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Cover crop species and mycorrhizal colonization on soil phosphorus dynamics

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ABSTRACT

Phosphorus (P) plays an important role in the physiological plant processes; however, in tropical soils, P is one of the most limiting nutrients for crop yield due to its low mobility, determined by the adsorption of this element to the soil. To enhance P-use and P-acquisition efficiency, this research aimed to evaluate the effect of cover crops and mycorrhizal colonization on changing soil P fractions, both organic and inorganic. A complete randomized block design was adopted in a field experiment, with four replications using four cover crops: i) pigeon pea (*Cajanus cajan*); ii) crotalaria (*Crotalaria juncea*); iii) millet (*Pennisetum glaucum*); iv) brachiaria (*Brachiaria ruziziensis*) and v) fallow, as control. The arbuscular mycorrhizal fungus colonization, the fungal spore density, soil P fractionation, and N, P, and K uptake were assessed. Our results show that cover crops affected the soil P cycling in deeper soil layers. Cover crops may increase arbuscular mycorrhizal inoculum potential for the succeeding crop in rotation or intercropping, when used as a green manure.

1. Introduction

Phosphorus (P) plays an important role in the physiological plant processes (Marschner, 2011). However, in tropical soils, P is one of the most limiting nutrients for crop yield due to its low mobility, with a rate of diffusion of P about 10^{-12} to 10^{-15} m^2 s^{-1} (Lewis and Quirk, 1967; Schachtman et al., 1998), which is determined by the adsorption of this element to the soil (Parfitt, 1979; Rodrigues et al., 2016), which is in turn driven by the abundance and distinct types of Fe/Al oxyhydroxides as consequence of the soil formation processes (Khan et al., 2010; Roy et al., 2016).

When adjusting P for plant requirements solely, some agricultural areas in Brazil have reached high P content because of the high amount of fertilizer used to overcome P losses by adsorption (Oliveira Lima et al., 2007; Withers et al., 2018; Oliveira et al., 2020), mainly using soluble fertilizers which causes immediate P solubilization. However, these sources also show a high P adsorption in the soil solid phase.

Beyond P fertilizer application, other strategies to increase P-use efficiency involve the use of cover crops that favour microorganisms' action in soils, aiming to ameliorate soil conditions for plant development (Soltangheisi et al., 2020). Cover crops used as green manure primarily act as a soil amendment and a nutrient source for subsequent crops (Cherr et al., 2006). Those crops have a potential to release low-molecular-weight organic acids, which can compete for soil P adsorption sites (Sposito, 2008). These compounds play a vital role in the solubilization of P, especially non-labile P, making it available for the subsequent crop, improving the use of soil residual P and consequently reducing the demand of P fertilizers (Chien and Menon, 1995).

Numerous cover crops may enhance symbiotic association with arbuscular mycorrhizal fungi (AMF) which are key drivers of P cycling, by increasing the root area through the extraradical hyphal network, permitting a more efficient exploration of a larger soil volume (Mikkelsen et al., 2008; Fortuna et al., 2012) thus facilitating the contact between roots and P, improving the plant uptake (Karasawa and Takebe, 2012). This may help P cycling and maintain arbuscular mycorrhizal spores in the soil for root colonization of the subsequent crop season (Njeru et al., 2013; Turrini et al., 2016). These dynamics of P under tropical environments justifies more research related to

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Table 1
Chemical[a] and granulometric[b] characterization of the soil in three layers 0–5; 5–10; 10–20 cm before trial establishment. Piracicaba - SP, Brazil.

Soil Layer	pH_{CaCl2}	P	Al	H + Al	Ca	Mg	K	V	Clay	Silt	Sand
cm		mg dm^{-3}						%	g kg^{-1}		
0–5	5.5	31	<9	569	1082	146	235	72	574	126	299
5–10	5.5	19	<9	611	1202	146	145	71	596	107	297
10–20	5.6	13	<9	535	1022	146	70	70	594	121	285

[a] (Raij et al., 2001)
[b] (Camargo et al., 1986)

soil-plant-microorganism interactions, to acquire more information about the P dynamics in these conditions.

We hypothesised that cover crop plants may establish fungi mycorrhizal colonization, increasing P solubilization from soil, which could improve P-use efficiency in the cropping system over time. We aimed to evaluate the effect of cover crops and mycorrhizal colonization on changing soil P fractions, both organic and inorganic.

2. Material and methods

2.1. Site description

The study was established in the experimental area of Luiz de Queiroz College of Agriculture – ESALQ/USP, in Piracicaba-SP, Brazil (22°41′32″S, 47°38′39″W), altitude 560 m above sea level. The local climate is classified as Cwa (C: temperate; w: dry winter; a: hot summer) (Köppen, 1931), with average annual temperature of 20.8 °C and average annual precipitation of 1255 mm. The soil is a Typic Acrustox (Soil Survey Staff, 2014). Before trail establishment, the area was cropped with maize (*Zea mays*), soybean (*Glycine max*) and fallow, in the last three summer crop seasons, respectively. Soil was characterized for initial chemical and granulometric parameters as presented in Table 1.

2.2. Experimental design and treatments

The experiment was carried in a randomized block design with four cover crops species: i) pigeon pea (*Cajanus cajan*); ii) crotalaria (*Crotalaria juncea*); iii) millet (*Pennisetum glaucum*); iv) brachiaria (*Brachiaria ruziziensis*) and v) fallow, as control.

Treatments were replicated in four blocks and plot size was 5 × 5 m, totalling 25 m^2. The row spacing used for all crops at sowing was 0.40 m, and the seed density was: i) pigeon pea: 35 kg ha^{-1}; ii) crotalaria:12 kg ha^{-1}; iii) millet: 12 kg ha^{-1}; and iv) brachiaria: 10 kg ha^{-1}. Cover crops were sown in November of each year and cultivated during the rainy season (summer) of 2012/2013 and 2013/2014, with winter fallow for all plots except for the perennial brachiaria, which was kept growing over the two years. The management of the cover crops was based on the recommendation for each species. During summer, the weeds in the fallow treatment were controlled monthly through the application of herbicide, glyphosate (2 L a.i. ha^{-1}). Weeds were controlled through manual weeding in cover crop plots.

2.3. Soil and plant evaluations

Soil samples were collected in April 2014, at 0–5; 5–10 and 10–20 cm layers, for chemical P fractionation. Each soil sample was composed of five subsamples. The soil samples were air dried and P fractionation was performed according to Hedley et al. (1982), modified by Condron et al. (1985). Briefly, 0.5 g of soil was used for a sequential extraction. The first extractor was the anion-exchange membrane resin (AER) which was shaken (16 h; 33 rpm) in an end-over-end shaker with water (10 mL) and the soil. Afterwards, the P extracted from the soil by the resin was transferred to a 0.5 M HCl solution to determine inorganic readily available P (Pi_{AER}). Then, the water was separated from the soil by centrifuging to be discarded. In the same soil the next extractor was added: a solution (10 mL) of 0.5 M $NaHCO_3$ at pH 8.5 and shaken (16 h; 33 rpm) in an end-over-end shaker. Afterwards, the extractor was separated from the soil by centrifuging to determine the inorganic labile Pi (Pi_{NaHCO3}). This procedure was made subsequently for the extractors: 0.1 M NaOH ($Pi_{NaOH0.1}$); 1.0 M HCl (Pi_{HCl}) and 0.5 M NaOH ($Pi_{NaOH0.5}$). After sequential extraction, the soil was oven dried (24 h; 60 °C), macerated and submitted to a digestion with saturated MgCl, H_2SO_4 and H_2O_2 ($P_{Residual}$).

Additionally, an aliquot of all the alkaline extractors were sampled to proceed the digestion in autoclave with H_2SO_4 and $(NH_4)_2S_2O_8$ (2 h; 121 °C) for the total P determination (inorganic + organic). The organic fractions were then estimated by calculating the difference between total and inorganic P in each extractor. The determination of P in the acid extracts was done as by Murphy and Riley (1962); and in the alkaline extracts as by Dick and Tabatabai (1977). P fractions were clustered by lability: labile P comprised the Pi_{AER}, Pi_{NaHCO3}, and Po_{NaHCO3}; moderately labile P comprised the fractions $Pi_{NaOH0.1}$, $Po_{NaOH0.1}$, and P_{HCl}; and non-labile P comprised $Pi_{NaOH0.5}$, $Po_{NaOH0.5}$, and $P_{residual}$. Balance of soil P fractions was calculated by the difference of the weighted means (according to the soil layers: 0–5; 5–10; and 10–20 cm) as follows:

$$Pb = Pcc - \mathrm{pf}$$

where Pb: P balance (mg kg^{-1}); Pcc: P of the cover crop (pigeon pea, crotalaria, millet, brachiaria) and; Pf: P of the fallow treatment.

Plant tissue was sampled in April of 2013 and 2014, when most of the crops were in the reproductive/final stage (except brachiaria). Shoot samples were cut at the soil surface, harvesting 1 m^2 in each plot. Then, the samples were dried at 60 °C and weighted to estimate dry mass (DM). For nutritional status, shoot samples from the harvest in 2014 were used (1 mm; Wiley). Chemical digestion was performed to estimate N, P and K content (Malavolta et al., 1997), which was used later for determining total uptake of N, P and K.

At harvest in 2014, soil was also sampled for spore density analysis within each plot at five equidistant points to form a composite sample at a depth of 0–20 cm. These samples were kept refrigerated (4 °C) until the time of the analysis. The determination of the spore density was carried out according to Gerdemann and Nicolson (1963). This opportunity was also used to collect roots of all cover crops for mycorrhizal colonization evaluation, selecting some of the thinnest and most superficial roots of each species, and stored in 70% ethyl alcohol before analysis. For colonization analysis, the roots were stained with blue ink (Vierheilig et al., 1998) and analysed according to Giovannetti and Mosse (1980).

2.4. Statistical analysis

All the data were tested for normality with Shapiro-Wilk's tests, and homogeneity with Bartlett's tests. When suitable, transformations were performed using Box-Cox techniques (Box and Cox, 1964). Outliers were removed when needed, before performing the analysis of variance (ANOVA).

The data were processed with one-way (cover crop) analysis of variance (ANOVA) at a 0.10 error probability. Soil P fractions and lability data were analysed, with each soil layer being analysed

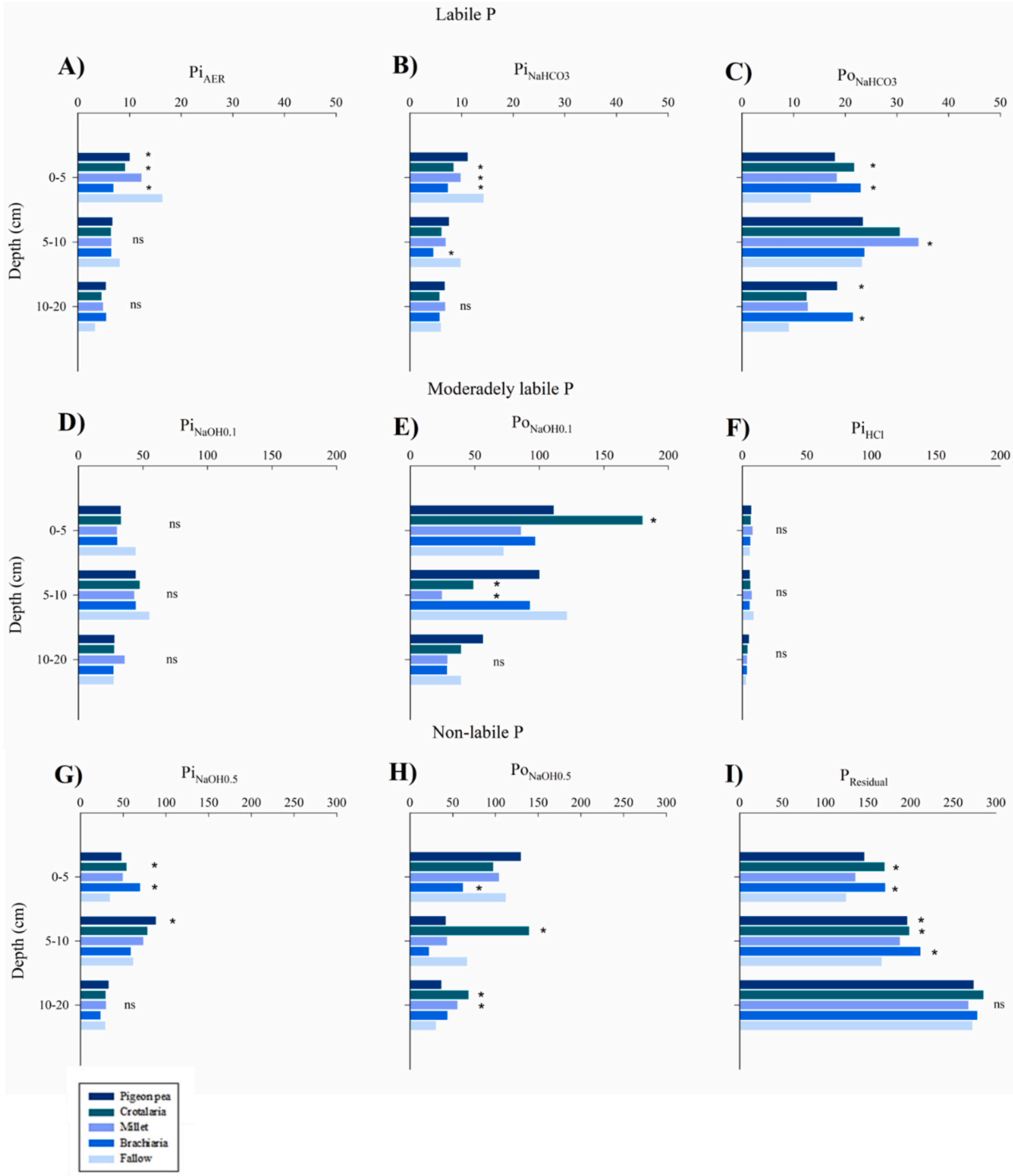

Fig. 1. Soil P fractions in the three soil layers 0–5; 5–10; 10–20 cm, following the growth of four cover crops (pigeon pea; crotalaria; millet; or brachiaria) and fallow. Results are presented according to the P fractions: **A)** Pi_{AER}; **B)** Pi_{NaHCO3}; **C)** Po_{NaHCO3}; **D)** $Pi_{NaOH0.1}$; **E)** $Po_{NaOH0.1}$; **F)** Pi_{HCl}; **G)** $Pi_{NaOH0.5}$; **H)** $Po_{NaOH0.5}$; **I)** $P_{Residual}$. * means significant difference of the cover crops in comparison to fallow by Dunnett test ($p \leq 0.10$). ns: non-significant by Dunnett test ($p > 0.10$).

separately. The means for soil P fractionation were compared using Dunnett test ($p \leq 0.10$). The mean for the plant nutrient uptake and mycorrhizal features were compared using Tukey test ($p \leq 0.10$). The program SAS 9.4 (SAS Inc., Cary, USA) was employed to conduct all statistical analysis and the graphs were designed in Sigma Plot (Systat Software, San Jose, CA).

Multivariate analysis was performed using a principal component biplot for the variables: Labile P (weighted mean for 0–40 cm); moderately labile P (weighted mean for 0–40 cm); non labile P (weighted mean for 0–40 cm); shoot N uptake (2014); shoot P uptake (2014); shoot K uptake (2014); accumulated shoot dry matter (2013 and 2014); spore density (2014) and; mycorrhizal colonization (2014). The data were separated by plant groups: legumes (pigeon pea and crotalaria) and grasses (millet and brachiaria). Multivariate statistical and graph were performed using the program PAST 2.17c (Hammer et al., 2001).

3. Results

3.1. *Cover crops effect on soil P lability*

An overview of the results show that cover crops have depleted the inorganic labile P in the top-layer soil (0–5 cm) compared to the fallow treatment, irrespective of the plant species used (Fig. 1A and B). On average, cover crops dropped by 7 mg kg^{-1} of Pi_{AER} in this superficial layer compared to fallow (Fig. 1A). For Pi_{NaHCO3} the same trend was observed, dropping on average 5 mg kg^{-1} under cover crops compared to fallow (Fig. 1B). Similar dynamics for Pi_{NaHCO3} was observed in the

Table 2
Balance of soil P fractions under four cover crops (pigeon pea; crotalaria; millet; or brachiaria) compared to fallow as control. Results are the weighted means of the three soil layers: 0–5; 5–10; 10–20 cm. Balance is the sum of all the P fractions per lability. Negative values indicate P reduction and positive values indicate P surplus.

Cover crop	Labile P				Moderately labile P				Non-labile P			
	Pi_{AER}	Pi_{NaHCO3}	Po_{NaHCO3}	Balance	$Pi_{NaOH0.1}$	$Po_{NaOH0.1}$	Pi_{HCl}	Balance	$Pi_{NaOH0.5}$	$Po_{NaOH0.5}$	$P_{Residual}$	Balance
	mg kg^{-1}											
Pigeon pea - Fallow	−0,9	−0,9	5,9	**4,1**	−5,2	12,9	0,6	**8,3**	11,8	10,9	13,5	**36,2**
Crotalaria - Fallow	−1,6	−2,6	5,7	**1,5**	−4,5	3,2	0,2	**−1,1**	9,1	33,5	25,8	**68,4**
Millet – Fallow	−0,6	−1,4	5,8	**3,9**	−2,2	−26,1	0,6	**−27,6**	4,1	4,8	5,6	**14,5**
Brachiaria - Fallow	−3,1	−3,2	8,5	**2,2**	−6,2	−4,7	−0,3	**−11,3**	5,2	−17,0	25,6	**13,7**

5–10 cm layer, reducing on average 4 mg kg^{-1} under cover crops (Fig. 1B). Otherwise, cover crops were able to increase organic labile P (Po_{NaHCO3}) in all soil layers assessed (Fig. 1C), however this change was not always significant for some cover crops in all soil layers compared to fallow.

Moderately labile Pi ($Pi_{NaOH0,1}$ and Pi_{HCl}) was not affected by cover crops (Fig. 1D and F), but the Po pool ($Po_{NaOH0,1}$) was affected by cover crops, with a significant increase under crotalaria in the 0–5 cm layer (Fig. 1E), although all species have depleted this fraction in the layer 5–10 cm, compared to fallow.

Regarding the inorganic non-labile P, cover crops increased ~20 mg kg^{-1} of $Pi_{NaOH0.5}$ in the 0–5 cm layer, compared to fallow (Fig. 1G), with some increase also in the soil layer 5–10 cm. In the deepest layer (10–20 cm), cover crops increased the organic non-labile P ($Po_{NaOH0.5}$), on average, by 20 mg kg^{-1} compared to fallow (Fig. 1H). $P_{Residual}$ increased under cover crops compared to fallow, where crotalaria and brachiaria were the main contributors in the top-soil (0–5 cm) and pigeon pea, crotalaria and brachiaria contributed to the increase in $P_{Residual}$ in 5–10 cm layer (Fig. 1I).

Furthermore, cover crop species presented distinct effects on P pools. Pigeon pea showed higher labile organic P (Po_{NaHCO3}) in the 10–20 cm layer compared to fallow (Fig. 1C). This legume showed an incremental effect in the organic moderately labile P across the profile (0–40 cm) (Fig. 1E), resulting in an increase of 13 mg kg^{-1} in the moderately labile P balance compared to fallow (Table 2). Due to this increase in the moderately labile organic fractions, pigeon pea was the only cover crop able to rise the moderately labile P balance (Table 2).

Crotalaria showed an increase in the labile organic P (Po_{NaHCO3}) in the layer 0–5 cm (Fig. 1C). However, crotalaria was the crop with the lowest contribution of labile P (Table 2), mainly due to the reduction in inorganic labile P in comparison to fallow (Fig. 1A and B). This crop also showed the highest value of organic moderately labile P ($Po_{NaOH0.1}$), ~180 mg kg^{-1}, in the 0–5 cm layer (Fig. 1E). Moreover, in the layer 5–10 cm crotalaria increased the non-labile organic P ($Po_{NaOH0.5}$) by ~70 mg kg^{-1} in comparison to fallow (Fig. 1H), which was the highest increase of non-labile P balance (68.4 mg^{-1}) in the 0–20 cm soil profile (Table 2).

Millet was efficient at increasing the labile organic P in the 5–10 cm, with an increase of ~5 mg kg^{-1} in comparison to the fallow (Fig. 1C). However, millet reduced by ~100 mg kg^{-1} in the moderately labile organic P, in the layer 5–10 cm (Fig. 1E) and showed the most negative value in the moderately labile P balance (−27.6 mg kg^{-1}), in comparison to fallow (Table 2).

Brachiaria promoted an increase of organic labile P (Po_{NaHCO3}) in the 0–5 and 10–20 cm layers, compared to fallow (Fig. 1C), but maintained constant the labile organic P concentration in the whole 0–20 cm profile. In the 0–5 cm and 5–10 cm layer, brachiaria reduced organic non-labile P ($Po_{NaOH0.5}$) (Fig. 1H), increased $Pi_{NaOH0.5}$ in the layer 0–5 cm and increased the $P_{Residual}$ in the layers 0–5 and 5–10 cm, compared to fallow (Fig. 1G and I). Therefore, brachiaria had a high increase in inorganic non-labile P to the detriment of organic non labile P fractions.

3.2. Plant nutritional status

Brachiaria and pigeon pea showed the highest values of N uptake (54 and 49 kg ha^{-1}, respectively), followed by crotalaria (35 kg ha^{-1}) (Fig. 2A). For P and K uptake, brachiaria showed the highest values (88 and 141 kg ha^{-1}, respectively) compared to the other crops (Fig. 2B and C).

4. Mycorrhizal features and principal component analysis

Millet presented the highest spore density, with about 920 spores kg^{-1} of soil (Fig. 3A), followed by brachiaria (400 spores kg^{-1} of soil). In contrast, pigeon pea and crotalaria presented the lowest spore density. Furthermore, both legumes, followed by brachiaria showed the highest percentage of mycorrhizal colonization (Fig. 3B), but millet had a substantially lower percentage than the other crops.

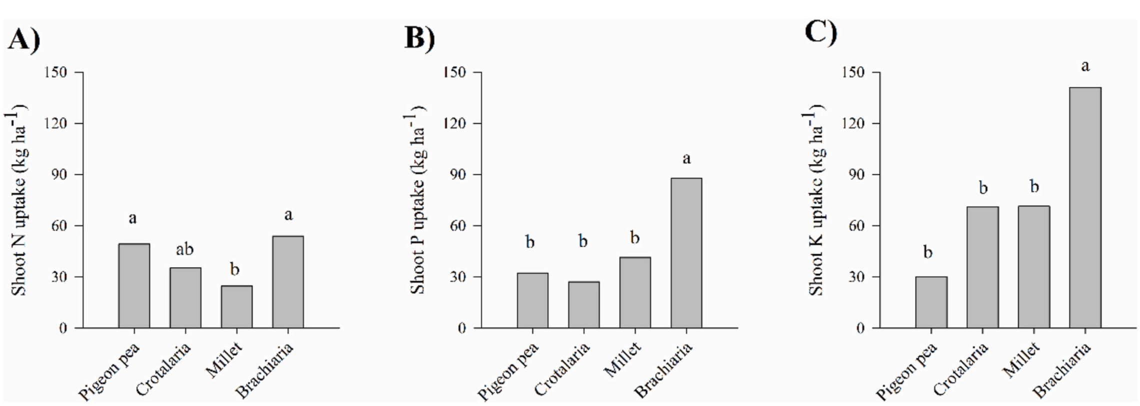

Fig. 2. Plant nutrient uptake (N, P, K) of four cover crops (pigeon pea; crotalaria; millet; or brachiaria) and fallow. **A)** Shoot N uptake; **B)** Shoot P uptake; **C)** Shoot K uptake. Same letters do not show significant difference between cover crops by Tukey test ($p > 0.10$). Values in A, B and C are referent to 2014 evaluation.

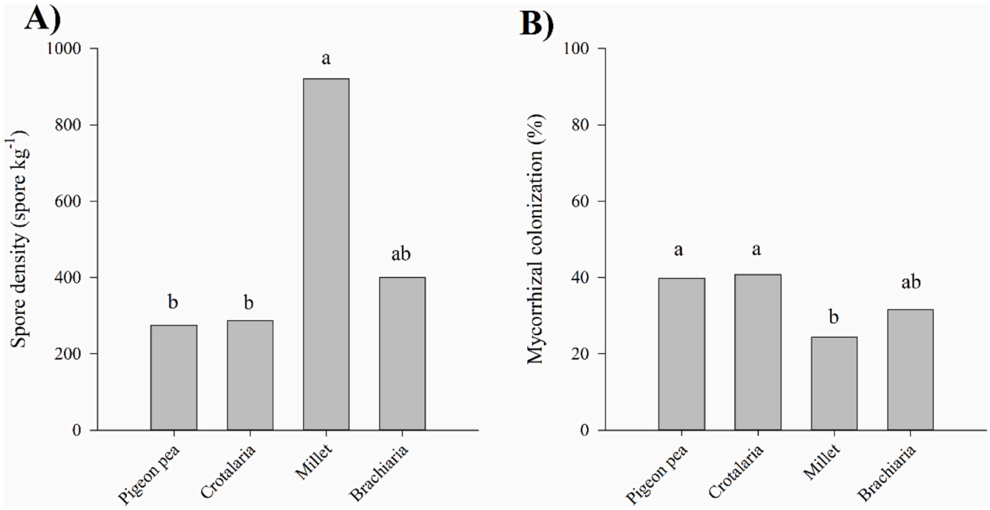

Fig. 3. **A)** Soil spore density; **B)** Root mycorrhizal colonization under four cover crops (pigeon pea; crotalaria; millet; or brachiaria) and fallow as control. Same letters do not show significant difference between cover crops by Tukey test ($p > 0.10$).

5. Discussion

We evaluated how cover crop species affected the soil P lability, plant features and mycorrhizal colonization after two cropping cycles. A biological effect on the P cycling of cover crops is evident.

5.1. *Cover crops effect on P solubility*

In general, cover crops reduced the inorganic labile P in the soil surface, showing the effect on the P uptake and recycling. Ge et al. (2000), using software simulations, showed that shallower root systems acquired more P than deep ones, which is attributed not only to the spatial coincidence of the P application along the time but also to the low inter-root competition for P in the shallower root systems. Besides the effect in upper soil layers, in general cover crops were also able to increase organic P in the deeper soil layers. This effect may be due to the root system, by increasing the soil exploration by roots, especially under no tillage system that keep the root system intact. Lynch (2007) suggested that the root system is critically important for nutrient acquisition, and crop genotypes with greater yield in low fertility soils will substantially reduce the negative environmental impacts of intensive fertilization.

As expected, no differences were observed in the P_{HCl} fraction under cover crops cultivation. This P fraction is characterized to represent P–Ca (Cross and Schlesinger, 1995), being related to the P fertilization with rock phosphate, such as apatite, which is composed mainly of P–Ca.

On the other hand, the non-labile inorganic P increased in the presence of cover crops. Although the non-labile P is not available to the plants, the accumulation of residual P reflects in the legacy P, which acts as a reservoir to the soil. Our results corroborate with Soltangheisi et al. (2020), who showed that cover crops may affect the legacy P, with more accumulation in non-labile forms.

Considering the specificity of each crop, the legume pigeon pea showed an increase in the labile organic P in the deeper soil layer. Furthermore, this legume was able to increase the moderately labile P balance across the profile, due to the increase of organic moderately labile P. In the same way, Kamh et al. (1999) observed an accumulation of organic P in the pigeon pea rhizosphere, related to the high microbial activity and building-up of more stable organic P forms. Also, Ae et al. (1990) and Ishikawa et al. (2002) showed that pigeon pea was efficient at solubilizing P–Fe and the authors attributed this to the root exudation of P-mobilizing and organic P-mineralizing compounds compared to several other crop species. Furthermore, Ishikawa et al. (2002)

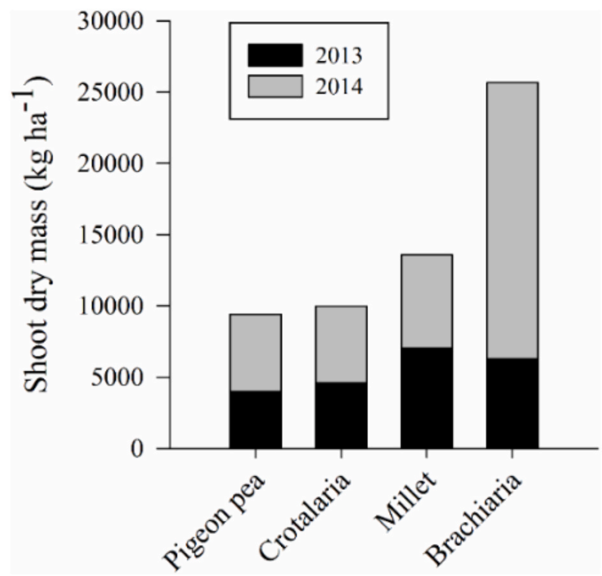

Fig. 4. Shoot dry matter of four cover crops (pigeon pea; crotalaria; millet; or brachiaria) and fallow. Values are referent to 2013 and 2014 evaluation.

described that pigeon pea could efficiently utilize various sources of P by identifying its root exudates such as citric, malic, malonic and succinic acids. As a nitrogen (N_2)-fixing legume, pigeon pea showed high N uptake, which improves soil fertility for the subsequent cash crop through accessing subsoil N pools and capturing available nutrient through its extensive root system (Fageria et al., 2014).

Crotalaria showed the highest increases in both organic and inorganic P fractions in the soil, concentrating its changes in the superficial layers. Using crotalaria as a green manure is a good alternative for a crop rotation, bringing the advantage of increases P in the upper soil layers for the next crop and incorporating N from atmospheric fixation. Furthermore, crotalaria showed high mycorrhizal colonization. Benkhoua et al. (2017) evaluated the benefits of *Crotalaria ochroleuca* and its effectiveness in improving the mycorrhizal soil potential and concluded that crotalaria reduced the current negative effect of the soil overexploitation.

Millet showed the highest spore density in the soil, and this may be an important tool to promote native AMF for the next crops. Mycorrhiza fungi is mostly attributed to helping plants to acquire diffusion limited

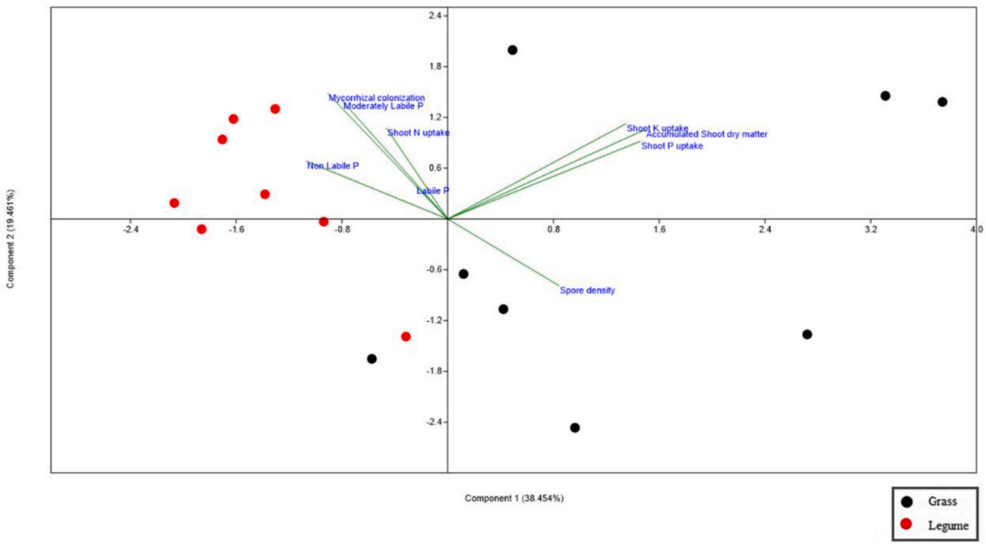

Fig. 5. Principal component biplot following the growth of two legumes (pigeon pea; crotalaria) and two grasses (millet; brachiaria): labile P (means weighted for 0–40 cm); moderately labile P (means weighted for 0–40 cm); non labile P (means weighted for 0–40 cm); shoot N uptake (2014); shoot P uptake (2014); shoot K uptake (2014); accumulated shoot dry matter (2013 and 2014); spore density (2014) and mycorrhizal colonization (2014).

nutrients such as P by the fungi hyphal network, and so augmenting native AM fungal activities in soil through manipulating agricultural practices, such as cover crops use, has the potential to tighten nutrient cycling in those systems, increasing P nutrition and yield (Bagyaraj et al., 2015; Hallama et al., 2018). Furthermore, millet increased the labile organic P and reduced the moderately labile organic P in 5–10 cm layer, showing again the high potential of providing organic labile P into the intermediate soil layer for the next crop. Pavinato et al. (2008) studied the P in the leaching solution of different crops and found that millet was one of the most efficient crops to reduce P in the solution, and attributed this to the combining of phosphate and organic compounds.

Brachiaria was able to accumulate much more P than other species in the shoot due to its capacity to mine P from poorly-available P pools. It is likely this cover crop used organic acids and/or enzyme exudation to access the non-labile P forms bound to Fe and Al oxides (Häussler et al., 2006; Merlin et al., 2015). Kamh et al. (1999) showed that cover crops with high P uptake may contribute to the next crop in a rotation or intercropping system. Brachiaria have a high dry matter production, and when the biomass is kept in the soil (Fig. 4) may be a source of P through its biomass. Dube et al. (2014), studied grasses under low P input and observed that the P provided via cover crops to the crash crops, as part of the system cycle, may reduce the need for P fertilizers.

When considering the plant and mycorrhizal features in a multivariate vision, a clear separation between legumes and grasses was observed (Fig. 5). While the legume species (crotalaria and pigeon pea) showed similar patterns to each other, the grasses (brachiaria and millet) were not only very distinct from legumes, but also presented some dispersion from each other. The grasses showed a strong association with shoot P and K uptake, accumulated shoot dry matter and spore density. Otherwise, the leguminous species showed a weak association with the aforementioned features, and the grouping was more related to soil P fractions, shoot N content and mycorrhizal colonization (Fig. 5).

Thus, the crops tested here showed a distinct behaviour between grasses (Poaceae) and legumes (Fabaceae). The grasses, brachiaria and millet, were able to increase the P uptake, in comparison to the legumes. This may be related to the fasciculate root system that increases the volume of roots, which are likely to be a source of organic deposition. Roots are the organ responsible for turnover, as well as rapid growth and high DM production which is an important feature for grass (Fort et al., 2013), and this contributes to a higher accumulation of plant straw in the soil surface, reflecting in more P cycling. On the other hand, the legumes were more related to the shoot N uptake, and increase in the soil P, regardless the lability.

The usage of cover crops as green manure must take into account the particular purpose of application, either the nutrients in the soil or the biological amendment such as mycorrhization. Our results show that pigeon pea showed a capacity to improve the labile organic P in deeper soil layers and accumulate N in the shoot that may be used for the cash crop; crotalaria presented a good capacity to improve P in the upper layers; millet showed high density of mycorrhizal spores in the soil which may be a source for the next crop; brachiaria showed a good P uptake and high dry matter production, indicating it to be a good plant residue to leave in the soil for physical protection and long-term nutrient cycling.

6. Conclusions

Cover crops alter P fractions, increasing the organic labile pool in the top-soil, 0–10 cm, and increase AMF abundance for the succeeding cash crop. Indeed, cover cropping has different abilities as green manures that may contribute to nutrient cycling and soil protection, and the chosen species will depend on the requirements for the production system.

Declaration of competing interest

"All authors declare no conflict of interest related to this manuscript."

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