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INTERCROPPING SYSTEMS AND SOIL AMENDMENTS UNDER LONG-TERM NO-TILL ON PHOSPHORUS DYNAMICS

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“Blessed are those who find wisdom,
those who gain understanding.”

Proverbs 3:13
(tradução nossa)

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ABSTRACT

The management of weathered tropical soils, with low availability of phosphorus and the presence of a dry season in winter, is a challenge to favor the levels of organic matter and improve the efficiency of phosphate fertilization. Intercropping maize second crop with cover crops has improved soil quality, enhancing the input of straw in the production system, favoring nutrient cycling and efficient use of natural resources by commercial crops, increasing productivity. The effects of intercropping systems on off-season (autumn-winter) cropping and changes in soil acidity on soil P dynamics were evaluated in a randomized block experiment in split plots. The single or intercropped maize cultivation system with signal grass + sunn hemp were considered as the main plots, and the acidity correction through silicate, limestone or without correction were treated as subdivided plots. Soy is grown as a main crop in the summer seasons. The intercropping of maize in the off-season increases the yield of maize and soybeans by approximately 30 and 9%, respectively. The greater input of plant residues through intercropping temporarily reduces the lability of Po and Pi in the soil at 0-0.05 m depth, but does not limit P uptake by crops. Liming, regardless of the corrective used, increases the pool of Pi in the soil, specifically for labile forms due to the release of P linked to Al and Fe. Intercropping maize second crop with Brachiára and Sunn hemp is a good option for plant diversification in the area, increasing land use efficiency and SP sustainability in tropical agriculture, providing higher yields compared to the monoculture system.

Key words: crop straw inputs; silicate; ruzigrass; maize; soil organic phosphorus.

RESUMO

O manejo de solos tropicais intemperizados, com baixa disponibilidade de fósforo e presença de uma estação seca no inverno, é um desafio para favorecer os índices de matéria orgânica e melhorar a eficiência das adubações fosfatadas. O consórcio do milho segunda safra com plantas de cobertura tem melhorado a qualidade dos solos, potencializando o aporte de palhada no sistema de produção, favorecendo a ciclagem de nutrientes e eficiência no uso dos recursos naturais pelas culturas comerciais, aumentando a produtividade. Os efeitos de sistemas de cultivo consorciados na cultura de entressafra (outono-inverno) e as alterações da acidez do solo sobre a dinâmica de P no solo foram avaliadas em um experimento de blocos ao acaso em parcelas subdivididas. Sendo o sistema de cultivo milho solteiro ou consorciado com capim braquiária + crotalária considerados como as parcelas principais, e a correção de acidez através do silicato, calcário ou sem correção foram tratados como parcelas subdivididas. A soja é cultivada como cultura principal nas estações de verão. O cultivo consorciado de milho na entressafra aumenta em cerca de 30 e 9% o rendimento das culturas de milho e soja respectivamente. O maior aporte de resíduos vegetais através da consorciação reduz temporariamente a labilidade de Po e Pi do solo a 0-0,05 m de profundidade, más não limita a absorção de P pelas culturas. A calagem independente do corretivo utilizado, aumenta o pool de Pi do solo, especificamente para formas lábeis em decorrência a liberação de P ligado a Al e Fe. O consórcio de milho segunda safra com braquiára e crotalária é uma boa opção para diversificação de plantas na área, aumentando a eficiência do uso da terra e a sustentabilidade do SP na agricultura tropical, proporcionando maiores produtividades em comparação com o sistema monocultivo.

Palavras-chave: resíduos vegetais; silicato; braquiária; milho; fósforo orgânico do solo.

SUMMARY

GENERAL INTRODUCTION

Population growth in the world, expected to reach 11 billion people in 2100, puts pressure on agriculture to increase food production with economic efficiency and socio-environmental responsibility, avoiding the depletion of natural resources (FOOD AND AGRICULTURE ORGANIZATION [FAO], 2018; WITHERS et al., 2018). The increase in demand for food in the world has triggered a greater need for the supply of phosphate fertilizers to agriculture, leading to the depletion of its reserves, where projections point to the depletion of 60% of this resource by 2100 (CORDELL; DRANGERT; WHITE, 2009; VAN VUUREN; BOUWMAN; BEUSEN, 2010).

Brazil currently produces 312 million tons of grains, 491% more compared to the 1980s (COMPANHIA NACIONAL DE ABASTECIMENTO [CONAB], 2023). Growing food production simultaneously led to an increase in fertilizer consumption, reaching values above 410% compared to the same period, with consumption of 41 million tons in 2022, with 67% of all P2O5 consumed coming from foreign sources (NATIONAL ASSOCIATION FOR DIFUSION OF FERTILIZERS [ANDA], 2019).

The high consumption of phosphate fertilizers is related to the characteristics of extremely weathered tropical soils, such as low levels of organic matter and high concentrations of iron (Fe) and aluminum (Al) oxides, which provide a high phosphorus adsorption capacity, reducing about 80% the efficiency of phosphorus fertilization (VOLKSWEISS; RAIJ, 1977; SANTOS et al., 2018). Due to these characteristics, it is common to consume high rates of phosphate fertilizers to overcome the processes of immobilization of the element in the soil and supply the nutritional demand of crops. As a result of this process, since the 60s, it is estimated that more than 22 million tons of P have been adsorbed in Brazilian soils, resulting in an increase in the reserve of this element in the soil, but with fractions not available to plants (CUNHA et al., 2014; WITHERS et al., 2018). Due to the important role that P plays in the plant cell, the restriction of its availability impairs the development and productivity of cultures (MARSCHNER, 2011), making it necessary to increase its supply.

However, it is noteworthy that the increase in the recommended doses of P directly impact the production costs of crops, whose nutritional management corresponds to values above 30% in the total cost for the production of commodities such as soybeans and corn (CONAB, 2016; HIRAKURI; ALVES; MONTAGNER, 2018). Considering that 67% of P consumption comes from imports, combined with the fact that it is a finite resource, the increase in demand for P raises concerns about its scarcity and cost of acquisition, making essential improvements in the efficiency of use of this nutrient by plants and obtaining more sustainable alternatives to favor greater P availability (WITHERS et al., 2018). Among the alternatives, one can mention the use of soil acidity correctives and the diversification of crops with species that provide a large amount of straw on the soil.

Among the management methods for chemical correction of the soil, the use of limestone revolutionized agriculture in acid soils, due to the increase of OH- ions in the soil solution, allowing an increase in pH, precipitation of Fe and Al, reducing the complexation and precipitation of anions phosphates and also promoting the deprotonation of hydroxyls in clays, which reduces the adsorption sites and increases the available P content in the solution, in addition to acting as a source of Ca and Mg and reducing problems with toxicity of plants to Al and Mn (NOVAIS; SMYTH, 1999).

In addition to limestone, acidity correction can be performed using calcium and/or magnesium silicates. These silicates are minerals with the structure and composition of wollastonite (CaSiO3), belonging to the pyroxene group, which allow them to be used in agriculture not only to correct acidity, but also as a source of calcium and silicon for plants with low acquisition costs. (MARTINS et al., 2010; CASTRO; CRUSCIOL, 2013).

The solubility and concentration of nutrients in silicates depend on the origin and industrial process to which the mineral is subjected, and the finer the final product, the greater its solubility, reaching up to 6.78 times greater dissolution than limestone, giving in these conditions greater mobility in the soil (ALCARDE; RODELLA, 2003; DATNOFF; RODRIGUES; SEEBOLD, 2007; PEREIRA et al., 2009).

Silicon in the soil solution, in the pH range between 4.0 and 6.5, is found as monosilicic acid [Si (OH)4], which is absorbed by plants (EPSTEIN; BLOOM, 2006). In the soil, transformation to H3SiO4- occurs, competing for the same P adsorption sites in the mineral fraction, with specific adsorption occurring on the Fe oxide surfaces, so that Si can desorb P from colloids into the soil solution, and vice versa. -versa, reducing phosphate fixation and making it more available to plants (OBIHARA; RUSSEL, 1972; CARVALHO et al., 2000; DEMATTÊ et al., 2011). In the work carried out by Castro et al. (2016), silicating provided an increase in the availability of P in the soil and allowed an increase in the foliar P content in the soybean crop. Therefore, although there is evidence of greater availability of P in the soil through the use of silicates, the evaluation of this practice in long-term experiments becomes even more relevant, especially in association with diversified production systems that favor a high supply of straw, such as is the case of the consortium.

In addition to acidity correction, management techniques that contribute to the production of straw allow increases in the levels of organic matter in the soil, which makes the environment less oxidative and decreases the processes of P fixation (COSTA, 2000). In addition, the high production and permanence of straw on the soil surface contribute to the availability of P, due to the increase in the concentration and release of organic acids (AO) of low molecular mass in the soil. These acids participate in several reactions in the soil: Al complexation and reduction of its toxicity, ion adsorption, occupation of phosphate adsorption sites, chemical constitution of the rhizosphere and Ca leaching in the soil (FRANCHINI et al., 2003). The ability of AO to compete with P sources for adsorption sites depends on their composition, concentration, persistence of these anions in the soil and soil pH (STEVENSON, 1967).

For the availability of P through organic matter, by increasing the negative charges in the soil and reducing the sites of phosphate adsorption, the sorption and desorption of P depends on the persistence of organic carbon in the soil, which is governed by microbial activity, metabolic availability of carbon substrate and sorption to soil colloids (PAVINATO; MERLIN; ROSOLEM, 2008). The most active AO are citrus, oxalic, gluconic, lactic and malic, which chelate Fe and Al oxides, increasing P solubility in the soil, a fact that also occurred in the presence of humic and fulvic acids. In addition to these, Ca phosphates in the presence of carbonic acid formed from microbial and root respiration can also be solubilized, making the retained P available (GUPPY et al., 2005). The sorption of simple AO follows the preferential sequence for the adsorption sites: phosphate >>> oxalate > citrate > malate >> acetate (GUPPY et al., 2005).

In the process of solubilization and mineralization of P in the soil, bacteria and fungi are closely linked to these processes, composing the biogeochemical cycle of this nutrient, whose dynamics is dependent on the production system (RICHARDSON, 2001). The way plants acquire P can be modulated by microorganisms, through mycorrhization, release of phytohormones, excretion of AO and protonation, production of siderophores and phosphatase enzymes (CARDOSO; ANDREOTE, 2016). Thus, production systems that promote plant diversification, such as intercropping, can favor soil microbiota and, consequently, greater release of P to crops.

The adoption of vegetation covers in integrated grain production systems enhances the cycling of nutrients, which recover part of the fixed or precipitated P, subsequently making it available to successive crops. As an example, the cultivation of Urochloa ruziziensis favors the availability of P in the soil. In addition, this forage provides an increase in the levels of this element in the humic fraction of the soil, keeping it in organic fractions and reducing adsorption processes (MERLIN; HE; ROSOLEM, 2014). In intensive grain production systems in regions with a dry winter, maintaining the vegetation cover on the ground is a difficulty, which can be overcome by intercropping maize with Urochloa. This practice favors greater accumulation of straw, increased levels of organic matter, pH, P availability and base saturation (CRUSCIOL et al., 2015). In addition to the intense development of the root system of these forages and their ability to solubilize non-labile forms of P, it provides greater accessibility and absorption of this nutrient by plants, favoring cycling and availability for cultures in succession (ALMEIDA; ROSOLEM, 2016).

However, up to 80% of all organic phosphorus (Po) is found in forms not available to plants, such as monoester orthophosphates, formed by inositol phosphates from mono to hexa, including myo-inositol hexaphosphate acid, called of phytic acid (MAGID; TIESSEN; CONDRON, 1996). Inositol phosphates accumulate in the soil due to their adsorption to colloids and the formation of precipitates with insoluble salts, which reduces their biodegradation through enzymes called phytases (OGNALAGA; FROSSARD; THOMAS, 1994; TURNER et al., 2002; TANG et al., 2006). Citrate, followed by oxalate and malate, released from plant roots, are the most efficient for the solubilization of more stable forms of Po, capable of hydrolyzing forms of phytates that are precipitated with Al and Fe, releasing P (TANG et al. ., 2006). Thus, measures that allow the cycling of P retained in phytate forms, such as phytase secretion and AO production, can impact on the management of phosphate fertilization due to the increase of Pi in the soil, enhancing the rate of absorption by plants.

In the soil, P is found in the most varied forms of Po and Pi, grouped in labile, moderately labile and non-labile forms. Therefore, in order to know the influences of the different production systems on the P lability in the soil, the fractionation method proposed by Hedley, Stewart and Chauhan (1982) allows the understanding of this dynamic, considering its different fractions. From a sequential extraction, it is possible to separate Po from Pi, depending on the chemical stability of P in relation to specific reagents (SHARPLEY, 1995). Thus, changes in the dynamics of soil P forms depend on the management system, the amount of P exported at harvest, the replacement rate of P exported from the system, and the ability of plants to utilize P reserves in less labile forms. (TIECHER; SANTOS; CALEGARI, 2012).

The fractionation of P in the soil was studied by Pavinato, Merlin and Rosolem (2008), with the addition of different organic compounds extracted from plant species, allowing to verify that the different compounds led to the accumulation of Pi in the labile and moderately labile fraction, up to 5 cm deep; they also found that plants with a higher concentration of malic acid provided a higher level of P available in the soil. Therefore, it is assumed that the different production systems provide differentiated adsorption and solubility of P, depending on the specificities of crop rotations over time. This will make it possible to infer which systems will reduce the need for phosphorus fertilization due to greater efficiency in the use of P, thus promoting greater sustainability.

Based on the aforementioned reports, it appears that studies on processes involving P dynamics in long-term experiments conducted under conservationist management, in addition to being important, are scarce in Brazil. Understanding the availability of P to plants involving diversity of species for soil cover is still rare, as it involves interactions between production systems and the biogeochemical cycle of this element. Therefore, it is proposed that the study in experiments with long-term production systems can contribute to the understanding of these dynamics involved.

CHAPTER 1

SOIL PHOSPHORUS DYNAMICS UNDER LONG-TERM NO-TILL WITH OFF-SEASON INTERCROPPING SYSTEM[1]

Abstract

A long-term no-till study was conducted to determine whether off-season intercropping systems with maize as the cash crop increase crop residue inputs, soybean yield and soil P lability. The experiment was conducted between 2019 and 2021 in a randomized complete block design with four replications and four cropping systems in the off-season (fall-winter): maize alone; maize + palisade grass (*U. brizantha*); maize + sunn hemp (*C. spectabilis*); and maize + palisade grass + sunn hemp. Leaf P content, crop residues and soybean and maize yields were analyzed, and chemical P fractionation was performed at soil depths of 0-0.05, 0.05-0.1 and 0.1-0.2 m. The intercropping systems affected the labile and moderately labile P pools at a depth of 0-0.05 m. On average, the intercropping systems decreased soil inorganic P (Pi) extracted by anion exchange resin (Pi_{AER}) by 26% compared to maize alone. By contrast, the intercropping systems increased moderately labile organic P (Po) while simultaneously reducing the Pi pool. The changes in the Po pool suggest that intercropping palisade grass or sunn hemp with maize reduces Pi sorption by increasing Po in the soil. Intercropping palisade grass enhanced the yield of the main crop, i.e., soybean, but limited maize yield, presumably by creating an insufficient N supply for maize.

Key words: crop straw; off-season crop rotation; P fractionation; soil P lability.

1.1 INTRODUCTION

The main sources of P for fertilizer production are finite and non-renewable (Ashley et al., 2011), which is a growing concern for crop and food security (Chowdhury et al., 2017). In weathered tropical soils, P is the most limiting nutrient for crop production and cropping system sustainability (Pavinato et al., 2020). Hence, it is essential to improve P use in cropping systems in tropical regions (Rigon et al., 2022).

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One strategy for enhancing soil P use efficiency (PUE) is to add cover crops in rotation under no-tillage (NT) (Soltangheisi et al., 2018, 2019; Rodrigues et al., 2021). Cover crop species vary in their ability to acquire less labile soil P pools (Tiecher et al., 2012; Hallama et al., 2019). Moreover, some cereal/legume intercropping systems may substantially modify soil P availability over time (Tiecher et al., 2015; Teles et al., 2017; Tang et al., 2021). The release of P from crop residues under NT management depends on the forms of P accumulated in plant tissues (Oliveira et al., 2017) and on general residue quality, such as N content, C-N ratio, lignin-N ratio, and cellulose and hemicellulose contents (Rigon et al., 2022). Hence, soil P cycling varies according to the crop species and its residue production (Tiecher et al., 2015). In general, legumes promote the efficient utilization of P from the soil/fertilizer in acidic soils (Hedley et al., 1995), whereas grasses can explore deeper soil layers and recycle more P in the whole system (Almeida and Rosolem, 2016).

The positive effects of intercropping on resource use efficiency in agroecosystems (Tang et al., 2021) are driven by two main processes: i) resource partitioning between crops, which reduces crop competition (Fridley, 2001), and ii) positive interactions that alter the environment and enhance resource availability (Callaway, 2007). These processes vary depending on differences in rooting pattern or depth interactions between species or differences in P demand during plant growth (Hinsinger et al., 2011; Yu et al., 2015).

Soil organic carbon cycling controls biological P availability (Rheinheimer et al., 2019). Consequently, crop rotation systems comprising different species alone and/or intercropped under long-term NT are expected to impact soil P dynamics. We hypothesized that i) soil P lability is influenced by intercropping systems and ii) intercropping maize with palisade grass or sunn hemp in the off-season increases the soil organic P (Po) pool. To test these hypotheses, the present study assessed changes in soil P dynamics in different cropping and intercropping systems under long-term NT.

1.2 MATERIALS AND METHOD

1.2.1 Site characteristics

The experiment was initiated in 2006 at the Lageado experimental farm in Botucatu, São Paulo State, Brazil (48º 23' W, 22º 51' S, 765 m above sea level). The soil is a clayey Rhodic Hapludox (Soil Survey Staff, 2014) containing 440 g kg^{-1} clay, 469 g kg^{-1} sand and 91 g kg^{-1} silt at a depth of 0–0.2 m. The climate is highland tropical, with dry winters and wet, rainy summers (Figure 1). At the time of experiment establishment in 2006, the chemical properties of the soil in the 0–0.2 m layer as analyzed according to Raij et al. (2001) were as follows: soil organic matter = 18 g dm^{-3}; pH = 4.2 (1:2.5 soil:0.01 mol L^{-1} $CaCl_2$ suspension); P resin = 4 mg dm^{-3}; exchangeable K = 0.8 $mmol_c$ dm^{-3}, Ca = 12 $mmol_c$ dm^{-3}, Mg = 6 $mmol_c$ dm^{-3}; total acidity at pH 7.0 (H+Al) = 54 $mmol_c$ dm^{-3}; and base saturation = 24%.

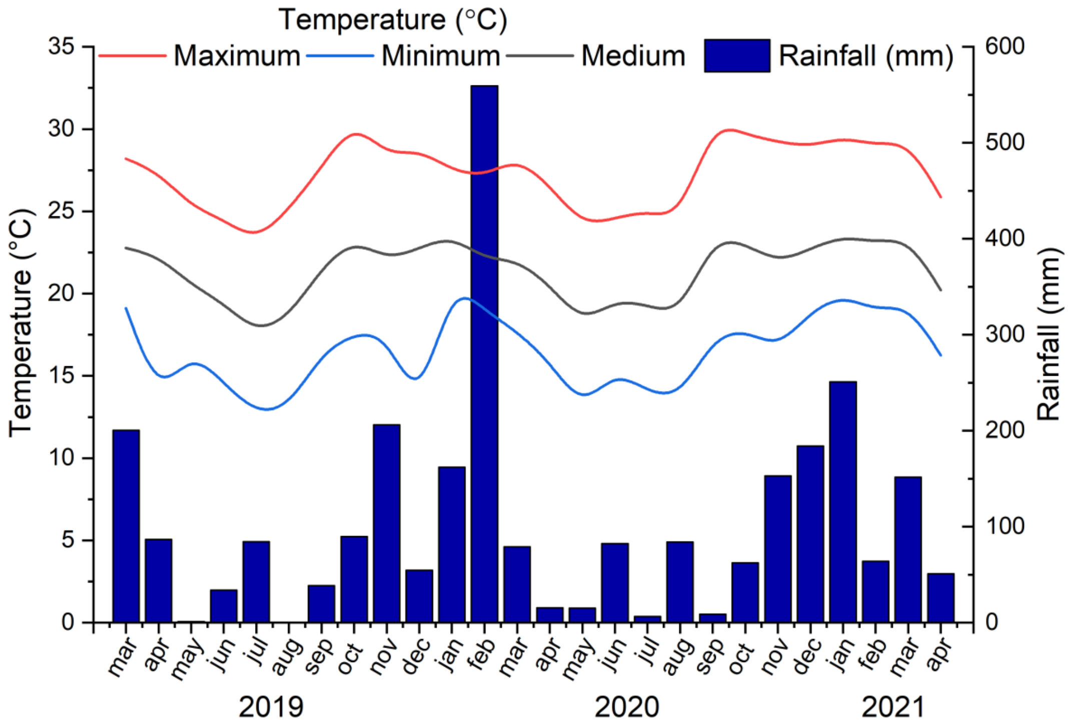

Figure 1. Average monthly maximum (red line, ˚C), minimum (blue line, ˚C), and medium temperature (black line, ˚C) and monthly rainfall (blue bars; mm) at the weather station located at Botucatu, Brazil.

1.2.2 Experimental design

The experiment was arranged as a randomized complete block design with four replications and four different cropping systems in the off-season/winter season with the same summer crop cultivated each year from 2007 to 2017. The summer grain crop choices were chosen based on the major crops cultivated in the Cerrado region according to the table 1.

Table 1. Cropping rotations since 2007 according to the off-seasons (fall-winter) and growing season (summer season).

year	**Season**	**off-season**	**Season**	**off-season**	**Season**	**off-season**	**Season**	**off-season**
	crop rotation I		**crop rotation II**		**crop rotation III**		**crop rotation IV**	
2006/07	Soy	fallow	Soy	Ruzigrass	Soy	pearl millet	Soy	Oat
2007/08	maize	fallow	Maize	Ruzigrass	Maize	Pigeon pea	maize	Bean
2008/09	Rice	fallow	Rice	Ruzigrass	Rice	sunn hemp	Rice	castor bean
2009/10	Soy	fallow	Soy	Ruzigrass	Soy	pearl millet	Soy	Sorghum
2010/11	maize	fallow	Maize	Ruzigrass	Maize	Lupine	Maize	Crambe
2011/12	Bean	fallow	Bean	Palisadegrass	Bean	pearl millet	Bean	Wheat
2012/13	Rice	fallow	Rice	Palisadegrass	Rice	sunn hemp	Rice	Wheat
2013/14	Soy	fallow	Soy	Palisadegrass	Soy	Fallow	Soy	Pousio
2014/15	Maize	fallow	Maize	Palisadegrass	Maize	Oat	Maize	Triticale
2015/16	Bean	fallow	Bean	Palisadegrass	Bean	pearl millet	Bean	Wheat
2016/17	Rice	fallow	Rice	Fallow	Rice	Fallow	Rice	Fallow
2017/18	Fallow	fallow	fallow	Fallow	Fallow	Fallow	Fallow	Fallow
2018/19	Soy	Maize	Soy	maize + Pg	Soy	maize + Sh	Soy	maize + Pg + Sh
2019/20	Soy	Maize	Soy	maize + Pg	Soy	maize + Sh	Soy	maize + Pg + Sh
2020/21	Soy	Maize	Soy	maize + Pg	Soy	maize + Sh	Soy	maize + Pg + Sh
2021/22	Soy	Maize	Soy	maize + Pg	Soy	maize + Sh	Soy	maize + Pg + Sh

Footnote: Soy, soybean; Pg, palisadegrass; Sh, sunn hemp.

In November 2018, soybean was sown in the total area. In March 2019, the cropping off season were altered to cropping system I) maize alone; II) maize + palisade grass (*U. brizantha*); III) maize + sunn hemp (*C. spectabilis*); and IV) maize + palisade grass + sunn hemp. Soybean was cropped as the main crop in the summer thereafter. A graphical scheme of the treatments is shown in figure 2.

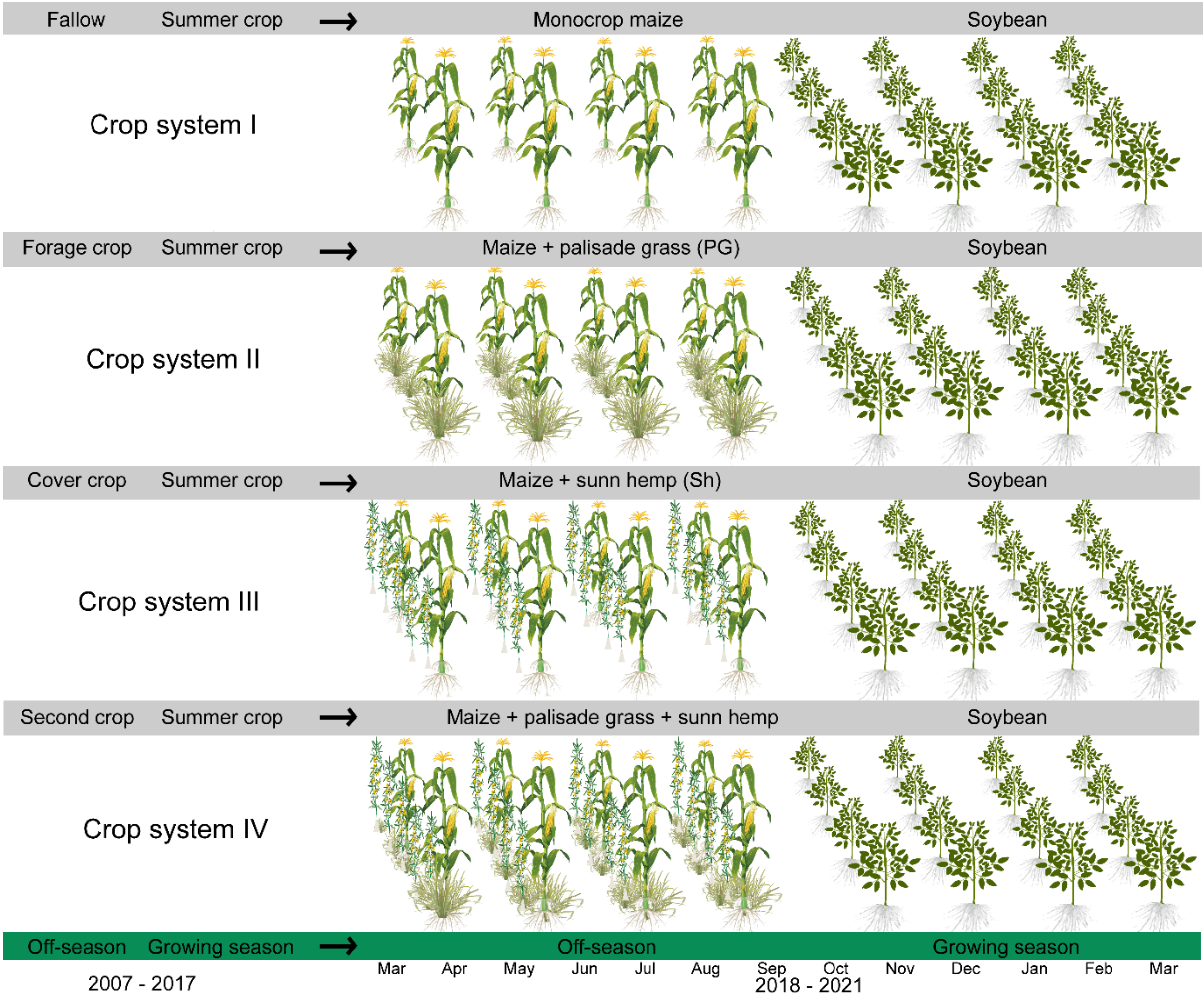

Figure 2. Schematic representation of the study timeline showing the cropping systems.

All cropping systems were managed under NT. Each plot had an area of 54 m^2 (5.4 m x 10 m). One row on each side of the plot and one meter at both edges were considered buffer zones and were not sampled.

Over the first 11 years of the field experiment, the soil was amended with calcium and magnesium silicate (SiO_2 = 220 g kg^{-1}) to increase the base saturation (BS) to 70%. The amendments were applied mechanically to the soil surface in October 2006 (before sowing the first crop), 2011, 2015, and 2018 (before sowing the summer crop) based on the results of BS determination (Raij et al., 1997). Adequate rates of NPK fertilizers were applied to the summer crops according to the results of soil chemical analyses and crop recommendations.

1.2.3 Planting and harvesting

At the time of installation of the experiment in 2018, the chemical properties of the soil in the 0–0.2 m layer as analyzed according to Raij et al. (2001) were as follows: soil organic matter = 27 g dm^{-3}; pH = 4.5 (1:2.5 soil:0.01 mol L^{-1} $CaCl_2$ suspension); resin P = 20 mg dm^{-3}; exchangeable K = 3.30 mmolc dm^{-3}, Ca = 31 mmolc dm^{-3}, Mg = 21 mmolc dm^{-3}; total acidity to pH 7.0 (H+Al) = 42 mmolc dm^{-3}; base saturation = 57%, CEC = 98 mmol dm^{-3}; clay = 63%; silt = 9%; sand = 28%.

The experiment began in November 2018 with the sowing of soybean (CD 2728 IPRO) in the total area after the application of calcium and magnesium silicate. The soybean was harvested in March 2019, and soybean cultivar TMG 7062 IPRO was planted on 12 November 2019 and 26 October 2020 and harvested on 15 March 2020 and 25 February 2021. Both of these soybean crops were fertilized at sowing with 20 kg ha^{-1} N, 50 kg ha^{-1} P_2O_5 and 150 kg ha^{-1} K_2O. After the soybean harvest, maize hybrid P3707 VYW was sown on 17 March 2019 and 23 March 2020 and harvested on 8 May 2019 and 6 may 2020. For both maize crops, 22 kg ha^{-1} N, 78 kg ha^{-1} P_2O_5 and 45 kg ha^{-1} K_2O were supplied in the maize sowing furrow. When the maize plants had 6 fully expanded leaves, N fertilization was performed at 90 kg ha^{-1} with ammonium sulfate. In system I, maize was not intercropped, and the area was fallow during the off-season. In system II, forage was sown simultaneously with the maize grain harvest at 8 kg of seeds ha^{-1}; the seeds were mixed together with the fertilizer a few hours before sowing. To sow the green fertilizer *Crotalaria spectabilis* in system III, the third box of the seeder (additional box of seeds) was used, and the seeds were sown at 17 kg ha^{-1} simultaneously with maize. In system IV, i.e., the maize + palisade grass + sunn hemp triple intercropping system, sowing was performed under the same conditions as for maize alone. Palisade grass was mixed with the fertilizer and sown at 8 kg ha^{-1}, and sunn hemp was sown at 17 kg ha^{-1} using the additional seed box.

1.2.4 Crop analyses

To evaluate the contributions of the crop residues from the cover crops intercropped with maize, samples of the crop residues were collected before soybean sowing, at the time of desiccation, i. e. 25 days before soybean sowing. Three subsamples were taken randomly from each subplot using a wooden square (0.25 ×

0.25 m). The collected material was dried until reaching a constant weight in a forced-air circulation oven at 65 °C and used to analyze dry matter and cumulative P content (Malavolta et al., 1997).

During the flowering periods of soybean and maize, leaf P levels were determined following the methodology proposed by Ambrosano et al. (1997) and Malavolta et al. (1997). For soybean, thirty samples of the third trefoil completely expanded from the apex were collected from each plot in the R2 stage. For maize, 30 samples of the leaf below and opposite the main ear were collected at the beginning of flowering.

Maize and soybean were harvested mechanically with a plot combine (NM Elite, Wintersteiger Seed Mech), and the crop yields were adjusted to 13% moisture. The P levels in the harvested maize and soybean grains (2019/2020 and 2020/2021 harvests) were analyzed according to the methodology of Malavolta et al. (1997). Soybean and maize grain P outputs were calculated by averaging the grain yields from both seasons (2019/2020, and 2020/2021) and multiplying the average grain yield by the P content.

1.2.5 Soil analysis

Three soil subsamples were collected in October 2021 from each experimental unit at a depth of 0–0.05; 0.05-0.1; 0.1-0.2 m, air-dried and sieved (2 mm). Chemical P fractionation was performed according to (Hedley et al., 1982) as modified by (Rheinheimer et al., 2000), changing the original sonication step to 0.5 M NaOH extraction. Soil P fractions were grouped into pools according to their potential plant lability (Cross and Schlesinger, 1995): “labile P” (PiRTA + PiBIC + PoBIC), “moderately labile P” (PiHID0.1 + PoHID0.1 + PiHCl) and “non-labile P” (PiHID0.5 + PoHID0.5 + P residual).

1.2.6 Soil analysis

Three soil subsamples were collected in October 2021 from each experimental unit at depths of 0–0.05, 0.05–0.1, and 0.1–0.2 m, air dried, and sieved (2 mm). Chemical P fractionation was performed according to Hedley et al. (1982) as modified by Rheinheimer et al. (2000), i. e., the original sonication step was replaced with extraction with 0.5 M NaOH. The soil P fractions were grouped into pools according to their potential lability (Cross and Schlesinger, 1995): labile P (Pi_{RTA} + Pi_{BIC} + Po_{BIC}), moderately labile P ($Pi_{HID0.1}$ + $PoH_{ID0.1}$ + Pi_{HCl}), and non-labile P ($PiH_{ID0.5}$ + $PoH_{ID0.5}$ + P residual), and to the organic and inorganic pools to the graphs.

1.2.7 Statistical analysis

All statistical analyses were performed using SAS. All data were tested for normality with the Shapiro–Wilk test in the UNIVARIATE procedure. Data were analyzed using the MIXED procedure (mixed linear model), while the Satterthwaite approximation was used to determine denominator degrees of freedom to test fixed effects. Cropping systems was considered fixed effect. Blocks were treated as a random effect. The least significant difference (LSD) test was used to separate means through the LSMEANS procedure at $p \leq 0.1$.

1.3 RESULTS

1.3.1 Crop residue inputs from intercropping

The cumulative crop residue on the soil surface and the residue P content differed significantly ($p<0.1$) depending on the crop species intercropped with maize (Table 2). The average crop residue on the soil surface was 10 Mg ha^{-1}. Surprisingly, intercropping sunn hemp with maize did not significantly affect the crop residue on the soil surface, whereas intercropping palisade grass with maize increased the crop residue by an average of 144% compared with maize alone. Intercropping both palisade grass and sunn hemp with maize increased crop residue by 109% ($p<0.1$) compared with intercropping only palisade grass with maize.

Table 2. Crop residue amount, phosphorus (P) content and cumulative input.

Cropping System	Crop residue amout	P content	cumulative P input
	(Kg ha^{-1})	(g kg^{-1})	(kg ha^{-1})
Maize alone	5,930 c	-	-
Maize + Pg†	12,404 b	1.92 a	23.82 a
Maize + Sh‡	7,170 c	1.70 a	12.19 b
Maize + Pg + Sh	14,476 a	1.03 b	14.91 b
Cropping system	p value		
	<0.01	<0.01	0.01

*Means followed by different letters differed by the t test ($p \leq 0.1$).

†Pg: palisade grass; ‡Sh: sunn hemp.

On average, the crop residue P content was approximately 75% higher ($p<0.1$) when maize was intercropped with palisade grass or sunn hemp than when maize was intercropped with both crops. Intercropping maize and palisade grass resulted in a cumulative P input of 23.82 kg ha^{-1}, 76% higher than the average of the other two intercropping systems.

1.3.2 Grain and leaf P contents

The cropping systems influenced grain and leaf P contents only in the maize crop grown in 2020 (Table 3). In this season, the leaf P content in maize intercropped with palisade grass was 31% higher than the average of the other intercropped systems. By contrast, the grain P content in maize intercropped with sunn hemp was 30% higher than the average of the other cropping systems.

Table 3. Phosphorus content on leaf diagnosis and in grains of maize 2019 and 2020 and of soybean 2019/2020 and 2020/2021 as affected by cropping systems.

Crop season	Cropping systems				p value
	Maize sole	Maize + PG	Maize + Sh	Maize + Pg + Sh	
	mg kg^{-1}				
maize leaf 2019	2.32	2.30	2.37	2.07	0.18
maize leaf 2020	0.85 b	1.20 a	0.92 b	0.97 b	0.01
soybean leaf 2019/2020	4.49	4.64	4.17	4.20	0.55
soybean leaf 2020/2021	3.95	3.80	3.80	3.75	0.84
maize grain 2019	2.94	3.09	2.92	2.82	0.85
maize grain 2020	3.98 bc	3.62 c	5.09 a	4.16 b	<0.01
soybean grain 2019/2020	5.30	5.30	5.30	5.50	0.68

*Means followed by different letters in line differed by the t test ($p \leq 0.1$).

‡Pg: palisade grass; Sh: sunn hemp.

1.3.3 Soybean and maize yields

The average maize yield was ~4,800 kg ha^{-1} in 2019 and 2020. As the main crop, the average soybean yield was 3.547 and 5.084 kg ha^{-1} in the 2019/2020 and 2020/2021 seasons, respectively. The long-term cultivation system significantly affected ($p<0.1$) maize yield in the 2019 and 2020 off-seasons, soybean yield in the 2019/2020 season, and the cumulative yields of both crops (Figure 3).

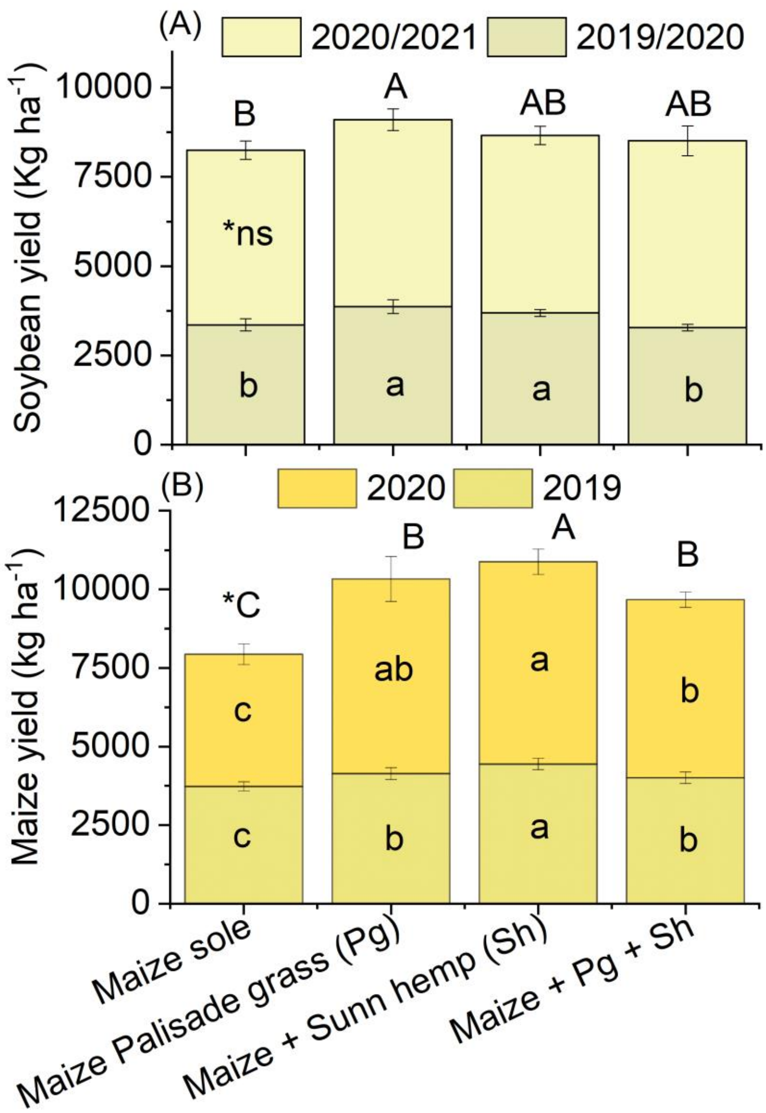

Figure 3. Soybean as a main crop and maize as off-season crop yield according to the cropping systems in 2019 and 2020 seasons. *Means followed by different letters differed by the t test ($p \leq 0.1$). Capital letters correspond to the cumulative data.

In the 2019 and 2020 off-seasons, maize yield was influenced by cropping system. In both harvests, the grain yield was highest when maize was intercropped with sunn hemp; in this cropping system, grain production was 19% and 53% higher than in the system with maize alone in 2019 and 2020, respectively. Compared with maize alone, intercropping maize with palisade grass increased the cumulative grain yield by 30%, and triple intercropping increased the cumulative grain yield by 22%. However, compared with the average of the other intercropped systems, triple intercropping reduced the cumulative grain yield by 10%.

For soybean grown in succession to maize, the different cropping systems influenced grain yield in the 2019/2020 harvest and cumulative grain yield. In the 2019/2020 season, soybean grain yield was highest after maize intercropped with palisade grass and maize intercropped with sunn hemp; in these cropping systems, soybean grain yield was 13% higher than in the system with maize alone and 15% than in the triple intercropping system. By contrast, the soybean grain yield in the 2020/2021 harvest did not differ between cropping systems. Compared with the system with maize alone, the cumulative soybean yield was 10% higher after maize intercropped with palisade grass.

1.3.4 Soil P pools

The cropping systems affected most of the soil P fractions in the labile and moderately labile pools at a soil depth of 0–0.05 m (Supplementary table). In the deeper soil layers, the cropping systems only affected Po_{NaHCO3} at 0.5-0.1 m and Pi_{AER} and $Pi_{NaOH0.1}$ at 0.1-0.2 m. On average, intercropping maize with palisade grass and/or sunn hemp significantly ($p<0.1$) decreased soil Pi_{AER} by 26% compared to maize alone. Interestingly, Pi_{AER} ($p<0.1$) and Pi_{NaHCO3} ($p=0.21$) decreased by 37% when maize was intercropped with sunn hemp. Among the moderately labile fractions, $Pi_{NaOH0.1}$ decreased ($p<0.1$) by 25%, on average, at a soil depth of 0-0.05 m when maize was intercropped, but opposite trends were observed in deeper layers. Compared to triple intercropping, cropping maize alone decreased $Pi_{NaOH0.1}$ by 35% and 25% at soil depths of 0.05-0.1 and 0.1-0.2 m, respectively, but only the difference in the surface layer was significant. At a soil depth of 0-0.05 m, cropping maize alone decreased ($p<0.1$) $Po_{NaOH0.1}$ by 28% and 37% compared to intercropping maize with sunn hemp or palisade grass, respectively, whereas $Po_{NaOH0.1}$ did not differ between maize alone and the triple intercropping system.

1.3.5 Soil P lability

The total soil P content did not differ between the cropping systems and averaged 936, 806, and 765 mg kg^{-1} in the 0-0.05, 0.05-0.1, and 0.1-0.2 m soil layers, respectively. In the surface soil layer, only 11.3% and 22.6% of the soil P stocks were allocated in the labile and moderately labile P pools, respectively (Figure 4). As expected, cropping systems impacted ($p<0.1$) soil P only in the upper soil layer (0-0.05 m). Regardless of the cropping system, intercropping palisade grass or sunn hemp reduced ($p<0.1$) soil labile and moderately labile P at a soil depth of 0-0.05 m (Figure 4A), driven mostly by inorganic P fractions (Figure 4B). A similar trend was observed in the inorganic non-labile pool (Figure 4D) but was not significant ($p=0.32$). Overall, the effects of the cropping systems differed depending on P pool lability: intercropping increased ($p<0.1$) moderately labile Po but slightly reduced ($p=0.12$) moderately labile Pi.

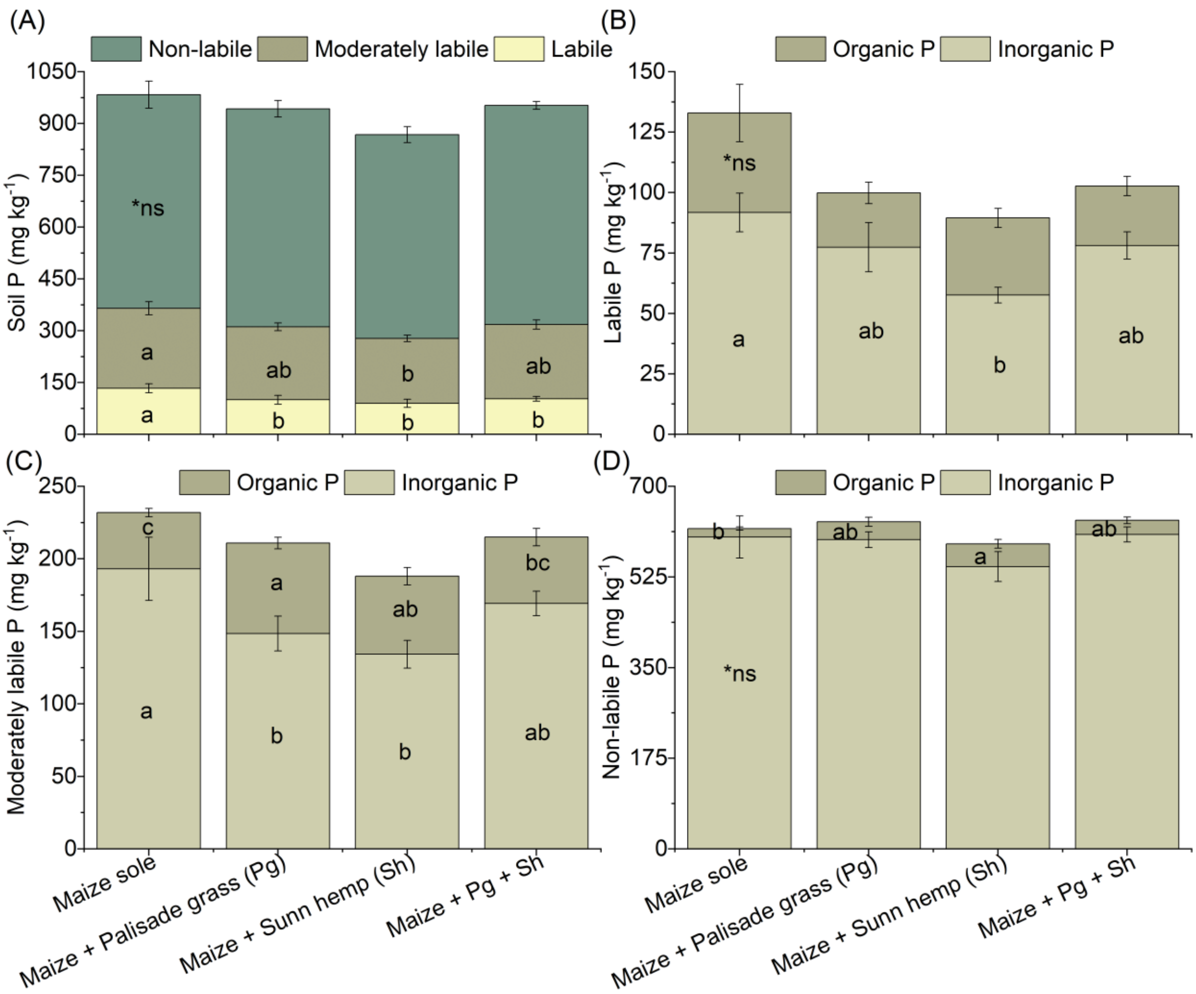

Figure 4. Soil P pools by lability (A), labile organic and inorganic P pool (B), moderately labile organic and inorganic P pool (C), and non-labile organic and inorganic P pool (D) at 0-0.05 m soil depth as affected by cropping systems.

*Means followed by different letters differed by the t test ($p \leq 0.1$). ns: not significant.

The contribution of soil labile P to P stocks was smaller in deeper soil layers but was not affected by cropping system. Intercropping maize with palisade grass reduced

(<0.1) the labile Po fraction by 58% at 0.05-0.1 m compared with intercropping maize with sunn hemp (Figure 5) and moderately labile Pi by 30% at 0.1-0.2 m (Figure 6) compared with triple intercropping.

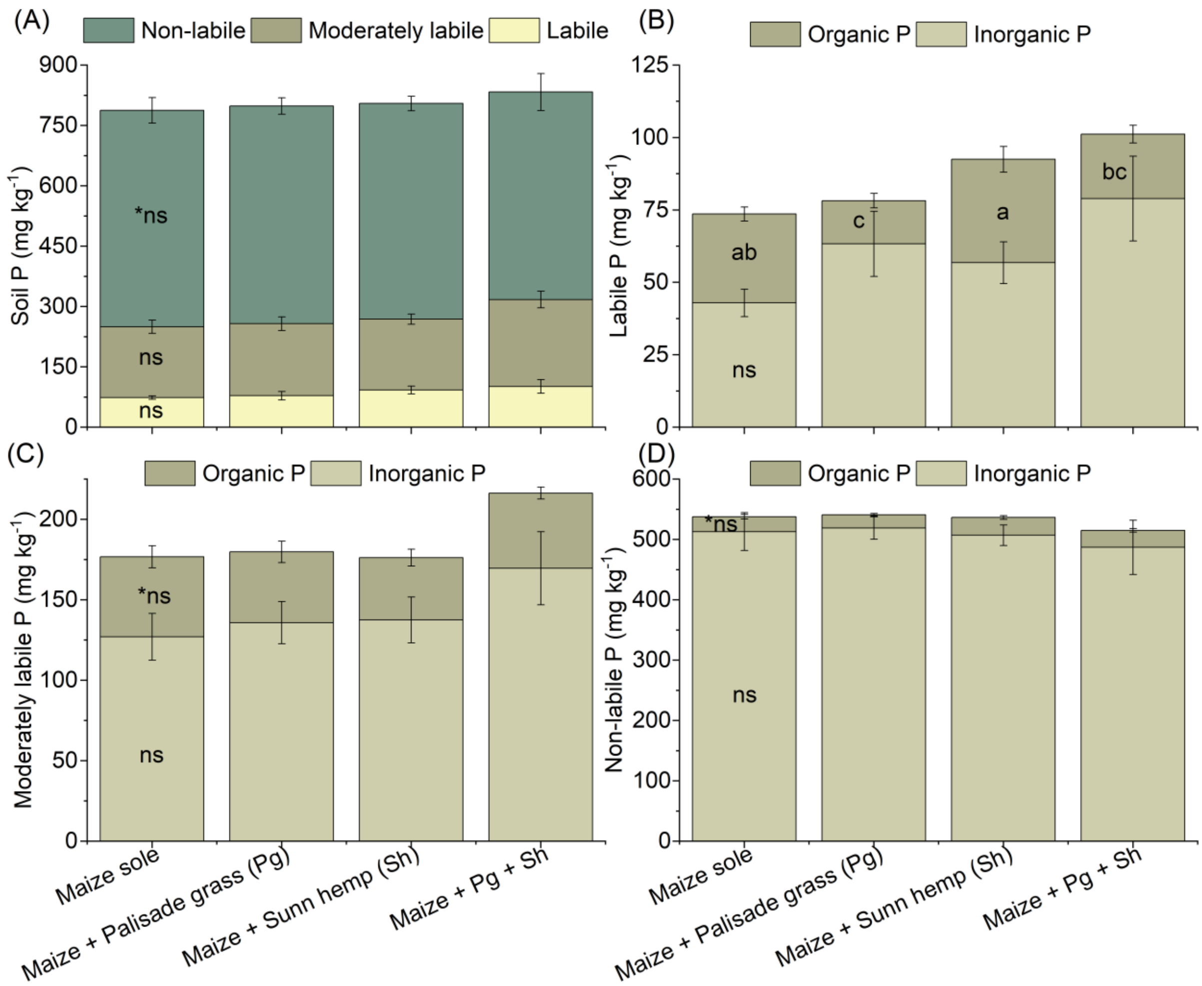

Figure 5. Soil P pools by lability (A), labile organic and inorganic P pool (B), moderately labile organic and inorganic P pool (C), and non-labile organic and inorganic P pool (D) at 0.05-0.1 m soil depth as affected by cropping systems.

*Means followed by different letters differed by the t test ($p \leq 0.1$). ns: not significant.

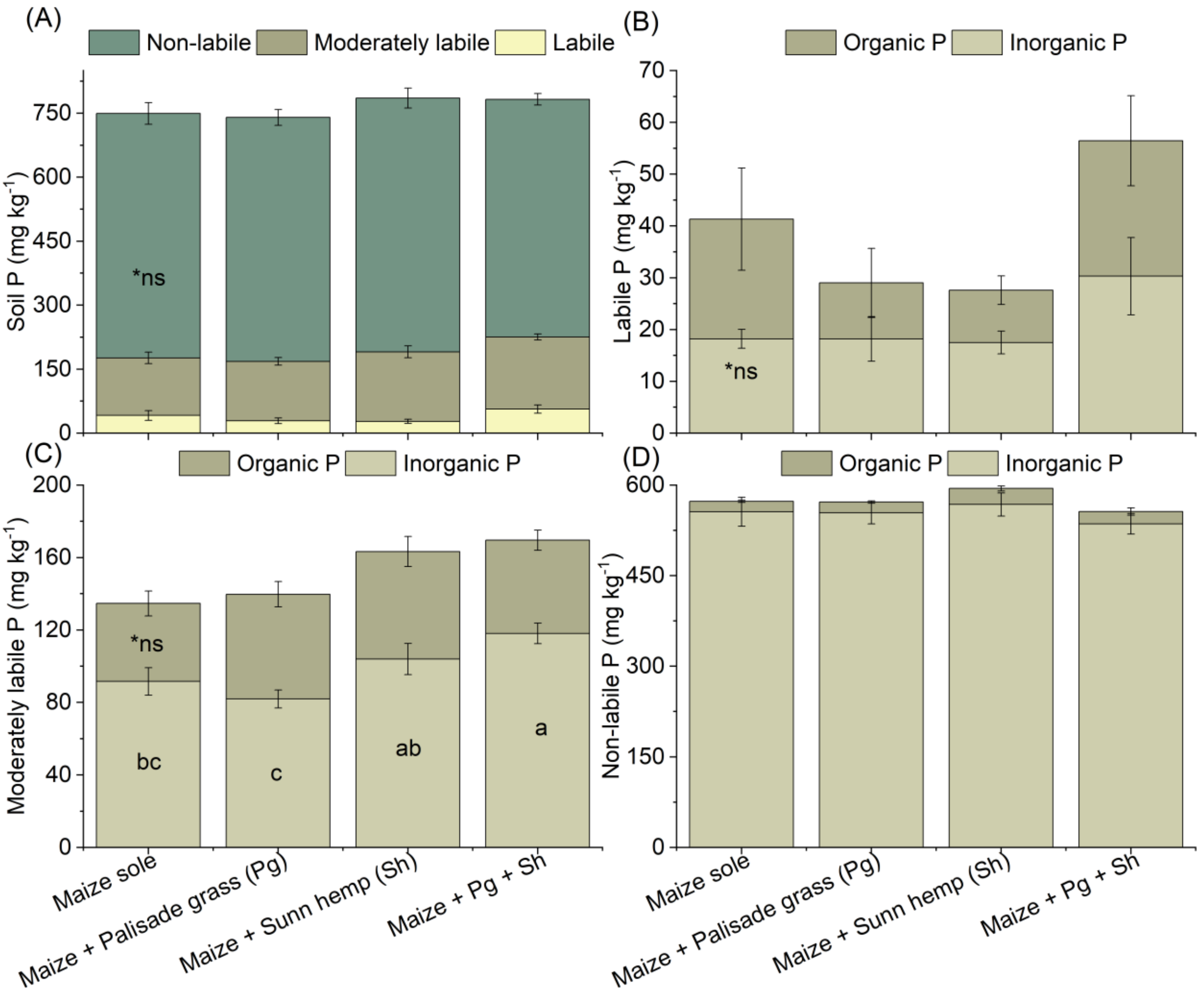

Figure 6. Soil P pools by lability (A), labile organic and inorganic P pool (B), moderately labile organic and inorganic P pool (C), and non-labile organic and inorganic P pool (D) at 0.1-0.2 m soil depth as affected by cropping systems.

*Means followed by different letters differed by the t test ($p \leq 0.1$). ns: not significant.

1.4 DISCUSSION

1.4.1 Crop residue inputs from intercropping

Intercropping systems are widely used to increase biomass production in the off-season in tropical soil, especially in regions with dry conditions (Crusciol et al., 2015). Under NT, residues on the surface of tropical soils decompose quickly, which increases the importance of enhancing crop biomass production (Lal, 2002; Ferrari Neto et al., 2020; Rigon and Calonego, 2020). Palisade grass has high biomass production capacity (Capstaff and Miller, 2018; Almeida et al., 2020); consequently, intercropping with forage greatly increased crop residue inputs compared with intercropping with sunn hemp. Legume species such as sunn hemp produce high-quality crop residues (Rigon et al., 2021), and intercropping maize with legumes can increase the supply of N to intensive production systems through biological fixation by the legume itself or the release of nitrogenous compounds from the decomposition of the legume's nodules and roots. However, legumes have low C/N ratios, which leads to rapid decomposition of their plant residues and reduced vegetation cover remaining on the soil (Kappes and Zancanaro, 2015).

The technical considerations for designing an intercropping system include competition for light, water and nutrients between plants, which can harm not only the productivity of the main crop but also the development of the cover crop (MacLaren et al., 2023). Because maize is a tall C4 crop with rapid initial growth, it is highly competitive with C3 species such as sunn hemp. In the intercropping systems evaluated in this work, residue accumulation was lowest when maize was intercropped with sunn hemp, with production similar to maize alone. The lower accumulation of plant residues in the sunn hemp intercropping system may reflect not only competition with maize for natural resources but also the sensitivity of sunn hemp to the photoperiod. For example, late sowing in the autumn-winter period can advance sunn hemp flowering by up to 30 days compared with summer sowing (Amabile et al., 1999; Timossi et al., 2011) found that sowing sunn hemp in March reduced dry matter accumulation by approximately 400% compared with sowing in November.

Compared with intercropping with sunn hemp, intercropping maize with palisade grass increased dry matter production. Arf et al. (2018) found that intercropping maize with palisade grass increased dry matter production by 23% compared with intercropping maize with sunn hemp. These increases are correlated with the greater ability of forage grasses to tolerate water deficits and with their high biomass production capacity (Foloni et al., 2008).

Biomass production was highest in the triple intercropping system, i.e., maize intercropped with both palisade grass and sunn hemp. Because the organic matter content of Brazilian soils is low, intercropping legumes in association with grasses tends to improve the soil N supply through the biological fixation of atmospheric N, thereby favoring biomass production by grasses (Cardoso and Andreote, 2016; Arf et al., 2018).

Although P content was high in both sunn hemp and palisade grass tissues, palisade grass had the highest cumulative P contribution due to its higher biomass production. Palisade grass has high P uptake efficiency, particularly in P-restricted soils, and improves plant-available P in long-term cultivation systems (Almeida et al., 2019, 2020). Our results show that plant P acquisition strategies and uptake capacities differ between cover crop species. By clearly highlighting the differences in P inputs between crop species intercropped with maize, this study provides a better understanding of the potential nutrient-cycling capacity of intercropping systems in tropical soils.

1.4.2 Grain and leaf P contents

In the 2019 season, maize leaf P content was within the range proposed for maize in all cropping systems and did not differ between cropping systems (Raij et al., 2001). By contrast, the cropping systems affected maize leaf P content in the 2020 season, but the values were below the ideal range for maize. The differences between seasons are likely attributable to differences in climatic conditions.

In 2020, maize leaf P content was highest when maize was intercropped with palisade grass and differed significantly between this cropping system and the other systems. This result is consistent with the high P accumulation and biomass production in this intercropping system. P is a component of protein modifications, and a portion of the P in soluble compounds may become available to successive crops, impacting leaf P levels (Mendonça et al., 2015). Leite et al. (2010) found that palisade grass accumulated 20.30 kg ha^{-1} P and released 63% of the total accumulated P within 100 days after desiccation. The P-cycling efficiency of palisade grass is further confirmed by the marked decrease in P export in maize grains in the system with maize intercropped with palisade grass. We assume that P export was lowest in this system because leaf P content was highest. However, increases in P content in maize grain are not always accompanied by corresponding increases in P content in straw (Xia et al., 2019).

1.4.3 Soybean and maize yield

In southern Brazil, dry conditions are typical during the fall/winter off-season (Cunningham, 2020). Water deficits may have intensified the competition between maize and palisade grass in the 2019 season, as these crops are physiologically similar (Vidal and Merotto Jr., 2010). Split application of N can increase the responses of both maize and forage grasses to N fertilization (Crusciol et al., 2020). Grass-grass rotations without N fertilization can promote significant N immobilization due to competition between plants and microorganisms (Kuzyakov and Xu, 2013), resulting in an insufficient N supply for maize intercropped with palisade grass. These effects may explain the increased yield of maize intercropped with sunn hemp; the introduction of this legume may have guaranteed a greater supply of N through biological fixation, ensuring greater N acquisition by the grass (i.e., maize) (Cardoso and Andreote, 2016).

The cumulative soybean yield was higher after maize intercropped with palisade grass than after maize alone, although soybean yield did not differ between the intercropping systems. The higher biomass production and P accumulation in straw in the intercropping systems may have improved soil quality and increased productivity (Chioderoli et al., 2012). For example, Calonego et al. (2011) reported that intercropping maize with ruzigrass reduced the mechanical resistance of the soil to penetration, improved soil structure and increased water availability in deeper soil layers. In addition, Crusciol and Borghi (2007) observed that intercropping maize with palisade grass increased soil organic matter content in deeper layers, soil pH, P availability and base saturation compared with cropping maize alone.

The contrasting effects of the cropping systems on the yields of the off-season and main crops highlight the importance of a holistic approach to cropping systems that does not focus solely on a specific crop.

1.4.4 Soil P pools

In the weathered tropical soils of the Cerrado, high annual P fertilization (± 50 kg P ha^{-1}) offsets the high P immobilization potential (Withers et al., 2018) and ensures adequate soil available P (P_{AER} averaged at a soil depth of 0-0.1 m) for main crops (Raij et al., 2001; Souza and Lobato, 2004). The soil P pools at the soil surface (0-0.05 m soil depth) confirmed the high soil P immobilization in the upper layers and the lack of downward movement (Soltangheisi et al., 2018). Compared with maize alone, the intercropping systems depleted P_{AER} at a soil depth of 0-0.05 m, which is attributable to higher crop uptake of P from fertilizer and temporary accumulation in crop residues (Rodrigues et al., 2021; Rigon et al., 2022). Pi_{BIC} was also depleted, indicating the transformation of relatively labile Po into Pi (Almeida and Rosolem, 2016; Rodrigues et al., 2021). These results suggest that the intercropping systems increased Pi immobilization to aid residue decomposition, as confirmed by the low labile Po (Rodrigues et al., 2016). Crop residue mineralization under NT occurs via transient microbial immobilization, which avoids faster Pi adsorption (Martinazzo et al., 2007), an important process in Oxisols.

Confirming our hypothesis, $Po_{NaOH\ 0.1M}$ was highest and $Pi_{NaOH\ 0.1M}$ was lowest when maize was intercropped with palisade grass or sunn hemp. Maize leaf P content was also highest in these two systems, demonstrating the influence of P availability on P uptake. Organic acids exuded from the roots of companion crops can promote the solubility of poorly labile P forms (Pavinato et al., 2008). Intercropping perennial grasses improves the Po pool through root development and organic acid exudates (Almeida et al., 2020; Almeida and Rosolem, 2016). Organic acids compete with P for adsorption sites on soil surfaces, thereby reducing P adsorption (Condron et al., 2005). The addition of legumes to rotation systems also affects the soil Po pool (Rigon et al., 2022). Consistent with the effects of intercropping maize with sunn hemp, cereal-legume intercropping systems have been shown to promote P uptake by the intercropped P-inefficient crop (Li et al., 2004; Yang et al., 2022). The results confirm that crop species impact soil P cycling, P use efficiency, and organic P pools in cropping systems (Teles et al., 2017; Soltangheisi et al., 2018; Hallama et al., 2019; Rigon et al., 2022).

A low contribution of Ca-precipitated P (P_{HCL}) on total soil P was expected because this P pool is more important in temperate soils (Jin et al., 2021). $P_{residue}$, which has been reported to function as a P input sink (Deiss et al., 2016; Soltangheisi et al., 2018; Rodrigues et al., 2021; Rigon et al., 2022), accounted for almost half of the soil P stocks but was not affected by the cropping system. Similarly, the cropping systems did not affect recalcitrant Pi and $Po_{NaOH0.5}$ pools.

1.4.5 Soil P lability

Our results show that long-term cropping systems can effectively change soil P lability, mainly at a soil depth of 0-0.05 m, thus partially confirming our hypothesis. We anticipated that after 14 years, the cropping systems under NT would substantially increase the labile P pool at the soil surface (~11%). This expectation was based on the ability of crop residues on the soil surface to reduce P fixation and stimulate P cycling and crop uptake. Presumably, these effects are restricted to the soil surface (Tiecher et al., 2017; Soltangheisi et al., 2018; Rigon et al., 2022) and are smaller or absent in deeper layers (Teles et al., 2017; Soltangheisi et al., 2018; Rodrigues et al., 2021). Tropical weathered soils, which are dominated by kaolinite, gibbsite, and hematite (Rigon et al., 2022), have high P adsorption (Schaefer et al., 2008), and most of the P added by fertilization accumulates in moderately labile and non-labile forms (Rodrigues et al., 2016; Withers et al., 2018), as observed in our study. It is possible to infer that the effects of P fertilization under NT and crop residues from intercropping systems are limited to the upper soil layers (Teles et al., 2017).

The higher crop residue inputs from the intercropping systems compared to maize alone explain the temporary P accumulation in residues and the reduced labile Pi labile (Rodrigues et al., 2021), which had cascading effects on the labile P pool. In weathered tropical soils, soil P lability depends more on biologically mediated Po turnover processes than Pi adsorption (Oberson et al., 2001). After mineralization, the organic pool is an important source of P for crops in these soils (Vincent et al., 2010), and growing crops in the fall-winter season under NT enhances the importance of this pool for P cycling (Tiecher et al., 2012; Rigon et al., 2022). These processes help explain the effects of the intercropping systems, particularly the effects of intercropping maize with palisade grass on the moderately labile Po fraction. In addition, our results confirm that intensive cropping systems under NT may maintain soil turnover to enhance the biological P pool (Cherubin et al., 2016). The Po pool plays an essential role in soil P bioavailability because it is less susceptible to soil adsorption in tropical soils (Damodar Reddy et al., 2000; Shears and Turner, 2007; Pavinato et al., 2017). Organic P is essential for P availability to plants in the rhizosphere, even though it has received little attention (Zhang et al., 2023).

Non-labile P fractions are strongly adsorbed by clay minerals with low reversibility; consequently, the cropping systems did not impact this soil P pool. The contribution of the non-labile P pool is greater than those of the labile and moderately labile P pools in tropical weathered soils (Pavinato et al., 2009; Rodrigues et al., 2016, 2021; Teles et al., 2017; Soltangheisi et al., 2020; Rigon et al., 2022). The contribution of this inaccessible pool to soil P in the surface soil layers despite long-term NT demonstrates the ability of soil management strategies to increase the efficiency and sustainability of cropping systems in tropical soils.

1.5 CONCLUSION

The differences in crop residue inputs between crop species intercropped with maize in the off-season under long-term NT affected soil P pools and P lability, but these effects were limited to the soil surface. By contrast, the high soil P immobilization capacity in weathered tropical soils did not permit changes in soil P stocks and the non-labile P pool. Intercropping palisade grass and/or sunn hemp with maize enhanced the soil biological P pool, which likely prevented inorganic phosphate adsorption by soil colloids and increased soil organic P content. The intercropping treatments had opposing effects on crop yields: palisade grass enhanced the yield of the main crop, soybean, but limited maize yield, suggesting that intercropped maize requires a higher N supply.

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SUPPLEMENTARY FILES

Table 4. Soil P fractions in depth layers of 0-0.05, 0.05-0.10, and 0.10-0.20 m affected by different cropping systems after 18 years.

Cropping system	soil P fraction (mg kg^{-1})								
	Pi_{AER}	**Pi_{NaHCO3}**	**Po_{NaHCO3}**	**$Pi_{NaOH0.1}$**	**$Po_{NaOH0.1}$**	**P_{Hcl}**	**$Pi_{NaOH0.5}$**	**$Po_{NaOH0.5}$**	**P_{Res}**
0-0.05 m layer									
Maize alone	39.4 a	52.5	41.1	120.3 a	38.9 c	72.8	137.1	16.4	465
Maize + PG	31.2 b	46.2	22.4	81.3 c	62.4 a	67.3	124.6	34.6	472
Maize + Sh	24.7 b	32.9	31.9	88.2 bc	53.9 ab	46.1	117.4	44.0	428
Maize + Pg + Sh	31.0 b	47.1	24.6	104.8 ab	45.8 bc	64.5	136.0	27.3	471
Source	p value								
Cropping system	0.02	0.21	0.39	0.04	0.05	0.43	0.4	0.17	0.59
0.05-0.10 m layer									
Maize alone	18.8	24.1	30.7 ab	89.8	49.7	37.2	109.5	24.8	404
Maize + PG	30.4	32.9	14.9 c	113.4	44.0	22.3	110.6	22.1	408
Maize + Sh	26.1	30.7	35.7 a	114.2	38.6	23.3	98.7	29.4	408
Maize + Pg + Sh	32.9	45.9	22.3 bc	139.1	46.7	30.5	123.8	28.1	364
Source	p value								
cropping system	0.31	0.2	0.01	0.34	0.68	0.54	0.18	0.37	0.74
0.10-0.20 m layer									
maize alone	6.2 b	12.0	23.2	77 bc	43.7	14.6	93	17.2	462
Maize + PG	6.1 b	12.0	10.9	71.4 c	57.8	10.5	85	17.9	469
Maize + Sh	6.0 b	11.4	10.1	92.0 ab	59.5	11.9	91	26.5	477
Maize + Pg + Sh	11.2 a	19.1	26.2	103.8 a	51.5	14.2	94	20.1	442
Source	p value								
Cropping system	0.04	0.67	0.47	0.05	0.53	4.13	0.67	0.49	0.61

Pi: inorganic phosphorus; Po: organic phosphorus; PAER: anion exchange resin; P NaHCO3: extracted by 0.5 M NaHCO3; P NaOH 0.1, and 0.5: extracted by 0.1 and 0.5 M; P HCL: extracted by 1 M HCl; P res: extracted by H2O2. * Means followed by different letters differ from each other by the paired t-test ($p \leq 0.1$).

CHAPTER 2

SOLE AND INTERCROPPING MAIZE UNDER LONG-TERM NO-TILL AND SOIL AMENDMENTS ON SOIL PHOSPHORUS FRACTIONS

Abstract

It is an additional task in weathered tropical soil with a dry winter off-season season to produce high crop residue inputs with naturally low P to crop availability. Changes in soil P dynamic and increasing soybean yield according to the sole and intercropped systems in the off-season (fall-winter), and the soil acidity amendments were assessed in a randomized split-plot complete block design experiment. Maize sole or intercropping with palisade grass + sunn hemp as the main plots and silicate, limestone, or no acidity amendment were treatments as split plots. P content in the leaf tissues, crop residues and soybean and mayze yield were analyzed and chemical P fractionation was performed at 0-0.05, 0.05-0.1 and 0.1-0.2 m soil depths. Soybean are cropped as a main crop in the summer seasons. Intercropping maize in off-seasons increases around 30 and 9%, respectively of maize and soybean crop yield and remarkedly residue inputs, and temporarily reduce soil Po and Pi lability at 0-0.05 m soil depth, and did not limit the crops P uptake. Soil acidy amendments increase soil Pi pools, specifically to the labile and P-Al and Fe bounded, and also total P stocks compared to control. Our results indicate that Intercropping is a good option for diversification enhancing the land-use efficiency and the NT sustainability of tropical agriculture providing higher crop yields compared to a monocroped system.

Key words: crop straw inputs; silicate; ruzigrass; maize; soil organic phosphorus.

2.1 INTRODUCTION

The predominance of Al and Fe oxides in weathered soils promotes high phosphorus (P) sorption and reduces P availability to crops (GÉRARD, 2016). It is recognized as relatively abundant organic P (Po) and inorganic P (Pi) pools in tropical soils. At the same time, could be considered the most limiting nutrient for crop production and cropping system sustainability (PAVINATO et al., 2020), owing to the low P to crop availability. Thus, it is essential to improve strategies of P fertilization by crop residue nutrient cycling (RIGON et al., 2022).

Soil acidity amendment is indispensable in weathered soils, to increase soil pH and reduce P fixation saturating Al and Fe ions. Many field experiments have been demonstrated the ameliorating impacts of lime and silicate as soil acidity amendments substantially changed the chemical forms of P and its soil availability (HONG; SU; LU, 2018).

Under no-till management (NT), cover crops have been used to improve soil P fertilization (RIGON et al., 2022; RODRIGUES et al., 2021; SOLTANGHEISI et al., 2020, 2018). The crop residue left on the soil surface impacts soil P cycling (TIECHER et al., 2015) and avoids the fast adsorption of inorganic P by the solid mineral phase (MARTINAZZO et al., 2007). It may release partially P to meet the requirements of a subsequent cash crop (DAMON et al., 2014; HALLAMA et al., 2019), but under low soil P status, an external P fertilizer is needed for sustained crop yield. Since, crop rotation increases soil organic P and microbial activity, which may stimulate P use fertilizer efficiency in agroecosystems (SIMPSON et al., 2011).

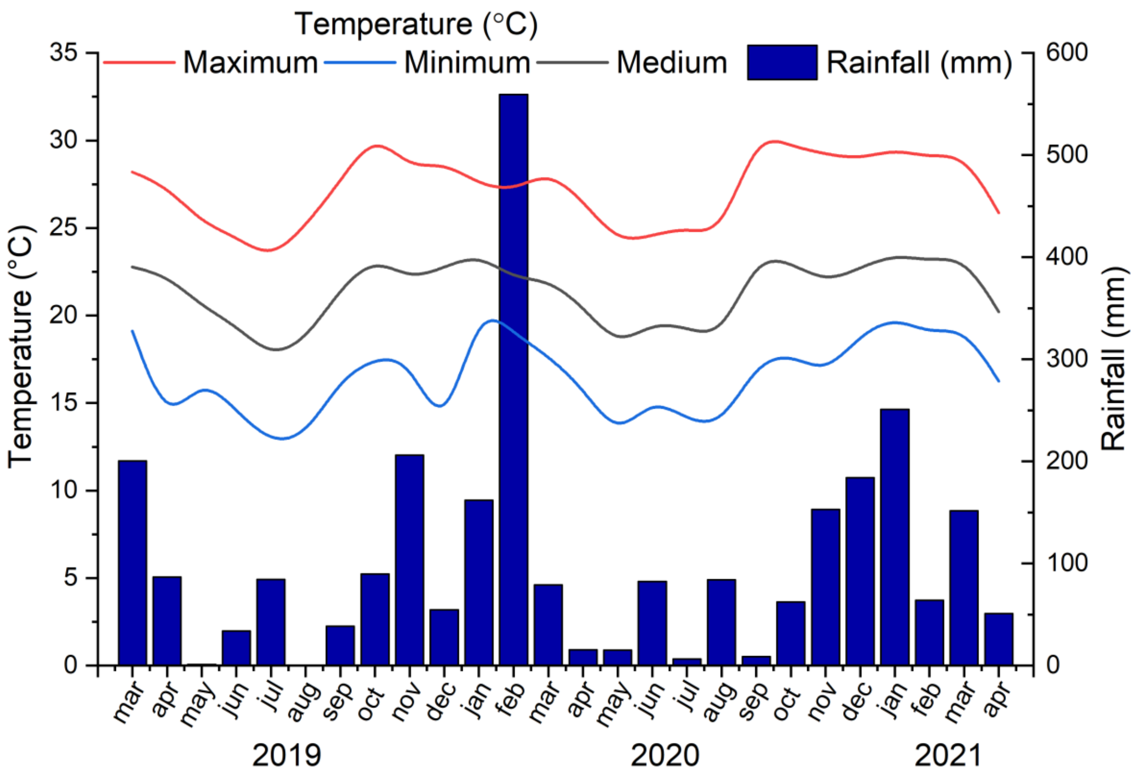
NT intercropping systems are characterized by alternation between cash crops and forage production during the growing season with or without animal grazing in the off-season (FRANZLUEBBERS; GASTAL, 2019). These cropping systems provides opportunities for enhancing resource use efficiency in agroecosystems (TANG et al., 2021). Considering that organic P (Po) is positively correlated with organic carbon (C) (RHEINHEIMER et al., 2019), it is expected that sole and intercropped systems with long-term NT lime or silicate application will differently impacts on soil P dynamics in Oxisols. Little is known about the impact of long-term soil amendments on sole and intercropping systems on soil P pools. We hypothesized that i) soil P lability is modified by intercropping systems; ii) growing maize intercropped with palisade grass and sunn hemp in the off-season increase soil Po pool; iii) soil acidity amendment increase Pi pool at soil surface. To confirm the hypothesis, changes in soil P dynamic according to the sole and intercropped systems and soil acidity amendment were assessed.

2.2 MATERIALS AND METHOD

2.2.1 Site characteristics and management

The experiment was initiated in 2006 in Botucatu, São Paulo State, Southeastern Brazil (48º 23’ W, 22º 51’ S, 765 m above sea level), on a clayey Rhodic Hapludox (SOIL SURVEY STAFF, 2014), with 440 g kg^{-1} of clay, 469 g kg^{-1} of sand and 91 g kg^{-1} of silt at a depth of 0 to 0.2 m. Characteristic climate condition is highland tropical, with dry winters and wet, rainy summers (Figure 1). At the time of experiment initiation, chemical properties in the upper 0.2 m were analyzed according to Raij et al. (2001) SOM [soil organic matter = 18 g dm^{-3}; pH = 4.2 (1:2.5 soil/$CaCl_2$ suspension 0.01 mol L^{-1}); P resin = 4 mg dm^{-3}; exchangeable K = 0.8 mmol$_c$ dm^{-3}, Ca = 12 mmol$_c$ dm^{-3}, Mg = 6 mmol$_c$ dm^{-3}; total acidity at pH 7.0 (H+Al) = 54 mmol$_c$ dm^{-3}; base saturation = 24%.

Figure 1 - Average monthly maximum (red line, ˚C), minimum (blue line, ˚C), and medium temperature (black line, ˚C) and monthly rainfall (blue bars; mm) at the weather station located at Lageado’s farm



Source: by the author.

2.2.2 Experimental design

The experimental design was a randomized split-plot complete block design with two cropping systems differentiated in the off-season/winter season as mains plots (maize sole; intercropping maize + palisade grass + sunn hemp), and three acidity amendment treatments as split plots (silicate, limestone and control). Soybeans are cropped as a main crop in the summer. Summer grain crop were sown in November and harvested between March and April. After the summer harvest, winter crops were sown without fertilizer. Winter crops were harvested between July and August. It is noteworthy that it was not possible to grow any crop/cover crop in the winter season 2014 due to adverse weather conditions (low precipitation). In 2016, the second crop did not grow owing to the insufficient precipitation necessary for the development of the crop during this season. During this study, all cropping systems were managed under NT. Each plot covered an area of 54 m^2 (5.4 m x 10 m). One row on each side of the plot and one meter at both edges were considered buffer zones and not sampled.

Over the 11 years of the field experiment, the soil amendment chosen to aiming to raise base saturation to 70%. Dolomitic lime (ECC = 90%, CaO = 360 g kg^{-1}, and MgO = 120 g kg^{-1}), Ca\\Mg silicate (ECC = 80%, CaO = 340 g kg^{-1}, MgO = 100 g kg^{-1}, and SiO2 =220 g kg^{-1}), and control (no amendment). Doses were applied mechanically in October 2006, followed by a second application on the soil surface in October 2011, aiming to raise base saturation to 70%. Actual rates of material applied were 3.8 and 4.1 Mg ha^{-1} for limestone and silicate, respectively, in 2006 and 4.7 and 5.3Mg ha^{-1}, respectively, for lime and silicate in 2011. In the second application, characteristics of lime were: ECC=74%, CaO=350 g kg^{-1} and MgO=120 g kg^{-1}, and characteristics of silicate were: ECC= 66%, CaO= 320 g kg^{-1}, MgO=90 g kg^{-1}, and SiO2 =220 g kg^{-1}. The mechanical application on soil surface were in October 2006 (before sowing the first crop), 2011, 2015, and 2018 (before sowing summer crop) based on the method of base saturation (BS) (RAIJ et al., 1997). Adequate rates of NPK fertilizers were applied for summer crops according to soil chemical analyses and recommendations.

2.2.3 Planting and harvest time

At the installation of the experiment in 2018, the chemical properties in the layer 0 – 0.2 m were analyzed according to Raij et al. (2001), presenting: soil organic matter

= 27 g dm^{-3}; pH = 4.5 (1:2.5 soil/$CaCl_2$ suspension 0.01 mol L-1); resin P = 20 mg dm^{-3}; exchangeable K = 3.30 mmolc dm-3, Ca = 31 mmolc dm^{-3}, Mg = 21 mmolc dm^{-3}; total acidity to pH 7.0 (H+Al) = 42 mmolc dm^{-3}; base saturation = 57%, CTC = 98 mmol dm^{-3}; clay = 63%; silt = 9%; sand = 28%.

The conduction of the experiment began in November 2018, with the sowing of soybean (CD 2728 IPRO) in the total area, after the application of calcium and magnesium silicate. The harvest was carried out in March 2019, the soybeans were planted again on 11/12/2019 and 10/26/2020, with the cultivar TMG 7062 IPRO and harvested on 03/15/2020 and 02/25/2021, both soybean crops received fertilization at sowing with 20 kg ha^{-1} of N, 50 kg ha^{-1} of P_2O_5 and 150 kg ha^{-1} of K_2O. The maize crop was sown after the soybean harvest, in the first year on 03/17/2019 and in the second year on 03/23/2020. The hybrid used was P3707 VYW in both harvests. The maize harvest took place on 05/08/2019 and 01/08/2020. In the maize sowing furrow in both years, 22 kg ha^{-1} of N, 78 kg ha^{-1} of P_2O_5 and 45 kg ha^{-1} of K_2O were supplied. When the crop had 6 fully expanded leaves, nitrogen fertilization was carried out in coverage with 90 kg ha^{-1} with ammonium sulfate. In system I, in which maize was not intercropped, the area was fallow during the off-season. In the intercropping constituted by system II, forage sowing was simultaneous with the grain harvest, the seeds were mixed together with the fertilizer a few hours before implantation, using 8 kg ha^{-1} of seeds. For the sowing of the green fertilizer Crotalaria spectabilis (system III), the third box of the seeder (additional box of seeds) was used, using 17 kg ha^{-1}, occurring simultaneously with the maize sowing. Considering system IV, with the triple intercropping maize + palisade grass + sunn hemp, sowing took place under the same conditions when they were placed alone with maize, for palisade grass 8 kg ha^{-1} of seeds were used, inserted together with the fertilizer and for sunn hemp 17 kg ha^{-1}, using the additional seed box.

2.2.4 Crop analyses

The contributions of crop residues from cover crops intercropped with maize were evaluated. The samples were collected before sowing the soybean crop, at the time of desiccation, 25 days before sowing. Three subsamples were taken randomly from each subplot using a wooden square (0.25 × 0.25 m). The collected material was dried until reaching constant weight in an oven with forced air circulation at 65 °C, for analysis of dry matter and accumulated P content (MALAVOLTA et al., 1997).

During the flowering period of soybean and maize, P levels were determined in the leaf tissues of both cultures, following the methodology proposed by Ambrosano et al. (1997) and Malavolta, Vitti and Oliveira (1997). Thirty samples were taken per plot, considering in soybeans the third trefoil completely expanded from the apex, when the crop was in R2. For the maize crop, 30 samples were collected, considering the leaf below and opposite the main ear at the beginning of flowering for determination of P.

The maize and soybeans were harvested mechanically with a plot combine (NM Elite, Wintersteiger Seed Mech) and crop yields were adjusted to 13% moisture. After harvesting, P levels in maize and soybean grains (2019/2020 and 2020/2021 harvests) were analyzed according to the methodology described by Malavolta, Vitti and Oliveira (1997). Soybean and maize grain P output was calculated by averaging soybean and maize grain yield seasons (2019/2020, and 2020/2021), multiplying by the P content in soybean and maize grains.

2.2.5 Soil analysis

Three soil subsamples were collected in October 2021 from each experimental unit at a depth of 0–0.05; 0.05-0.1; 0.1-0.2 m, air-dried and sieved (2 mm). Chemical P fractionation was performed according to (HEDLEY; STEWART; CHAUHAN, 1982) as modified by (RHEINHEIMER; ANGHINONI; KAMINSKI, 2000), changing the original sonication step to 0.5 M NaOH extraction. Soil P fractions were grouped into pools according to their potential plant lability (CROSS; SCHLESINGER, 1995): “labile P” (PiRTA + PiBIC + PoBIC), “moderately labile P” (PiHID0.1 + PoHID0.1 + PiHCl) and “non-labile P” (PiHID0.5 + PoHID0.5 + P residual).

2.2.6 Statistical analysis

Data were tested for homogeneity of variance and normality. Afterwards, data were subjected to analysis of variance. Mean values were compared by t-test (LSD), and declared significant at $p = 0.1$.

2.3 RESULTS

2.3.1 Crop residue inputs from intercropping

Intercropping palisadegrass (Ph) and punn hemp (Sh) with maize increased ($p<0.1$) 133% the crop residue inputs compared cropping maize sole in off-season (Table 1). Adding any soil acidity amendment, which did not differ from each other, increased ($p<0.1$) in average, around 28% of the crop residue inputs. The phosphorus (P) content on crop residue did not differ among soil acidments, but impacted the cumulative amount of these nutrient inputted. Although the correctives evaluated did not differ from each other in terms of P content accumulated in crop residues, the chemical correction of the soil using limestone allowed an accumulation of 12.37 kg ha^{-1} of P, 54% above the control treatment, without adding soil acidity corrective.

Table 1 – Crop residue amount, phosphorus (P) content and cumulative P input as affected by cropping systems and soul acidity amendments

Cropping system	Crop residue amount (Kg ha^{-1})	P content (g kg^{-1})	cumulative P input (kg ha^{-1})
Maize sole	5.710 b	-	-
Maize + Pg + Sh	13.306 a		
Control	8.014 b	1,0	8,01 b
Silicate	10.203 a	1,0	10,20 ab
Limestone	10.308 a	1,2	12,37 a
Source		p value	
Cropping system (CS)	0.01	-	-
		0.21	
Soil acidity amendments (SAA)	0.03		0.07
CS x SAA	0.21	-	-

Source: by the author.

Note: *Means followed by different letters differed by the t test ($p \leq 0.1$).

†Pg: palisade grass; ‡Sh: sunn hemp

2.3.2 P contents on grains and leaf diagnosis

It was expected that cropping systems had few impacts on P leaf diagnosis and grain content, but majority it did not occur. On the other hand, application of soil acidity amendment increased ($p<0.1$) around 11% the soybean P leaf diagnosis in both seasons compared to control.

As for the cropping systems, only the P content in maize grains during the 2019 harvest was influenced, and the use of the triple intercropping maize + Pg + Sh reduced the P content in the grains by 12% compared to single maize (Table 2).

Table 2 – P content on leaf diagnosis and in grains of maize 2019 and 2020 and soybean 2019/2020 and 2020/2021, as affected by cropping systems and soil acidity amendments

Crop season	Cropping systems (CS)		soil acidity amendments (SAA)			CS	SAA	CS x SAA
	Maize sole	Maize + Pg + Sh	Silicate	Lime	Control	----- p value -----		
	-------------- g kg^{-1} --------------							
maize leaf 2019	2,3	2,1	2,2	2,2	2,3	0,12	0,7	0,25
maize leaf 2020	0,9	0,9	0,9	0,8	1,0	0,57	0,11	0,31
soybean leaf 2019/2020	4,2	4,1	4,3 a	4,3 a	3,8 b	0,29	0,01	0,88
soybean leaf 2020/2021	3,8	3,6	3,8 a	3,8 a	3,5 b	0,13	0,05	0,56
maize grain 2019	3,2 a	2,8 b	2,9	3,1	2,9	0,02	0,41	0,33
maize grain 2020	4,3	4,2	4,0	4,3	4,5	0,76	0,46	0,40
soybean grain 2019/2020	5,4	5,4	5,4	5,5	5,4	0,92	0,85	0,68

Source: by the author.

Note: *Means followed by different letters in line differed by the t test ($p \leq 0.1$).

‡Pg: palisade grass; Sh: sunn hemp.

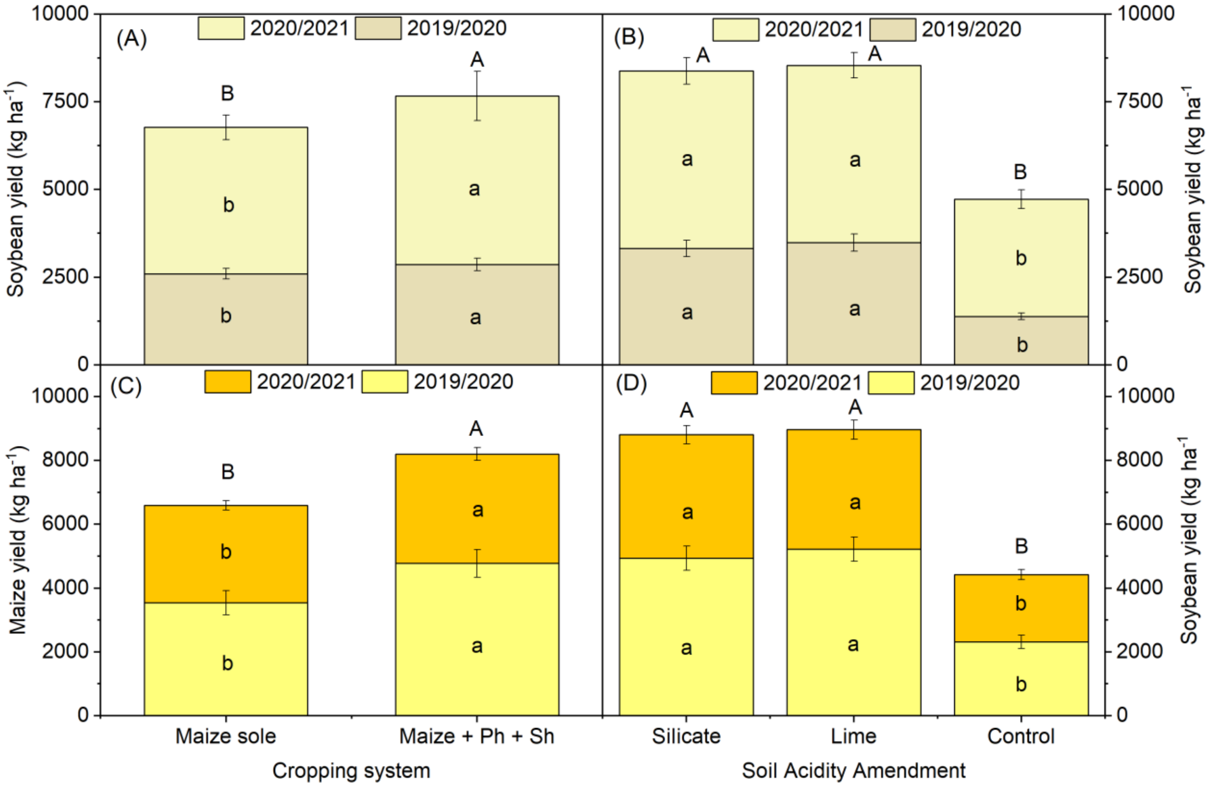
2.3.2 Soybean and maize yield

The Soybean and maize crop yields in both evaluated seasons were influenced by the production system and chemical correction of the soil (Figure 2).

As for the cropping system, the triple intercropping Maize + Palisade grass + Sunn hemp increased soybean productivity by 10% in the 2019/2020 season and 15% during the 2020/2021 season compared to the single maize system. Regarding maize productivity, the triple intercropping favored grain productivity by 35% in 2019 and 12% in 2020 compared to the single maize system.

Regarding soil acidity amendment, the treatments did not differ from each other in both crops growth seasons, but differed both compared to the control treatment, (absence of soil acidity). The supply of soil acidity corrective increased 79% the accumulated soybean yield compared to the control treatment, and 100% for the accumulated maize yield.

Figure 2 – Soybean yield during the 2019/2020 and 2020/2021 harvests as a function of cropping systems (a) and as a function of corrective use (b). Maize yield during the 2019/2020 and 2020/2021 harvests as a function of cropping systems (c) and as a function of corrective use (d)



Source: by the author.

2.3.3 Soil P pool

Cropping systems impacted soil P fraction within labile and moderately labile pools, notably at 0-0.05 m soil depth, but did not affect soil deeper layers (Supplementary table 3). Cropping maize as sole in off seasons increased notably ($p<0.1$) labile fractions at 45, 35, 48, and 24%, respectively, to the P_{IAR}, $PiNaHCO_3$, $PoNaHCO_3$, and $PiNaOH_{0.1}$, compared to intercropping treatment, as also occurred an increased around 10% to the non-labile fraction $PiNaOH_{0.5}$ by sole maize. On the other hand, intercropping maize in off-season increased only the fraction $PoNaOH_{0.1}$, compared to maize cropped as a sole. That fraction interacted ($p<0.1$) between cropping systems and soil acidity amendments. Silicate or limestone application, differing among each other, decreased ($p<0.1$) respectively to 56 and 22% of $PoNaOH_{0.1}$, compared to control in cropping maize sole. While in intercropping treatment, the soil acidity amendments did not differ between them, but were also decreased, in average, 48% compared to control.

Specifically to the soil acidity amendments, in general silicate application increased ($p<0.1$), most labile fractions (P_{IAR} and $PiNaHCO_3$), and decreased the moderately labile fractions ($PiNaOH_{0.1}$ and $PoNaOH_{0.1}$), mainly compared to the control treatment. Exception could be atributted to the P_{HCL} fraction, on which was increased by silicate. Essentially, the limestone application followed the silicate trend, i. e. differing from control treatment in a few soil P fractions, but with intermediate values.

The cropping systems did not impact soil P fraction at 0.05-0.1 m soil depth (Supplementary table 4). However, the P_{IAR} at 0.1-0.2 m soil depth was 76% highest in intercropping maize than cropped as sole in off season (Supplementary table 5). Soil acidity amendments only influenced on deeper layers soil P fractions in non-labile fractions. Silicate had greatest P_{HCL}, $PiNaOH_{0.5}$, $PoNaOH_{0.5}$ at 0.05-0.1 m soil depth compared to control treatment, and changing to the lowest P_{RES}, differing from control and limestone application. At 0.1-0.2 m soil depth soil acidity amendments had contrasting influence on moderately labile pool. Control increased $PoNaOH_{0.1}$ and decreased following limestone application the P_{HCL}.

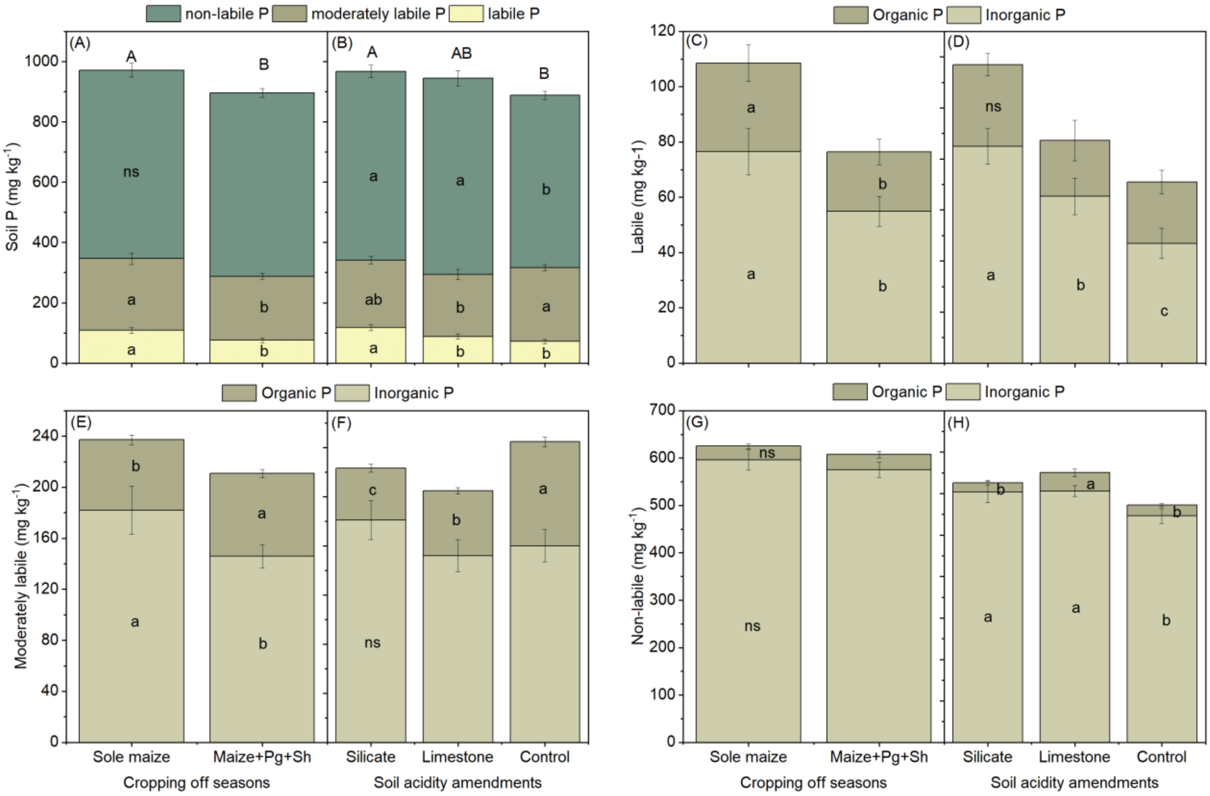
2.3.4 Soil P lability

Cropping maize sole in off season increased ($p<0.1$) soil Po and Pi labile and moderately labile at 0-0.05 m soil depth (Figure 3A), compared to intercropping treatment, and did no differ about the non-labile pool. Soil P stock was 9% greatest cropping sole maize compared to intercropping. The soil acidity amendments impacted the soil P lability. Firstly, silicate increased ($p<0.1$) 33 and 64% soil labile P compared to limestone application and control treatment (Figure 3B). Curiously, no application of soil acidity amendment resulted in the highest soil moderately-labile P ($p<0.1$), compared to limestone and no differing from silicate. While the non-labile P pool Soil acidity amendment increased similarly between each other, differing to the control.

Specifically to the organic and inorganic pools, cropping maize sole increased labile organic and inorganic P differing ($p<0.1$) to intercropping treatment (Figure 3C, and 3D), as well as occurred to moderately labile inorganic soil P pool (Figure 3E). On the other side, the moderately labile inorganic P was increased ($p<0.1$) with the intercropping treatment, and cropping systems did no impact in non-labile soil inorganic or organic P pools (Figure 3G).

Concerning to the soil acidity amendments, the silicate increased 30% the inorganic labile P pool compared to silicate, and reached up to 81% compared to control treatment (Figure 3D). Only applying silicate to the soil surface increased at 8% of sol P stocks, compared to control treatment. Organic labile did not was impacted to the soil acidity amendments, as inorganic moderately labile pools (Figure 3F). On the other hand, control has the greatest organic moderately labile P pool, following to limestone and silicate. Contrary to the cropping systems, soil acidity amendments impacted ($p<0.1$) inorganic and organic non labile pools (Figure 3H). Limestone and silicate increased ($p<0.1$) inorganic non-labile pool compared to control. But, only limestone maintain the predominance on organic non-labile, and control and silicate did not differ each other (Figure 3 H).

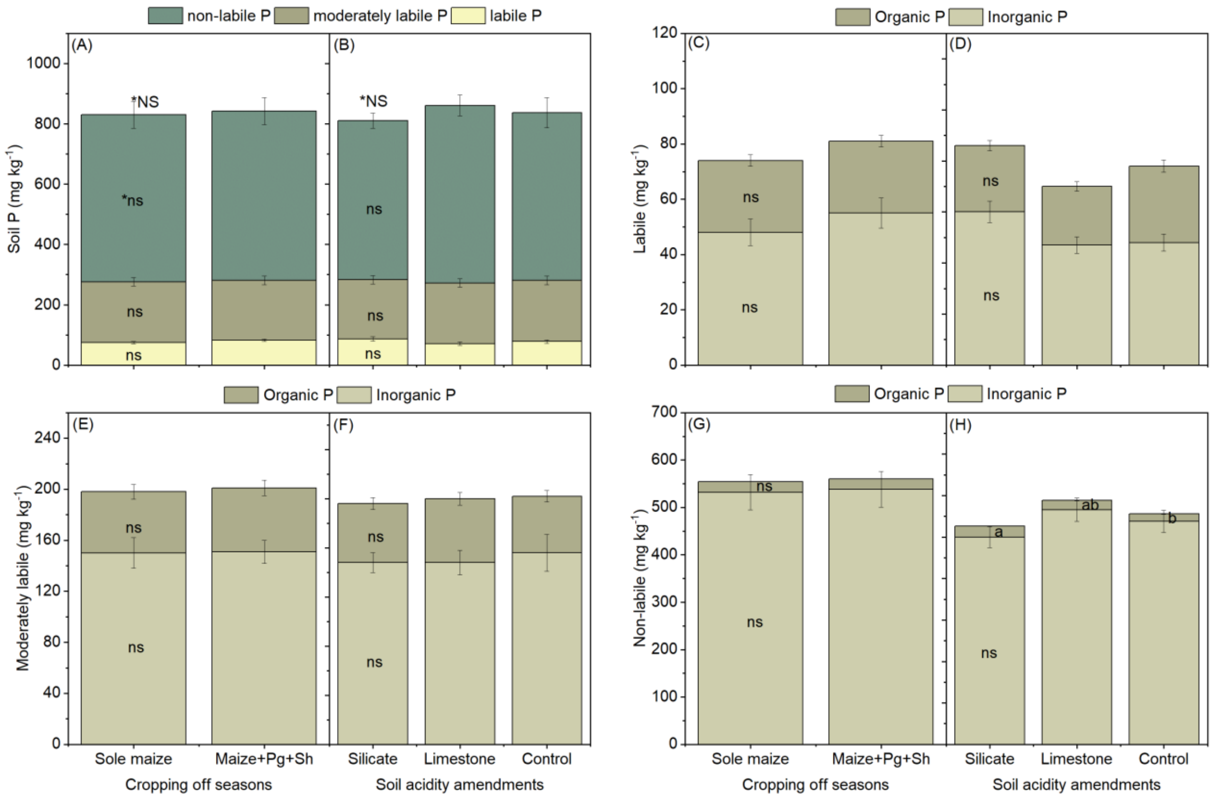
Figure 3 – Soil P lability (A, B), labile organic and inorganic P pool (C, D), moderately labile organic and inorganic P pool (E, F), and non-labile organic and inorganic P pool (G, H) at 0-0.05 m soil depth according to cropping systems and soil acidity amendments



Source: by the author.

Note: *Means followed by different letters differed by the t test ($p \leq 0.05$). ns: not significant

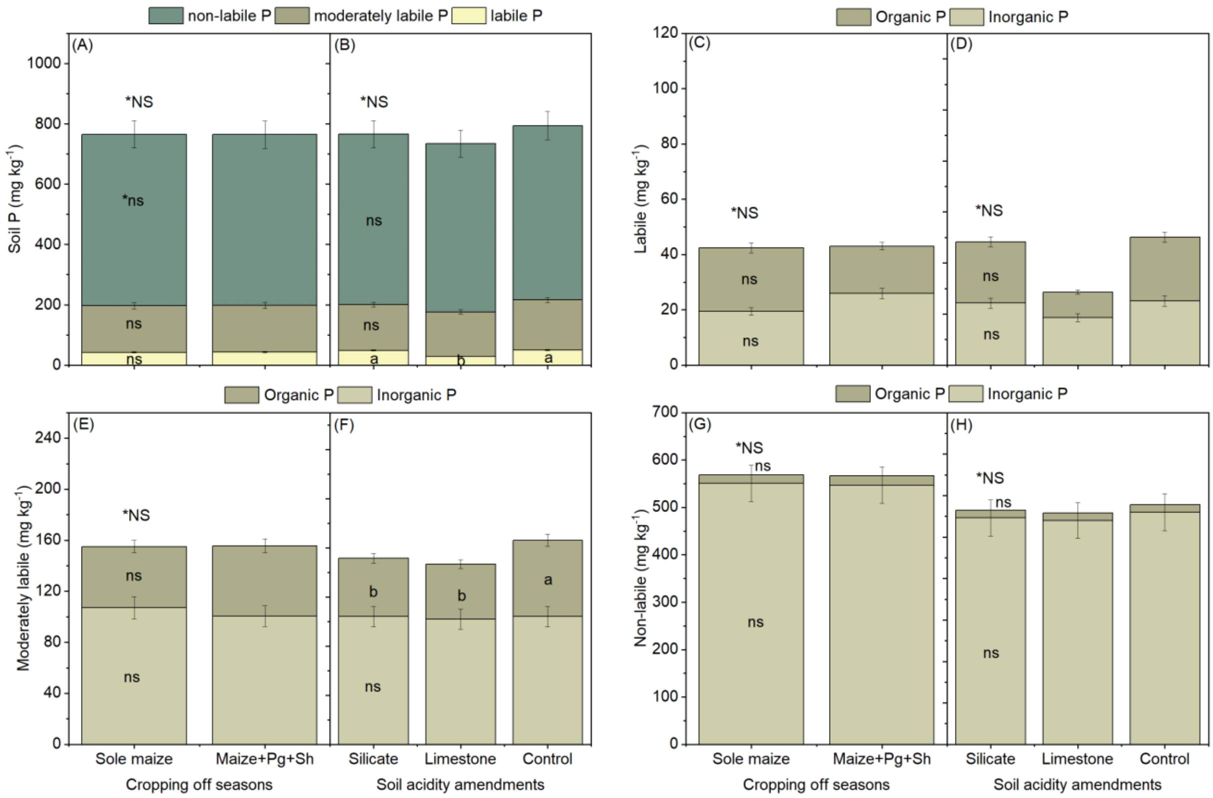
Figure 4 – Soil P lability (A, B), labile organic and inorganic P pool (C, D), moderately labile organic and inorganic P pool (E, F), and non-labile organic and inorganic P pool (G, H) at 0-0.05 m soil depth according to cropping systems and soil acidity amendments



Source: by the author.

Note: *Means followed by different letters differed by the t test ($p \leq 0.05$). ns: not significant.

Figure 5 – Soil P lability (A, B), labile organic and inorganic P pool (C, D), moderately labile organic and inorganic P pool (E, F), and non-labile organic and inorganic P pool (G, H) at 0-0.05 m soil depth according to cropping systems and soil acidity amendments



Source: by the author.

Note: *Means followed by different letters differed by the t test ($p \leq 0.05$). ns: not significant.

2.4 DISCUSSION

2.4.1 Crop residue inputs

Maize intercropping is an alternative to increase crop residue left on soil surface after harvest improving the NT in tropical areas (MINGOTTE et al., 2020). The synergy between grasses and legume species confirm the remarkedly greater crop residue by intercropping compared to maize sole in off-season. Perennial grass addition in intercropping has been used to increase biomass production (CRUSCIOL et al., 2015), mainly under tropical with dry off-season, which stimulates a fast crop residue decomposition on soil surface (RIGON et al., 2021). Biomass production during that period is an essential trait of interest in a tropical cropping system (FERRARI NETO et al., 2020), becoming more usual in those Brazil regions (BORGHI et al., 2013). Soil acidity amelioration with long-term of silicate or limestone application and its benefits of soil nutrient availability and greater crop residue inputs on cropping system are well known (CASTRO; CRUSCIOL, 2013; CRUSCIOL et al., 2019; FERRARI NETO et al., 2020) confirming our results. The greater nutrient contents in crops residue observed was due to the cumulative crop residue yield.

2.4.2 P contents on grains and leaf diagnosis

The long-term crop rotation system can alter leaf nutrient compositions, depending on the crop species grown and its recycling potential (BORGHI et al., 2013). However, impacts were mainly observed through the application of soil acidity correctives. It is noteworthy that improving soil acidity increases the availability of soil nutrients and nutrient uptake by crops, especially P (VICTORIA et al., 2019).

Regardless of the corrective used, the pH correction increased the levels of P in the leaf tissues of the soybean crop. It is known that the use of correctives increases the concentration of OH- ions in the soil, raising the pH, leading to Fe and Al precipitation, decreasing the complexation and precipitation of phosphates, which leads to an increase in the available P content in the solution of the soil, favoring the acquisition of this nutrient by crops (NOVAIS; SMYTH, 1999). Bossolani et al. (2020) when evaluating the use of liming on the development of soybeans, found that long-term soil management with limestone increased the soil pH, triggering an increase in P content in the soybean leaf, improving the photosynthetic aspects of the crop with increased productivity.

2.4.3 Soybean and maize yield

Usually intercropping two or more species enhances the use efficiency of resource and often increases crop yield per unit land area (WU et al., 2021). Normally cereal-legume are used to reduce intra-specific competition environmental resources (e.g. light, water, and nitrogen) (YU et al., 2015). The advantages occurs when inter-specific competition is weaker than that (ZHANG et al., 2020). The mixed crops were used to explore complementarities characteristics, as previously commented, and a presumably negative impact could occur between maize and palisade grass owing to the characteristics of the similar crops. However, the competition was presumably negligible in treatment, considering the greatest soybean and maize yield by intercropping. In addition, it infers that intercropping treatment has appropriately density and according fertilized (CANISARES et al., 2021; CRUSCIOL et al., 2020). Intercropping or rotating maize with soybean trend to achieve high and stable maize grain yield (ALVAREZ; STEINBACH; DEPAEPE, 2017; CHIMONYO; SNAPP; CHIKOWO, 2019). Similarly, soybean grown under NT after maize and palisade grass intercrop improves soil N and P stocks and crop yields (BOSSOLANI et al., 2021; ALMEIDA et al., 2020; SILVA et al., 2020). Maize intercropped with palisade grass increases nutrient cycling in crop residue (PARIZ et al., 2016). In adittion, crop residue retention is an effective way to increase crop grain yield (HAN et al., 2021), and it also helps to explain the highest amount of crop residue in the cumulative soybean and maize grain yield, and soil acidity amendments compared to control. Soil acidity amendments reduce the exchangeable Al^{3+} availability, improving soybean nutrition and grain yield, particularly when it followed intercropped maize (BOSSOLANI et al., 2021), and its effective practice to improve crop production on acid soils (FAGERIA; BALIGAR, 2008). Hence, intercropped maize in off-season increase crop residue inputs under NT and maize and soybean yield, enhancing sustainability of the cropping system.

2.4.4 Soil P pool

Cropping systems under long-term NT normally shows an adequate recycling of P from crop residue on the soil surface (RIGON et al., 2022). It is clearly by the pronounced effect at 0-0.05 m soil depth (Figure 3), exhibiting also the soil P immobilization at soil surface (SOLTANGHEISI et al., 2018; TIECHER; SANTOS; CALEGARI, 2012). Growing crops generally deplete temporary Pi_{AER} owing to the by crop uptake of P fertilizer added (RODRIGUES et al., 2021; TELES et al., 2017). It helps to explain the greatest Pi_{AER} in sole maize compared to the intercropping, showing this trend in labile pool as also in the Pi $NaHCO_3$ and $PoNaHCO_3$ fractions, indicating a relevant labile transformation into Po and Pi pools. Besides the crop residue inputs changes the concentrations of various soil P pools (ALAMGIR et al., 2012; RIGON et al., 2022), we hypothesize that the higher C N ratio and amount from intercropping did not release enough P to promote an increase in it fractions owing to the microbial immobilization of Pi (CHEN; HE; HUANG, 2000). However, it well know that in the long-term different crop rotation alters soil P polls and its availability (CHAVARRÍA et al., 2016; RIGON et al., 2022; RODRIGUES et al., 2021).

Our study shows that the Pi_{AER} surpassed the adequate soil P available for main crops in Cerrado (15 mg P kg^{-1} soil) (RAIJ et al., 2001; SOUZA; LOBATO, 2004). In addition, the annual seed furrow P fertilization (50 and 78 kg ha^{-1} P_2O_5 $year^{-1}$ within soybean and maize sowing respectively) seems an adequate way to P input in tropical soils (NUNES et al., 2020). It also infers that the amount sustained a positive soil P balance, considering of 12.0 and 14.7, respectively of maize and soybean P output in grains in 2019/2020 season, and 15.0 + 22.5 kg ha^{-1} of maize and soybean P output in grains in 2020/2021 season (Table 2 and Figure 2). On the other side, it was expected that the high crop residue from intercropping enhances mostly Po pools, but it occurred only at the moderately labile fraction, not confirming our hypothesis. Hence, soil P dynamics is complex in weathered soils, and understanding adequate P fertilization and its transformations to crop utilization is an additional task in tropical regions (GOTZ et al., 2023; RIGON et al., 2022).

The Pi_{HCL} (Ca-precipitated P) had low contribution from cropping systems, as expected in weathered tropical soil (RODRIGUES et al., 2021). On the other side, soil acidity amendments change it fraction, as well as mostly increasing soil P pools lability. It also confirms our hypotheses that limestone or silicate enhances the Pi at soil surface.

The P_{RES} fraction represented almost ½ of total soil P. This fraction has an unknown chemical nature, including several Pi and Po components (CORREIA et al., 2023) and indicates the strong adsorption by clay minerals, confirmed the no impact from cropping systems and soil acidity amendments. In most cases, no differences ($p>0.1$) in recalcitrant fractions and soil deeper layer were observed by cropping systems. Considering that different P fertilizer applications may alter crop uptake, modifying soil P dynamics and the P dynamic at soil profile (HANSEL et al., 2017). So, the no impact in deeper soil P indicates that the P fertilization into seed furrows limited P downward movement in the soil profile.

Soil P sorption capacity varies according to the soil type, mainly by Al and Fe Oxides in tropical regions (HAYNES, 1982). Since, lime or silicate application in weathered soils has been used to increase soil pH, decrease Al toxicity, and increase P availability for crop uptake. In our study, both soil acidy amendments increase soil Pi pools, and specifically to the P-Al and Fe bounded, and also total P stocks compared to control. In general, silicate application trended to a slightly greatest effect compared to limestone, presumably to the higher solubility and faster reaction (ALCARDE; RODELLA, 2003). It may help to explain the greater P_{HCL}, $PiNaOH_{0.5}$ and lower P_{RES} at 0.05 – 0.1 m soil depth by silicate application (Table 4). However, it was expected few more impacts in deeper soil. Surface soil acidity amendments NT application trended a soil P gradient (ISMAIL; BLEVINS; FRYE, 1994). NT may stimulate preferentially shallow root growth owing to the water retention and nutrients stratification (BLANCO-CANQUI, 2023).

2.4.5 Soil P lability

Long-term NT across 14 years cropping systems changed soil P lability, and increased soil P stocks, but only at 0-0.05 m soil depth confirming partially our first hypothesis. Considering that crop residue left on soil surface under NT reduce P fixation reactions and stimulates P cycling and crop uptake (RIGON et al., 2022; SOLTANGHEISI et al., 2020; TIECHER et al., 2017), but the impact was reduced or did not occur in deeper soil layers (RODRIGUES et al., 2021; SOLTANGHEISI et al., 2018; TELES et al., 2017; TIECHER; SANTOS; CALEGARI, 2012). It clearly demonstrates that tropical weathered soils, has high P adsorption (SCHAEFER; FABRIS; KER, 2008). Since, it is presumable that most of the P added by fertilization has been accumulated in moderately and non-labile forms (RODRIGUES et al., 2016; WITHERS et al., 2018), as observed in our study. It is possible to infer that the effects of P fertilization under NT and crop residue from cropping systems are limited to upper soil layers (TELES et al., 2017).

Crop residue inputs increase both organic carbon (C) content and Po content of soil particulate fractions (WEI et al., 2016). Hence, it was expected that intercropping in off-season under NT enhances the Po pool considering the greatest crop straw input across the years, but it did not occur. Only the lability of Po was modified by intercropping, changing partially the labile Po to moderately labile Po fraction, resulting in the same Po pool from sole maize.

Soil acidity amendments application on weathered soils raises pH, facilitating the release of phosphate ions fixed in Fe and Al oxide surfaces increasing the soil P available to the crops (YIGEZU; LAEKEMARIAM; KIFLU, 2023), as occurred and hypothesized as Pi forms in our study. Concerning to the Po fraction, there are limited data on the long-term effects by liming on it P pool under field conditions (SIMONSSON et al., 2018), and liming could deplete the Po stocks in an acid soil as hypothesized by the authors. In our study, only the labile Po pool was depleted by the soil acidity amendments compared to the control. It could be assumed by the soil acidity amendments stimulates soil microbial activity through greater soil respiration (INAGAKI et al., 2017), by crop residue mineralization (AYE; SALE; TANG, 2016; FERRARI NETO et al., 2020), which in turn can enhance soil available P (SIMONSSON et al., 2018). Silicate highlighted as the soil acidity amendment that most increased soil labile Pi and P stock, but the enhancement was observed only in non-labile P pool. Hence, it indicates the difficulty task to improve the soil P available on deeper soils focusing on the increase crop residue inputs and grain yield in off-seasons to maintain sustainability of tropical weathered cropping systems.

2.5 CONCLUSION

Soil P lability and soil P stocks could be modified by cropping systems under long-term NT limited to upper soil layers and accumulated in moderately and non-labile forms. Intercropping maize with palisade grass and sunn hemp in off-seasons increases crop residue inputs and soybean and maize grain yield, and temporary reduce soil Po and Pi lability at 0-0.05 m soil depth owing to the greater residue P accumulation, and did not limit the crops P uptake. Soil acidy amendments increase soil Pi pools, specifically to the labile and fractions of P-Al and Fe bounded, and also total P stocks compared to control. Hence, our results indicates that intercropping is a good option for diversification enhancing the land-use efficiency and the NT sustainability of tropical agriculture providing higher crop yields compared to single cropped system.

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SUPPLEMENTARY FILES

Table 3 - Soil P fractions at 0–0.05 m soil depth affected by cropping systems after 18 years of management

Cropping system	soil P fraction (mg kg^{-1})								
	Pi_{AER}	Pi_{NaHCO3}	Po_{NaHCO3}	$Pi_{NaOH0.1}$	$Po_{NaOH0.1}$	P_{Hcl}	$Pi_{NaOH0.5}$	$Po_{NaOH0.5}$	P_{Res}
maize sole	33,48 a	43,0 a	32,0 a	134,5 a	55,1 b	48,1	128,3 a	29,1	467,9
Maize + Pg + Sh	23,06 b	31,8 b	21,5 b	108,4 b	64,7 a	38,3	116,3 b	32,4	459,4
Soil acidity amendments	Pi_{AER}	Pi_{NaHCO3}	Po_{NaHCO3}	$Pi_{NaOH0.1}$	$Po_{NaOH0.1}$	P_{Hcl}	$Pi_{NaOH0.5}$	$Po_{NaOH0.5}$	P_{Res}
Silicate	35,2 a	49,7 a	32,8	112,5 b	42,3 c	68,6 a	136,5 a	21,8 b	468
Limestone	27,6 b	37,7 b	22,9	108,2 b	52,7 b	44,2 b	129,4 a	44,3 a	477
Control	21,9 b	24,9 c	24,5	143,5 a	84,7 a	16,7 c	100,9 b	26,1 b	445
Source	p value								
Cropping systems (CS)	0,01	0,01	0,09	0,01	0,01	0,14	0,07	0,5	0,57
soil acidity amendments (SAA)	< 0,01	< 0,01	0,36	< 0,01	< 0,01	< 0,01	< 0,01	0,01	0,23
CS x SAA	0,77	0,48	0,68	0,29	< 0,01	0,59	0,39	0,6	0,72

Source: by the author.

Note: Pi: inorganic phosphorus; Po: organic phosphorus; PAER: anion exchange resin; P *NaHCO₃*: extracted by 0.5 M $NaHCO_3$; P NaOH 0.1, and 0.5: extracted by 0.1 and 0.5 M; P HCL: extracted by 1 M HCl; P res: extracted by H_2O_2. * Means followed by different letters differ from each other by the paired t-test ($p \leq 0.1$).

Table 4. Soil P fractions at 0.05-0.1 m soil depth affected by cropping systems after 18 years of management.

Cropping system	soil P fraction (mg kg^{-1})								
	Pi_{AER}	Pi_{NaHCO3}	Po_{NaHCO3}	$Pi_{NaOH0.1}$	$Po_{NaOH0.1}$	P_{Hcl}	$Pi_{NaOH0.5}$	$Po_{NaOH0.5}$	P_{Res}
Maize sole	20,2	28	26	126	48	24	106	22	426
Maize + Pg + Sh	23	32	26	129	50	21	109	22	428
Soil acidity amendments	Pi_{AER}	Pi_{NaHCO3}	Po_{NaHCO3}	$Pi_{NaOH0.1}$	$Po_{NaOH0.1}$	P_{Hcl}	$Pi_{NaOH0.5}$	$Po_{NaOH0.5}$	P_{Res}
Silicate	25,8	35	26	114	48	34 a	116 a	26,4 a	384 b
Limestone	18,4	29	23	126	52	21 b	108 ab	22,7	457 a
Control	20,7	27	30	141	46	15 b	98 b	17,7 b	440 a
Source	p value								
Cropping systems	0,52	0,47	0,98	0,81	0,73	0,61	0,48	0,84	0,9
Soil Acidity Amendments (SAA)	0,37	0,52	0,55	0,28	0,68	0,02	0,03	0,04	0,04
CS x SAA	0,2	0,09	0,29	0,08	0,69	0,85	0,37	0,62	0,29

Source: by the author.

Note: Pi: inorganic phosphorus; Po: organic phosphorus; PAER: anion exchange resin; P *$NaHCO_3$*: extracted by 0.5 M $NaHCO_3$; P NaOH 0.1, and 0.5: extracted by 0.1 and 0.5 M; P HCL: extracted by 1 M HCl; P res: extracted by H_2O_2.* Means followed by different letters differ from each other by the paired t-test ($p \leq 0.1$).

Table 5. Soil P fractions at 0.1- 0.2 m soil depth affected by cropping systems after 18 years of management.

Cropping system	soil P fraction (mg kg^{-1})								
	Pi *AER*	*Pi* *NaHCO3*	*Po* *NaHCO3*	*Pi* *NaOH0.1*	*Po* *NaOH0.1*	P Hcl	*Pi* *NaOH0.5*	*Po* *NaOH0.5*	*P* *Res*
Maize sole	6,7 b	12,5	22	94,9	47,9	12,2	93,2	17,1	458
Maize + Pg +	11,8 a	14,1	17	89,2	55,1	11,4	88,8	19,7	458
Soil acidity amendments	*Pi* *AER*	*Pi* *NaHCO3*	*Po* *NaHCO3*	*Pi* *NaOH0.1*	*Po* *NaOH0.1*	P Hcl	*Pi* *NaOH0.5*	*Po* *NaOH0.5*	*P* *Res*
Silicate	8,7 ab	15,6	24,6	90	47,6 b	14,4 a	94,1	18,7	452
Limestone	5,91 b	12,6	10,5	91	44,7 b	10,8 b	89,8	18,1	450
Control	13,3 a	11,7	25,1	94	62,2 a	10,1 b	89,1	18,4	471
Source	p value								
Cropping	0,09	0,69	0,41	0,48	0,1	0,47	0,31	0,36	0,9
Soil acidity Amendments	0,12	0,67	0,18	0,93	0,01	0,01	0,6	0,98	0,49
CS x SAA	0,63	0,45	0,43	0,01	0,98	0,58	0,55	0,76	0,5

Source: by the author.

Note: Pi: inorganic phosphorus; Po: organic phosphorus; PAER: anion exchange resin; P *NaHCO*$_3$: extracted by 0.5 M $NaHCO_3$; P NaOH 0.1, and 0.5: extracted by 0.1 and 0.5 M; P HCL: extracted by 1 M HCl; P res: extracted by H_2O_2. * Means followed by different letters differ from each other by the paired t-test ($p \leq 0.1$).

FINAL CONSIDERATIONS

Intercropping maize with Brachiaria and Sunn hemp under long-term no-tillage modifies P reservoirs and its effects are restricted to the soil surface, being accumulated in moderately labile and non-labile forms.

These consortia increase the input of crop residues in the area, favoring grain yield, but temporarily reducing the lability of Po and Pi in the soil in the 0-0.05 m depth layer, due to the increase in the biological stock of P. The increase in biomass production through intercropping contributes slightly to preventing the absorption of inorganic phosphate by soil colloids, increasing the organic P content of the soil without impairing the absorption of this nutrient by crops.

Liming, regardless of the corrective used, increases the pool of Pi in the soil, specifically for labile forms due to the release of P linked to Al and Fe.

Thus, the results indicate that the second crop corn intercropping with Brachiára and sunn hemp is a good option for plant diversification in the area, increasing land use efficiency and NTS sustainability in tropical agriculture, providing higher yields compared to the monoculture system.

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