactos sobre a saúde do solo*. ESALQ-USP.

Collier, L. S., Arruda, E. M., Campos, L. F. C., & Nunes, J. N. V. (2018). Atributos químicos do solo e produtividade de milho em residual de leguminosas em sistema agroflorestal. *Revista Caatinga*, *31*(2), 279-289. https://doi.org/10.1590/1983-21252018v31n203rc

Condron, L. M., & Goh, K. M. (1989). Effects of long-term phosphatic fertilizer applicationson amounts and forms of phosphorus in soils under irrigated pasture in New Zealand. *Journal of Soil Science*, *40*(2), 383-395. https://doi.org/10.1111/j.1365-2389.1989.tb01282.x

Fietz, C. R., Fisch, G. F., Comunello, E., & Flumignan, D. L. (2017). *O clima da região de Dourados, Mato Grosso do Sul*. Embrapa Agropecuária Oeste.

Guo, L., Yu, Z., Li, Y., Xie, Z., Wang, G., Liu, X., Liu, J., Liu, J., & Jin, J. (2022). Plant phosphorus acquisition links to phosphorus transformation in the rhizospheres of soybean and rice grown under $CO_2$ and temperature co-elevation. *Science of the Total Environment*, *823*, 153558. https://doi.org/10.1016/j.scitotenv.2022.153558

Hansel, F. D., Diaz, D. A. R., Amado, T. J. C., & Rosso, L. H. M. (2017). Deep banding increases phosphorus removal by soybean grown under no-tillage production systems. *Agronomy Journal, 109*(3), 1091-1098. https://doi.org/10.2134/agronj2016.09.0533

Hedley M. J., Stewart J. W. B., & Chauhan, B. S. (1982). Changes in inorganic and organic soil phosphorus fractions induced by cultivation practices and by laboratory incubations. *Soil Science Society of America Journal*, *46*(5), 970-976. https://doi.org/10.2136/sssaj1982.03615995004600050017x

Horii, J. A. (2004). A qualidade da matéria prima, na visão industrial. *Visão Agrícola*, *1*(1), 91-93.

Leite, J. N. F., Cruz, M. C. P., Ferreira, M. E., Andrioli, I., & Braos, L. B. (2016). Frações orgânicas e inorgânicas do fósforo no solo influenciadas por plantas de cobertura e adubação nitrogenada. *Pesquisa Agropecuária Brasileira*, *51*(11), 1880-1889. https://doi.org/10.1590/S0100-204X2016001100010

Lenth, R. V., Banfai, B., Bolker, B., Buerkner, P., Giné-Vázquez, I., Herve, M., Jung, M., Love, J., Miguez, F., Piaskowski, J., Riebl, H., & Singmann, H. (2025). *emmeans: Estimated marginal means, aka least-squares means (Version 1.11.0)*. CRAN. https://rvlenth.github.io/emmeans/

Lu, D., Song, H., Jiang, S., Chen, X., Wang, H., & Zhou, J. (2019). Integrated phosphorus placement and form for improving wheat grain yield. *Agronomy Journal*, *111*(4), 1998-2004. https://doi.org/10.2134/agronj2018.09.0559

Murphy, J., & Riley, J. P. (1962). A modified single solution method for the determination of phosphate in natural waters. *Analytica Chimica Acta*, *27*, 31-36. https://doi.org/10.1016/S0003-2670(00)88444-5

Oliveira, L. E. Z., Souza, D. M. G., Figueiredo, C. C., Nunies, R. S., & Malaquias, J. V. (2020). Long-term phosphate fertilization strategies evaluation in a brazilian oxisol. *Agronomy Journal*, *112*(5), 4303-4320. https://doi.org/10.1002/agj2.20324

R Core Team. (2022). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Rigby, R. A., & Stasinipoulos, D. M. (2005). Generalized additive models for location, scale and shape. *Journal of the Royal Statistical Society Series C: Applied Statistics*, *54*(3), 507-554. https://doi.org/10.1111/j.1467-9876.2005.00510.x

Rotta, L. R., Paulino, H. B., Anghinoni, I, Souza, E. D., Lopes, G., & Carneiro, M. A. C. (2015). Phosphorus fractions and availability in a haplic plinthosol under no-tillage system in the Brazilian Cerrado. *Ciência e Agrotecnologia*, *39*(3), 216-224. https://doi.org/10.1590/S1413-70542015000300002

Rheinheimer, D. S., Anghinoni, I., & Conte, E. (2000). Fósforo da biomassa microbiana em solos sob diferentes sistemas de manejo. *Revista Brasileira de Ciência do Solo*, *24*(3), 589-597. https://doi.org/10.1590/S0100-06832000000300012

Rheinheimer, D. S., Fornari, M. R., Bastos, M. C., Fernandes, G., Santanna, M. A., Calegari, A., Canalli, L. B. S., Caner, L., Labanowski, J., & Tiecher, T. (2019). Phosphorus Distribution After Three Decades of Diferente Soil Management and Cover Crops in Subtropical Region. *Soil and Tillage Research*, *192*, 33-41. https://doi.org/10.1016/j.still.2019.04.018

Santos, H. G., Jacomine, P. K. T., Anjos, L. H. C., Oliveira, V. A., Lumbreras, J. F., Coelho, M. R., Almeida, J. A., Araújo Filho, J. C., Oliveira, J. B., & Cunha, T. J. F. (2018). *Sistema Brasileiro de Classificação de Solo* (2. ed.). Embrapa.

Sousa, D. M. G., Nunes, R. S., Rein, T. A., & Santos Júnior, J. D. G. (2016). *Manejo da adubação fosfatada para culturas anuais no cerrado*. Embrapa Cerrados.

Teixeira, P. C., Donagemma, G. K., Fontana, A., & Teixeira, W. G. (2017). *Manual de métodos de análise de solo* (3. ed.). Embrapa.

Tiecher, T., Gomes, M. V., Ambrosini, V. G., Amorim, M. B, & Bayer, C. (2018). Assessing linkage between soil phosphorus forms in contrasting tillage systems by path analysis. *Soil and Tillage Research*, *175*, 276-280. https://doi.org/10.1016/j.still.2017.09.015

Yang, J. X., Richards, R., Yi, J., & Jin, H. (2022). Both biomass accumulation and harvest indez drive the yield improvements in soybean at high and low phosphorus in south-west China. *Field Crops Research*, *277*, 108426. https://doi.org/10.1016/j.fcr.2021.108426

Zhu, P., Abdelaziz, O. Y., Hulteberg, C. P., & Riisager, A. (2020). New synthetic approaches to biofuels from lignocellulosic biomass. *Current Opinion in Green and Sustainable Chemistry*, *21*, 16-21. https://doi.org/10.1016/j.cogsc.2019.08.005