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MIXTURES OF PHOSPHORUS SOURCES OF DIFFERENT SOLUBILITIES AND UPTAKE EFFICIENCY IN CORN INTERCROPPED WITH COVER CROPS

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ABSTRACT:
Tropical soils have chemical characteristics that promote the fixation of Phosphorus, causing phosphate fertilizers to have low uptake efficiency. The present work aimed to evaluate the efficiency of phosphate fertilization in corn crops with different crop systems, different sources of P and their mixtures. A completely randomized design with subdivided plots was adopted. The plots were formed of three treatments (corn cultivation systems): corn crop alone, corn intercropped with *Crotalaria juncea*, and corn intercropped with pigeon pea (*Cajanus cajan*). The subplots were formed of five treatments, created with two P sources and three mixtures between them, as follows: T1: 100% soluble phosphate (SP); T2: 75% SP – 25% partially acidulated phosphate rock (PAPR); T3: 50% SP – 50% PAPR; T4: 25% SP – 75% PAPR; T5: 100% PAPR. The consortium with the pigeon pea and the crotalaria species reduced the productivity regardless of the source or mixture of sources used. The consortium cultivation, however, made a better use of the applied fertilizer, which means it can be a tool for improving levels of P uptake in the Brazilian agriculture.

Keywords: Phosphate, *Crotalaria juncea*, *Cajanus cajan*.

MISTURAS DE FONTES DE FÓSFORO E A EFICIÊNCIA DE USO PELO MILHO EM CULTIVO CONSORCIADO COM LEGUMINOSAS

RESUMO:
Solos de regiões tropicais possuem características químicas que promovem a fixação do elemento P, fazendo com que os fertilizantes fosfatados nestes solos tenham baixa eficiência. O presente trabalho teve como objetivo avaliar a eficiência da adubação fosfatada em diferentes sistemas de cultivo, diferentes fontes de P e mistura entre essas fontes na cultura do milho. O delineamento utilizado foi o inteiramente casualizado com parcelas subdivididas. As parcelas foram formadas por três tratamentos (sistema de cultivo de milho): milho solteiro, milho consorciado com Crotalaria juncea (*Crotalaria juncea*) e milho consorciado com guandu (*Cajanus cajan*). As subparcelas foram formadas por cinco tratamentos: T1: 100% fosfato solúvel (FS); T2: 75% FS – 25% fosfato natural parcialmente acidulado (FNPA); T3: 50% FS – 50% FNPA; T4: 25% FS – 75% FNPA; T5: 100% FNPA. O consórcio com as espécies de guandu e crotalária reduziu a produtividade independente da fonte ou mistura de fontes utilizadas. No cultivo consorciado, há maior aproveitamento do fertilizante aplicado. Portanto o cultivo consorciado pode ser uma ferramenta para melhorar os níveis de utilização de P na agricultura brasileira.

Palavras-chave: Fosfato; *Crotalaria juncea*, *Cajanus cajan*.

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INTRODUCTION

The world population has about 8.0 billion people. Considering the growth rates of the recent years, it is estimated that the world population will reach 9.7 billion people by 2050 (Gu et al., 2021). This increase can strongly affect food security. For this reason, food production will have to increase by 70% in comparison to the current levels (FAO, 2018). In 2019, according to the National Supply Company (CONAB)'s numbers, Brazilian production reached 250 million tons of grains. This makes Brazil one of main food producers of the world.

The efficient use of P is of particular concern for food security and sustainable production (Parry and Hawkesford 2010). In Brazil, agriculture has grown and occupied a great part of Cerrado (Grecchi et al., 2014). In this region, Oxisols are predominant (Macedo, 1995). These soils have excellent physical characteristics to grow grains at large scales. However, considering their chemical properties, Oxisols are naturally poor in P, have high P uptake, making P one of the main restrictive factors in agricultural production. (Goedert, 1983; Novais et al., 2007; Malhi et al., 2002; Johnston et al., 2014; Roy et al.; 2016).

When P is added to the soil, it can be absorbed in labile or non-labile forms, caused mostly by precipitation and adsorption. The precipitation occurs with Fe, Al, and Ca ionic forms. The adsorption occurs with chemical bonds between phosphate ions and Fe and Al oxides present in soil (Novais; Smyth, 1999). This process limits P availability to crops and causes low P uptake efficiency (Souza et al., 2016). Sometimes, high quantities of P may be necessary, making the process expensive without obtaining high productivity.

As P is a limited resource, its use in large quantities in agriculture brings problems to the future. This way, it is necessary to look for alternatives to increase P uptake efficiency. Among some alternatives, soil management practices that increase the efficiency of phosphate fertilization are necessary. Practices such as no-till farming, which does not disturb the soil tillage, crop rotation and the maintenance of crop residues may promote an increase in organic P relative to total P. This practice may reduce P fixation because the organic form of P is less susceptible to loss, due to reduced contact of phosphate ions with soil colloids (Syers et al., 2008). A greater proportion of organic P also becomes the main reservoir of the element in the soil and nutrient supply for solution (Núñez et al., 2003; Gatiboni et al., 2007).

Some plant species can change non-labile fractions of P to its increase availability to cultures intercropped or sown later (Wang et al., 2007; Dissanayaka et al., 2017). These species promote pH changes in rhizosphere, usually by acidification, what increases the availability of species like P-Fe and P-Al. Also, they exudate substances that can chelate with Ca, Fe and Al, solving part of the P linked with the cations. Finally, they can increase acid phosphatase in rhizosphere, transforming organic P into inorganic P what improves the supply to both crop species (Marschner, 1992; Li et al., 2007).

Li et al. (2007) show corn and faba bean (*Vicia faba* L) intercropped during four years with low P rates (40 kg ha^{-1}) had an increase of 43% in the production of corn and 26% in the production of faba bean in comparison with the crop alone. The authors state that this increase in productivity occurs because the P mobilization promoted by exudates in the faba bean rhizosphere brings benefits to P uptake in both crops.

In addition to the improvement in P availability promoted by the reactions in the rhizosphere of the legume, there is an increase in the uptake efficiency of this nutrient. This benefit occurs due to a growth in root mass and, consequently, a larger nutrient uptake. Also, there is a temporal benefit in the nutrient uptake since the species have a maximum demand for nutrients in different periods (Seran; Brintha, 2010; Matusso et al., 2014).

Several studies with lower P solubility attest its good efficiency. However, a mixture of different solubilities is an alternative not much explored that brings good results and increases P uptake efficiency. Bedin et al. (2003) and Motomiya et al. (2004) have shown that the mixture between soluble sources with low solubility sources presents similar results to sources with total solubility.

As presented above there are several alternatives that seek to improve the performance of phosphate fertilization. The combined use of these alternatives in a management system may be an efficient measure. Therefore, the objective of this work is to evaluate the mixture of P sources with different solubilities associated with the use of legumes intercropped with corn and analyze their effects on corn productivity and the P uptake efficiency in these systems.

MATERIAL AND METHODS

The experiment was carried out in the experimental station of the Federal University of Tocantins, at Gurupi, located at coordinates 11º43`S and 49º04`W, in a soil classified as Oxisoil (Santos et al., 2018). The soil characteristics can be found in Table 1 and the weather data during the cultivation period in Figure 1.

Table 1. Soil chemical and textural analysis of the cultivated area 60 days before planting.

Ca	Mg	K	Al	H+Al	T	V%
	--------------------------------	cmol$_c$ dm^{-3}	--------------------------------			
2,1	0,4	0,06	0,3	1,9	4,5	56,8
m%	pH CaCl$_2$	P mg dm^{-3}	Org. Matter g kg^{-1}	Sand	Clay	Silt
				--------------	g kg^{-1}	------------
12,7	5,4	10,0	26,9	470,1	330,9	199,0

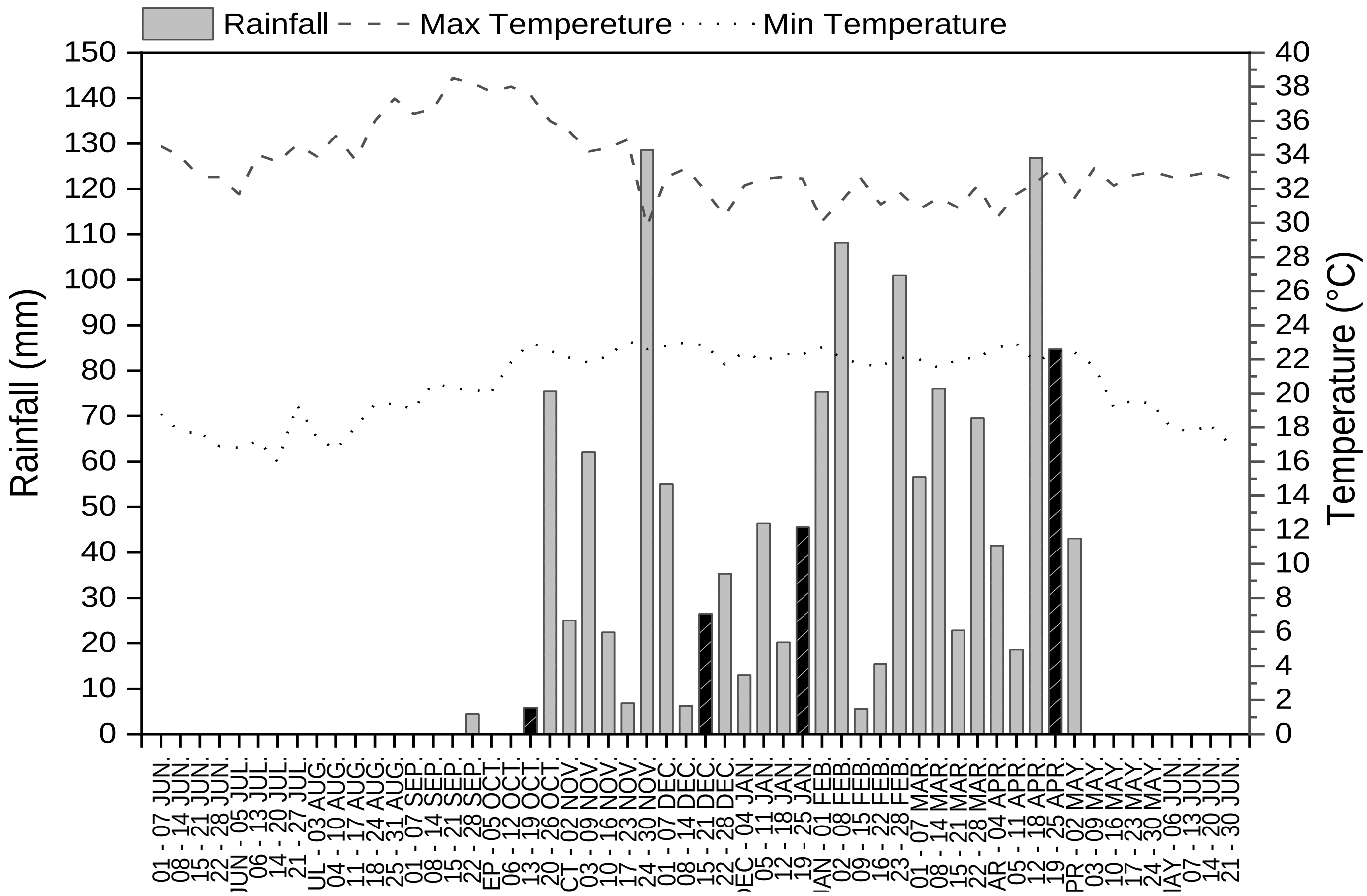

Figure 1. Climate data of the cultivation period in the region of Gurupi, Tocantins, Brasil. The black bars indicate the operations with the covers crops, 1st cut, corn planting, 2nd cut and harvest.

The experiment was conducted in an area that had been under no-till system for seven years. A completely randomized design with subdivided plots and four replications was adopted. The plots were formed of three treatments (cultivation systems of corn): single corn, corn intercropped with *Crotalaria juncea*, and corn intercropped with pigeon pea (*Cajanus cajan*).

The subplots were formed of five treatments created from two P sources and three mixtures between them: T1: 100% soluble phosphate (SP); T2: 75% SP – 25% partially acidulated phosphate rock (PAPR); T3: 50% SP – 50% PAPR; T4: 25% SP – 75% PAPR; T5: 100% PAPR. The SP was applied as simple superphosphate and the PAPR used presents guaranties 9% P_2O_5 in Neutral ammonium citrate, 16% of Ca, and 2,9% of S. The P dose used was 100 kg ha^{-1} of P_2O_5.

To implement the experiment, cover plants were initially sown (*C. juncea* and pigeon pea) in alternating rows with 1.5 m between them. 65 days after sowing (DAS) the cover plants, cover plants were cut at 40 cm height and their residues were put on the soil surface to create a cover. The corn was sown three days after the cut of the cover plants. In the intercropped treatments, the corn was sown on the cover plant side. The phosphate fertilizer was applied banded to the surface of the soil close to the corn. To complete the corn nutrition, N and K were applied in top-dressing fertilization in two parts, at 18 and 35 DAS. The dose applied was 130 kg ha-1 of N and 100 kg ha-1 of K_2O, with urea and KCl as sources respectively.

At 35 days after sowing the corn, before the second application of N and K, the cover plants were cut again to avoid competition for light with the corn. The residues of the cover plants were put on the soil surface again. On this occasion, the dry mass production of the cover crops was determined and a part of the residues were used for foliar analysis.

The corn was harvested at 120 DAS. The parameters evaluated were the dry mass and the grain production. To determine the dry mass production of the corn and the cover plants, two plant samples were collected from each plot, put in a paper bag, and dried for 72 hours at 65 ºC. After the dry mass determination, the material was milled in the Willey mill with 20 mesh sieves and sent to the laboratory for nutrient analysis. To determine the grain production, all ears of each plot were harvested, thrashed, and weighed in an analytical scale to obtain the productivity value in kg ha-1. The data were submitted to analysis of variance and, when necessary, the averages obtained were compared to the Scott-Knott test at 5% significance.

Production data and P levels in the cover plants and the corn were used to calculate the partial nutrient balance (PNB), as described in Syers et al. (2008). This method calculates P uptake efficiency considering the amount of nutrients applied and extracted by the culture.

RESULTS AND DISCUSSION

The dry mass results of the cover crops obtained in the second cut 100 days after sowing the cover plants and 35 days after sowing the corn are in Table 2. The *C. juncea* presents a higher productivity of 626,8 kg ha^{-1} than the pigeon pea. This result may occur due to the slow initial development of the pigeon pea in relation to the *C. juncea*, as reported by Almeida (2001), Formentini (2008) and Rayol & Alvino-Rayol (2012). This slow development results in a slower absorption of light, water, and nutrients.

The cover crops did not respond to the phosphorus sources and mixtures, not presenting a significant difference between these treatments in dry mass production. This occurs because the species used have P solving capacity. Therefore, the initial P levels in the soil are not a limitation for these species.

Table 2. Dry Mass of cover plants 100 DAS (2nd cut) under different phosphorus sources and mixtures.

Cover Plant	*C. juncea*	*Pigeon pea*	Average
Treatment	------------------------------ kg ha^{-1}	--------------------------------	
T1	2004,5	1352,25	1678,38 a
T2	1849,00	1348,75	1598,88 a
T3	1780,75	1096,75	1438,75 a
T4	1930,25	1297,50	1613,88 a
T5	1843,5	1178,75	1511,13 a
Average	1881,6 a	1254,8 b	

Averages followed by the same letters do not differ by the Scott-Knott test at 5%.

Some rhizobacteria make symbiosis with legume plants such as the rhizobium genus, which acts to promote growth via P solubilization in the rhizosphere of the legume plants (Deshwal et al., 2003; Sridevi et al., 2007). This way, the low PAPR solubility is not the problem, since the root microorganisms in the *C. juncea* and the pigeon pea can improve P uptake for the plants. Results like these are found in Pott et al. (2007) where they used pigeon pea and obtained higher dry mass using phosphate rock (PR) due to the legume's high P uptake efficiency. Likewise, the roots of *C. juncea* are colonized by mycorrhizal fungi which have high capacity to solve species of P present in the soil, increasing P uptake by the plants (Colozzi; Cardoso, 2000; Germani; Plenchette, 2005; Benkhoua et al., 2017).

In Table 3, the results of corn production in different system cultivation can be found. There was no significant difference in the Scott-Knot test between the cultivation systems. The single corn treatment presented higher production averages, followed by the corn intercropped with pigeon pea. The cut of the cover plants made in the initial stage of the corn growth, reduced competition for light, allowing for a good corn development, regardless of the consortium.

Table 3. Production of corn grains under different cultivation systems and different sources of phosphorus and mixtures.

Cultivation system	Single corn	Corn and C. Juncea	Corn and pigeon pea	Average
Treatment	kg ha $^{-1}$			
T1	6564,00 a	6415,00 a	5645,33 a	6208,11 b
T2	8126,00 a	7249,33 a	6922,99 a	7432,77 a
T3	6842,66 a	5059,66 b	6496,60 a	6132,97 b
T4	8422,33 a	5470,00 b	5598,99 b	6497,10 b
T5	8533,83 a	6868,00 a	7820,00 a	7740,61 a
Average	7697,76 a	6212,39 a	6496,78 a	

Averages followed by the same letters do not differ among themselves in the Tukey test at 5% probability, CV between plots 15.5% and for subplots 14.5%.

Studies carried out by Pereira et al. (2011) with consortium corn/crotalaria have shown that the fast development of cover plants can limit corn productivity due to competition. However, the cut made in the initial stage of the corn promoted balance in the system, reducing the negative effects of competition.

In relation to the treatments with phosphate fertilizers, the highest productivity was obtained using T5, followed by T2, both differing from the other treatments. The treatment T5 is 100% of PAPR. This fertilizer is made by adding sulfuric acid or phosphoric acid in low quantities to the phosphatic concentrate. This process increases P availability. In some cases, agronomic efficiency becomes equivalent to a totally soluble source or even surpasses it (Rajan,1985; Bolland et al., 1992).

The PAPR presents two P release and solubility profiles. One part is quickly solved and the other is solved in a moderate way, creating a slow release profile (Bolan et al., 1990; Hoffman et al., 2013; Diatta et al., 2018). This helps to explain the highest performance of T5, where the fast soluble P part was enough to start the development of the corn, while the slow release part helped to reduce losses in P fixation and supplied the plant throughout the remaining cycle. Rodriguez and Herrera (2002) report that the use of PAPR can be an interesting tool for tropical soils and the increase of P efficiency.

P content in corn tissues can be found in Figure 2. The results do not show differences between the cultivation systems and treatments with different sources and mixtures. The average of P content is within the range considered satisfactory for corn culture (Martinez et al., 1999). In this case, P is not a limitation to the experiment.

It was also observed that the intercropped corn had higher P content in foliar tissue, in which the average had 0,82 g kg-¹ to a consortium with *C. juncea* and pigeon pea and 0,69 g kg-¹ to single corn. This result occurred due to N natural fixation promoted by the legume cover plants. High N supplement promotes an increase in P absorption (Akinnifesi, et al., 2007; Oliveira et al., 2009; Larimer et al., 2014). This way, a *C. juncea* and pigeon pea had influence in P uptake, as shown in the results found by Silva et al. (2012).

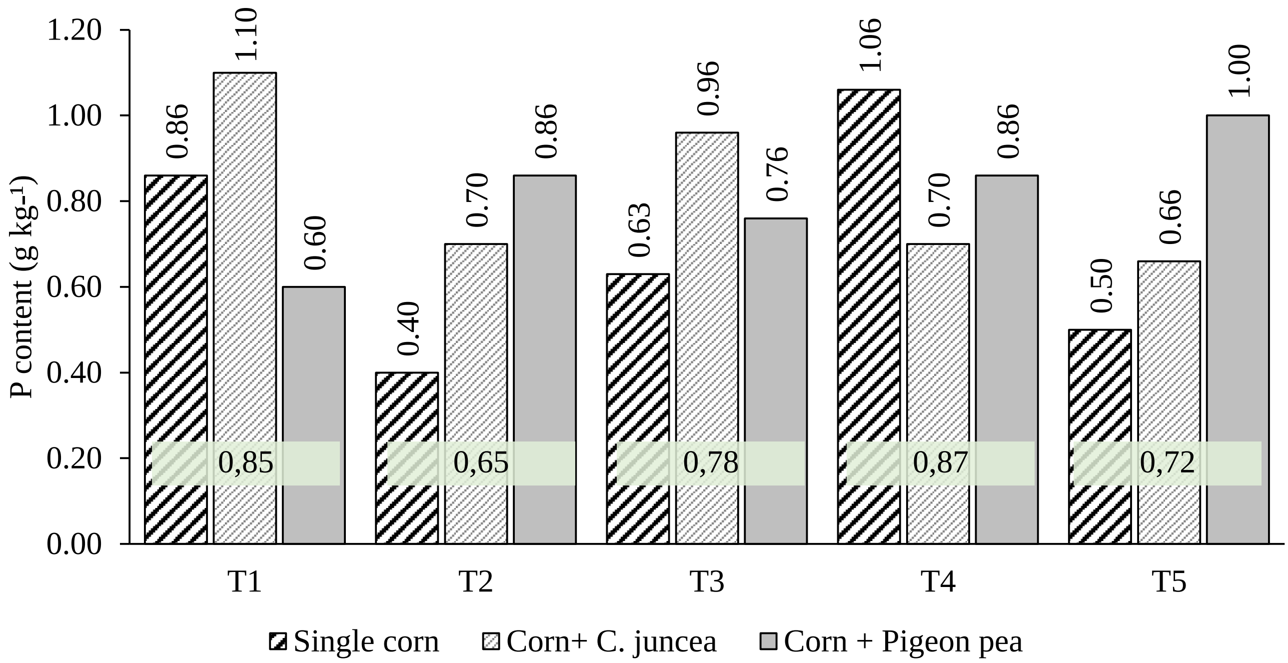

Figure 2. P content accumulated in the shoot of the corn submitted to different types of cultivation and different phosphate fertilization treatments.

Using the corn and the legume production data and their respective P foliar content, the PNB was calculated to verify the P uptake efficiency in different crop systems and combinations of sources. The adopted method was based on the ratio between the P removed by the harvest (phosphorus coming from the applied fertilizer and from the soil reserves) and the P applied to the soil system via fertilizations. The ideal balance for a cultivation system is when values range between 0.5 and 0.7. If the nutrient balance shows values higher than one, it means the plant absorption was higher than what was applied, what can lead to soil reserves exhaustion. On the other hand, if the balance is below 0,5, it means that the P fertilizer used was inefficient, that is to say, the applied P did not influence the productive potential of the cultivation system (Syers et al., 2008; Roberts; Johnston, 2015). The results of PNB are in Figure 3.

Adopting PNB to evaluate P uptake efficiency, it was observed that the average efficiency was 18% to single corn, 32%, and 29% when intercropped with *C. juncea* and pigeon pea respectively. In relation to the sources and their mixtures, the results are similar. T3 and T5 showed the lowest efficiency (20%) and T4 had the highest efficiency (23%). The consortium corn/legume regardless of the source or mixture increased P uptake efficiency by 12,5%. However, even with improvement, the levels are considered low according to Syers et al. (2008).

Silva et al. (2012), using P recovery rate as a method to evaluate P uptake efficiency in corn, vefied that the consortium presented a better average of around 13,12% in efficiency. Some studies using 32P showed that P efficiency in corn rarely reaches 10% (Franzini et al. 2009). These researchers also report that low P efficiency in phosphate fertilizers is the result of many causes, mainly associated with P dynamics in the soil. Roberts and Johnston (2015) reinforce that the evaluation of the efficiency of phosphate fertilizers in the year of its application can be very incipient since it is known to range between 10 and 15%.

The efficiency of phosphate fertilizers regardless of the source increases with time if an adequate management is adopted, according to Nunes (2014). Evaluating phosphate fertilization in Cerrado soils for 17 years, the author found that in the first years there is a "soil correction phase" in which the efficiency is below 20%.

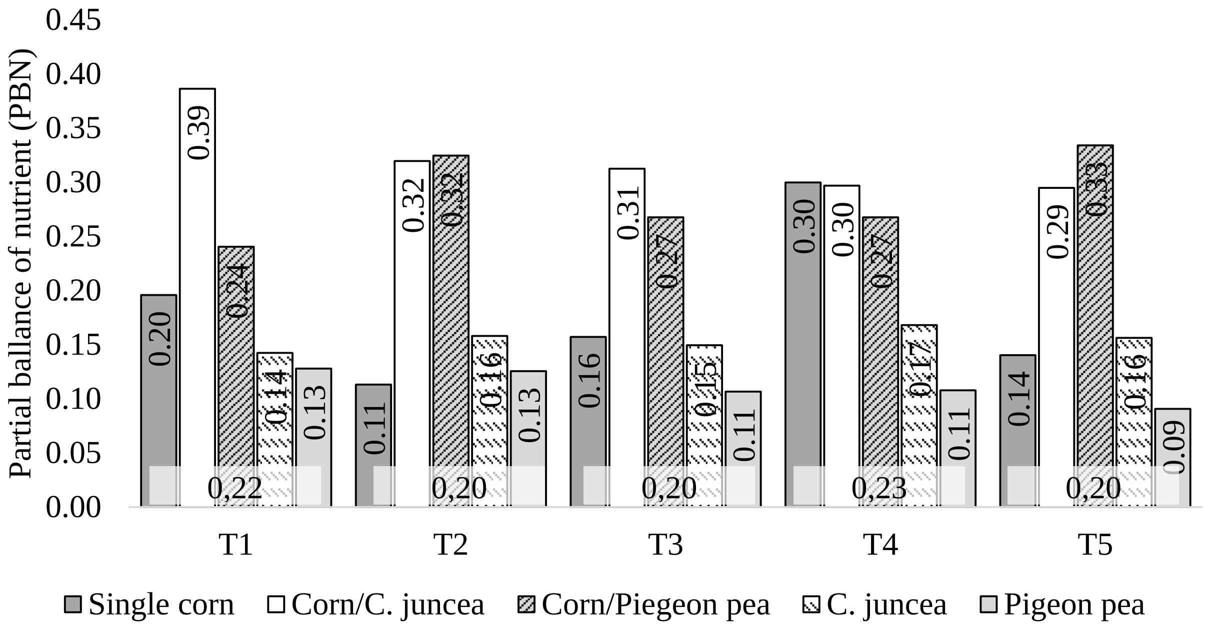

Figure 3. Balance of nutrient uptake by the corn and cover crops under different combinations of phosphorus sources.

However, with time, this efficiency can reach 80% in no-till systems. The successive cultivation without soil rotation, with alternation of cover plants between legumes and grasses, promotes an increase in organic matter and microbial activity of the soil that benefits nutrient cycling (Collier et al., 2008; Heinrichs et al., 2005). Transformations of non-labile P into readily available P can occur to the corn. The presence of green manure in the consortium can be beneficial to the system, but it can also have negative effects to the production of corn and the production of vegetable mass in both species of the consortium (Chieza et al., 2017). This difference was observed in this work. Whether or not to choose the consortium must be the result of a thorough analysis that also takes into account economic aspects. In relation to using cover crops when compared to corn alone, both the crotalaria and the pigeon pea showed less P uptake efficiency supplied via fertilizer. This behavior may be the result of the low productive potential of the period they were introduced.

CONCLUSION

The mixture of different proportions of SP and PAPR brings different results to corn production. PAPR can be used as a whole or in part (up to 25%) in a mixture with another soluble source without any damage from an agronomic point of view. In addition, it constitutes an economic benefit since it is usually a cheaper source. The consortium with pigeon pea and crotalaria species reduced productivity regardless of the source or mixture of sources used. In consortium cultivation, there was a larger uptake of the applied fertilizer, which means that consortium cultivation can be a tool for improving levels of P uptake in Brazilian agriculture. The improvement obtained in the year of implementation of the phosphate fertilizer did not reach considerable levels, as about 70% of the applied P remained in the soil without being used and susceptible to reactions that promote unavailability in tropical soils. The continuity of this cultivation system may be the key for reaching adequate levels of the applied fertilizer uptake that promote the system sustainability. However, more studies are still needed to validate this hypothesis.

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