Communications in Soil Science and Plant Analysis

ISSN: 0010-3624 (Print) 1532-2416 (Online) Journal homepage: https://www.tandfonline.com/loi/lcss20

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To cite this article: Moniki Campos Janegitz, Ana Rita Helene Martins & Ciro Antonio Rosolem (2017) Cover Crops and Soil Phosphorus Availability, Communications in Soil Science and Plant Analysis, 48:10, 1240-1246, DOI: 10.1080/00103624.2017.1341918

To link to this article: https://doi.org/10.1080/00103624.2017.1341918

COMMUNICATIONS IN SOIL SCIENCE AND PLANT ANALYSIS
2017, VOL. 48, NO. 10, 1240–1246
https://doi.org/10.1080/00103624.2017.1341918

Cover Crops and Soil Phosphorus Availability

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ABSTRACT

Plants affect soil phosphorus (P) solubility through root exudates, but studies are lacking on species used as relay or cover crops in tropical environments. We evaluated the effect of cover crops on soil phosphorus (P) availability in an oxisol. Ruzigrass (*Brachiaria ruziziensis*), pearl millet (*Pennisetum glaucum*), peanut (*Arachis hypogaea*), crambe (*Crambe abyssinica*), and sorghum (*Sorghum bicolor*) were grown in pots with soil. Phosphorus uptake, soil inorganic and organic P, maximum P adsorption capacity, and plant root systems were assessed. When root length density is high, the efficiency of P uptake is low due to root competition. Crambe results in greater soil P availability, while peanut and sorghum decrease the soil maximum P adsorption capacity, probably by exuding or stimulating microbial production of organic acids and phenolic compounds. Hence, crambe, peanut, and sorghum are species that may be of interest to increase P use efficiency in cropping systems.

ARTICLE HISTORY
Received 23 August 2016
Accepted 2 February 2017

KEYWORDS
Crop rotation; fertilization;
P adsorption;
soil phosphorus

Introduction

Mainly in tropical and subtropical regions, phosphorus (P) is found in very low concentrations in soil solution. As soils develop and intemperization sets in, there is a decrease in P labile pools and a correspondent increase in non-labile P pools, the share of organic P in the soil increases and eventually biological processes tend to govern P availability in the system (Cross and Schlesinger 1995). Thus, these soils are poor in P available to plants, especially those soils containing high levels of iron (Fe) and aluminum (Al) oxides in its mineral composition.

Some plant species may affect soil P solubility, particularly non-labile P, through root exudation of organic acids, as demonstrated by Pavinato, Merlin, and Rosolem (2008), who observed a significant effect of organic acids from species used as cover crops on soil P solubilization. Palisade grass and ruzigrass can access sparingly soluble P supplied as Al oxide-P and goethite-P (Merlin, Rosolem, and He 2015) by exuding organic acids in the rhyzosphere. Several plants have specific mechanisms to mobilize soil phosphorus and increase P availability for subsequent crops (Horst and Kamh 2004)such as string bean and white lupin (Jemo et al. 2006). Legumes, in general, have shown to be more effective in P cycling when used as cover crops (Horst et al. 2001). The quantity and quality of exudates released by roots also alter soil chemistry and affect the bacterial community that colonizes the rhizosphere and uses these exudates as carbon source (Pavinato, Merlin, and Rosolem 2008). The bacterial community composition in the rhizosphere may also affect P availability to plants (Marschner, Solaiman, and Rengel 2006). The exudate composition may vary with plant age and genotype, metabolism, nutritional status, type of stress, and other environmental factors (Liu et al. 2004; Richardson et al. 2009). However, few studies have evaluated the effect of growing cover crops, especially tropical grasses, on-soil P fractions, the efficiency of P recycling and, consequently, on the nutrient availability for subsequent crops. In no-till systems, the straw on soil

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surface affects soil P dynamics, so that pearl millet results in higher movement of available P in the soil profile, while oats and Guinea sorghum affect mostly the organic P (Correa, Mauad, and Rosolem 2004). However, long-term studies with crop rotations under no-tillage systems have led to inconclusive results regarding the dynamics of labile P forms in soil (Pavinato, Dao, and Rosolem 2010; Pavinato, Merlin, and Rosolem 2009)

Considering the cost of P fertilization and that it is a limited resource, as well as the high capacity of P fixation in tropical and subtropical soils, we raised the hypothesis that the introduction of certain species as cover crops or in rotation with the main crop could solubilize soil P and increase its availability in the system, what could eventually improve P use efficiency. The objective of this work was to study the ability of some cover crops to recycle P and thus make it available to subsequent crops.

Material and methods

The experiment was conducted in a greenhouse in Botucatu, São Paulo. The soil was collected from the 0–20 cm layer of a Rhodic Hapludox (Soil Survey Staff 2014) in an area that had been cropped to soybeans in the summer in rotation with oats or triticale in autumn/winter and pearl millet in the spring, under no till, for 10 years. The result of soil analysis (Raij et al. 2001) is shown in Table 1, showing that P was very low. The experimental units consisted of pots with 6 kg of soil fertilized with 100 mg dm^{-3} of N, 100 mg dm^{-3} of P, and 100 mg dm^{-3} of K, as urea, triple superphosphate, and potassium chloride, respectively.

The treatments consisted of five cover crop species: ruzigrass (*Brachiaria ruziziensis*), pearl millet (*Pennisetum glaucum*), peanut (*Arachis hypogaea*), Crambe (*Crambe abyssinica*), and grain sorghum (*Sorghum bicolor*), plus a treatment without plants. Peanut and crambe are used in rotation, as a relay crop, and grain sorghum can be used both as a relay crop and just as a cover crop. Fifteen seeds were planted per pot and seedlings were thinned to two plants per pot after 14 days. Plants were grown for 53 days and soil moisture was monitored by daily weighing and maintained between 70% and 100% of the soil water retention capacity. The temperatures inside the greenhouse were monitored (Figure 1). After harvest, the soil was analyzed. The maximum phosphorus adsorption capacity (MPAC) was determined by shaking a solution containing 10, 25, 50, 100, 150, 200, 250 mg L^{-1} of P with soil samples at a ratio of 1:10 (soil:solution) for 48 h on horizontal shaker at 150 rpm. Thereafter, the samples were centrifuged at 6000 rpm for 10 min, and the amount of P remaining in solution was determined by molybdate-ascorbic acid method.

The plants were separated into shoot and root system. The shoots were washed first with tap water and then distilled water, dried in a forced-air oven at 65 °C to constant mass. Then the material was ground and the total P content in the tissue was determined (Malavolta, Vitti, and Oliveira 1997). Roots were separated from the soil by washing in running water over a 0.5 mm mesh sieve. After washing the root system, a subsample of approximately 50% of the fresh weight was taken and stored in 70% alcoholic solution under refrigeration. The length, diameter, and surface of the roots were determined in a scanner coupled to a computer with the software WinRhizo (Regents Instruments, Québec, Canada). The remaining 50% of the root system was joined to the 50% used for morphological determinations and dried at 65 °C. Root dry weight was determined, and then ground, and P content in tissue was determined (Malavolta, Vitti, and Oliveira 1997). The average

Table 1. Selected chemical characteristics of the soil before the experiment[a].

pH	OM (g dm^{-3})	P_{resin} (mg dm^{-3})	K (mmol$_c$ dm^{-3})	Ca (mmol$_c$ dm^{-3})	Mg (mmol$_c$ dm^{-3})	CEC (mmol$_c$ dm^{-3})	Base saturation (%)
$CaCl_2$					—		
6.5	21	3.6	1.6	8.0	2.0	57	20

[a]Methods described by Raij et al. (2001): pH in $CaCl_2$, OM, Walkley-Black; P, K, Ca, and Mg extracted by pearl resin.
CEC, cation exchange capacity.

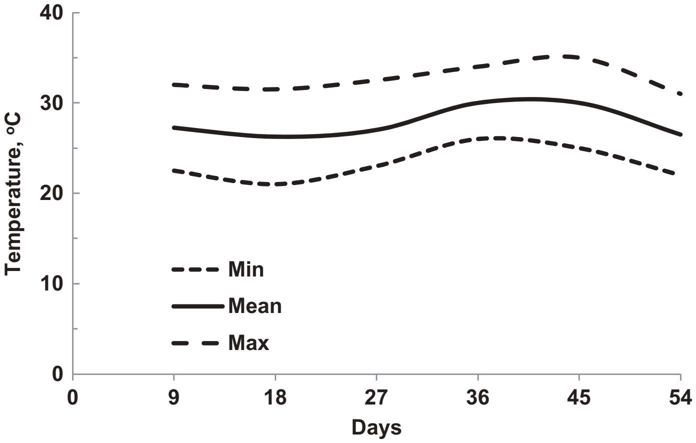

Figure 1. Maximum, mean, and minimum temperature during the experiment.

distance between roots was calculated using the expression D = $1/(\pi \times L)^{1/2}$, where D is distance between the roots, and L is root length density in centimeters (Baldwin, Nye, and Tinker 1973).

The total soil P was determined as in Brookes, Powlson, and Jenkinson (1982), in which total P was extracted with magnesium chloride, concentrated sulfuric acid, and hydrogen peroxide. The total organic P was determined according to Olsen and Sommers (1982), using 0.5 mol L^{-1} sulfuric acid, and total organic P was calculated as the difference between ignited and non-ignited P. The total inorganic phosphorus was determined by the difference between total P and total organic P.

The experimental design was a randomized block, with four replications. The results were submitted to ANOVA and means were compared using an unpaired t-test ($P < 0.05$).

Results and discussion

The experiment was run from October to December, when the average temperature is high (Figure 1), and grain sorghum is tolerant to drought and high temperature, and so is pearl millet, which in addition to tolerating high temperature has a deep and vigorous root system, what explains its high water and nutrient use efficiency (Payne 2000), these characteristics may explain why grain sorghum and pearl millet developed well and had a greater total and root dry weights (Table 2). Foloni et al. (2008) concluded that pearl millet is considered one of the most important cover crops for tropical areas, thanks to the high biomass production potential and its ability to recycle P in a relatively short time interval. These two treatments also had a higher root:shoot ratio, differing from other species (Table 2).

Shoot P concentration was below the range considered as adequate for all crops (Malavolta, Vitti, and Oliveira 1997). In this experiment, we analyzed the entire canopy, and not just the diagnose leaf,

Table 2. Root dry matter (RDM), plant dry matter (PDM), root/shoot ration (R/S ratio), shoot P contents (shoot P), root P contents (root P), and P uptake.

Treatment	RDM (mg)	PDM (mg)	R/S ratio	Shoot P (g kg^{-1})	Root P (g kg^{-1})	P uptake[a] (mg pl^{-1})
Peanut	570	6333	0.12	1.50	1.19	7.2
Ruzigrass	278	3270	0.07	1.81	1.27	5.8
Crambe	408	4480	0.10	1.63	0.75	10.1
Pearl millet	795	6458	0.17	1.25	0.91	11.2
Grain sorghum	933	7645	0.18	1.48	0.53	9.0
LSD**	162	1825	0.05	0.27	0.19	1.6

[a] P uptake per plant.

**Least significant difference ($P > 0.01$).

in which P concentration is higher than stems, which explains the lower P levels determined. Still, the species differed in their leaf and root P concentrations. Grain sorghum, pearl millet, and crambe accumulated more P than the other species, while ruzigrass had the lowest P uptake (Table 2). These results were more related to the dry matter production than P tissue concentrations. The feature of a cover crop taking up more P than others can be a decisive factor in the availability of P in the system. It has been observed that the positive effect of crop rotation with mobilizing P species on P availability for the next crop occurs mainly due to the transfer of readily available P from the plant residues to the soil (Horst et al. 2006).

Pearl millet had the highest root length and surface area, while crambe had the lowest (Table 3). Root diameter was low in crambe and ruzigrass, followed by pearl millet and groundnuts, which were similar. Grain sorghum was the species with larger root diameter, but there was no relation between root diameter and P acquisition (Tables 2 and 3). According to Barber (1995), thinner roots have a more favorable geometry for nutrient acquisition from the soil when the main transport mechanism is diffusion. Diffusion has been considered the main process of soil nutrient transport to the roots for low-mobility nutrients such as phosphorus (Barber 1995). The root system of plants usually occupies 1–2% of the soil volume (Barber 1995). This small volume of soil explored by the roots limits uptake of those nutrients reaching the roots by diffusion, especially of P, whose diffusion coefficient is quite low (Rosolem et al. 1999). Therefore, root growth has been considered an important feature of plant adaptation to poor P soils. However, it is important to consider that when plants are grown in pots with limited volume, root growth implies in decreased distance of one root from each other. This actually happened, because millet, with greater root length density, had roots closer to each other, unlike crambe. Although root morphology is an important factor determining P uptake ability (Barber 1995), in the present study no significant correlations were found between phosphorus uptake and any of the root morphological parameters. This may have occurred because the species with larger root systems confined in pots developed roots too close to each other, resulting in competition between roots of the same plant for soil phosphorus. Thus, as P is taken up by roots it becomes depleted in the rhizosphere, which shows a lower average P concentration as compared with bulk soil (Jungk 2002). In this situation, only an increase in soil P could result in increased uptake by eliminating the depletion zone developed in the root surface (Rosolem et al. 1999).

By dividing the amount of P absorbed by the root surface the uptake efficiency is determined, which had the following descending order: crambe (72 µg cm^{-2}), ruzigrass (72 µg cm^{-2}), peanut (40 µg cm^{-2}), grain sorghum (28 µg cm^{-2}), and pearl millet (13 µg cm^{-2}). Peanuts, grain sorghum, and pearl millet were classified as less efficient in P uptake, while ruzigrass was classified as intermediate in a pot experiment (Muraoka et al. 2006), what gives support to our results. Interestingly, total P uptake showed a high correlation with the average distance between roots (Figure 2), showing that indeed there was competition between the roots for soil P, which may have masked the response of some species. One consequence of this behavior with practical implication is that the use of plants with finer roots and abundant root system may result in lower P uptake and

Table 3. Root length, surface, mean diameter, mean distance between roots, and root length density of peanut, ruzigrass, crambe, pearl millet, and grain sorghum.

Treatment	Root length (cm)	Root surface (cm^2)	Root diameter (mm)	Root length density (cm cm^{-3})	Mean distance (cm)
Peanut	1571	230	0.46	0.31	0.50
Ruzigrass	1704	194	0.36	0.34	0.46
Crambe	1010	96	0.28	0.20	0.78
Pearl millet	4350	610	0.46	0.87	0.18
Grain sorghum	1713	369	0.64	0.34	0.46
LSD**	343	70.1	0.06	0.11	0.23

**Least significant difference ($P > 0.01$).

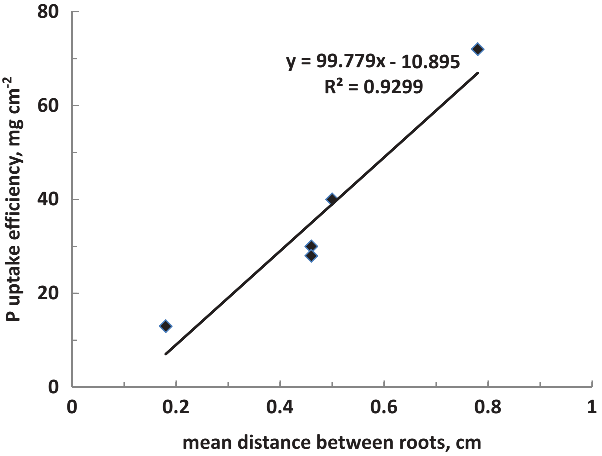

Figure 2. Relationship between the mean root distance and P uptake efficiency by cover crops.

use efficiency if the soil is compacted so as to prevent good root growth and exploitation of a large soil volume.

Legumes have a greater ability to mobilize less labile forms of soil P as compared with cereals (Horst et al. 2006; Nuruzzaman et al. 2005), and it was suggested that this was due to a greater exudation of organic acids by the legume roots, which could solubilize soil P (Jemo et al. 2006). In the present experiment this was not observed, since the transport of P to the root surface seemed to be more important in determining the final result in P uptake, as it had been already observed in cotton (Rosolem et al. 1999).

Generally, clay soils have a higher P adsorption capacity than sandy soils. It is known that the lower the adsorption, the greater P availability. Marx et al. (1997) observed that the rotation of grain crops with grasses (*B. ruziziensis*) resulted in lower maximum P adsorption capacity (MPAC) than legumes in rotation with corn. This may be due to a lower rate of decomposition of grasses residues relative to legumes. However, Pavinato, Merlin, and Rosolem (2009) have not found this decreased MPAC in a 10-year crop rotation. In the present study, soils grown to grain sorghum and peanuts had the lowest values of MPAC (Table 4). However, ruzigrass also has the potential to reduce soil MAPC (Marx et al. 1997). Crambe and pearl millet did not differ from the un-cropped control (Table 4), so it can be inferred that crambe and pearl millet had no effect on solubilization of adsorbed P, which would result in reduced use efficiency of this element by plants.

The plant species is critical in the solubilization of soil P, primarily non-labile P, as there are species that have the capacity to solubilize it through the exudation of organic acids and other compounds by roots, feeding available P in soil solution (Pavinato, Merlin, and Rosolem 2008). Nahas (2002) found in a study with microorganisms producing acid phosphatases that there was a decrease of fungi and bacteria in soil under pigeon pea when compared with ruzigrass. Plant residues

Table 4. Soil maximum P adsorption capacity (MPAC) as affected by plant species.

Treatment	MPAC (g kg^{-1})	Adsorption energy (L mg^{-1})
Peanut	0.07	0.13
Ruzigrass	0.10	0.11
Crambe	0.12	0.12
Pearl millet	0.13	0.17
Grain sorghum	0.09	0.10
Control	0.12	0.11
LSD**	0.02	0.03

**Least significant difference ($P > 0.01$).

Table 5. Soil organic, total inorganic, available (resin), and total P at the end of the experiment, as affected by the plant species.

Treatment	Organic P (mg kg^{-1})	Inorganic P (mg kg^{-1})	Total P (mg kg^{-1})	Available P (mg dm^{-3})
Peanut	228	248	476	59
Ruzigrass	215	235	450	43
Crambe	214	235	450	71
Pearl millet	304	289	593	42
Grain sorghum	250	314	564	37
Control	315	351	666	52
LSD**	22	33	37	9

**Least significant difference ($P > 0.01$).

kept on the soil surface can increase soil P availability by stimulating the microbial production of organic acids and phenolic compounds, which can result in the mobilization of adsorbed P by competing for the same adsorption sites (Hu, Tang, and Rengel 2005). It has been shown that legumes may have different effects on the various P forms and concentration in soil (Mat-Hassan et al. 2011). In the present experiment, growing crambe resulted in the greatest increase in available soil P (phosphorus extracted with resin), while the soil cropped to grain sorghum had the lowest level of available P (Table 5). In pots cropped to peanuts, ruzigrass, and crambe, the lowest total P contents were found (Table 5), and these species had the highest levels of P in the plant (Table 2). The soil of the uncropped pot (control) had the highest total P content, followed by pearl millet and grain sorghum. The relationship between plant P content and total soil P content is also valid for millet and sorghum, as they had the lowest tissue P concentrations (Table 2). In all treatments but pearl millet, soil inorganic phosphorus represented the largest percentage of total phosphorus.

Conclusions

Ruzigrass and peanut showed lower total P uptake, while pearl millet and crambe accumulate more P. In a confined environment, plant P uptake is not related to root length, area, or diameter, because when the root length density is high the mean distance between roots is small, and the roots compete for soil P. Pearl millet and grain sorghum reduce soil available P (extracted with resin), while crambe results in higher P availability. Grain sorghum and peanuts decrease soil maximum P adsorption capacity.

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