View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Repositorio da Producao Cientifica e Intelectual da Unicamp

Revista Brasileira de Ciência do Solo

Division - Soil Use and Management | Commission - Soil Fertility and Plant Nutrition

Brachiaria as a Cover Crop to Improve Phosphorus Use Efficiency in a No-till Oxisol

Moniki Campos Janegitz[(1)], **Elialdo Alves de Souza**[(1)] **and Ciro Antonio Rosolem**[(2)*]

[(1)] Universidade Estadual Paulista, Faculdade de Ciências Agronômicas, Departamento de Produção Vegetal, Programa de Pós-graduação em Produção Vegetal, Botucatu, São Paulo, Brasil.
[(2)] Universidade Estadual Paulista, Faculdade de Ciências Agronômicas, Departamento de Produção Vegetal, Botucatu, São Paulo, Brasil.

ABSTRACT: Oxidic soils are phosphorus drains in soil; hence, P availability is a limiting factor in tropical, weathered Oxidic soils. It has been shown that some brachiarias grown as cover crops may increase soil available P to subsequent crops. The objective of this study was to evaluate soil P cycling and availability, as well as the response of soybean to soluble and natural reactive phosphates as affected by ruzi grass (*Urochloa ruziziensis*, R. Germ. and C.M. Evrard, Crin) grown as a cover crop in a no-till system. Experimental treatments consisted of the presence or absence of ruzi grass in combination with a control (0.0 P) and soluble and reactive rock phosphate broadcast on the soil surface in the winter (80 kg ha^{-1} P_2O_5), plus three rates of P applied to soybean furrows (0, 30, and 60 kg ha^{-1} of P_2O_5) at planting, in the form of triple superphosphate. Soybean was cropped in two seasons: 2010/2011 and 2011/2012. Soil samples were taken before soybean planting (after desiccation of Brachiaria) at 0.00-0.05 and 0.05-0.10 m for soil available P. Total weight of dry matter and P accumulated in ruzi grass were determined, as well as soybean yields, P in soybean grains, and P use efficiency (PUE). The use of natural phosphate increased soil P availability. The highest yields were obtained with higher application rates of triple superphosphate in the planting furrow combined with broadcast rock phosphate. Broadcast application of Arad reactive phosphate increases and maintains soil available P, and this practice, associated with ruzi grass grown as a cover crop and the use of triple superphosphate applied to soybean furrows, results in higher use of P by soybeans.

Keywords: available phosphorus, phosphorus use efficiency, cover crops.

*** Corresponding author:**
E-mail: rosolem@fca.unesp.br

Received: February 26, 2015
Approved: November 18, 2015

How to cite: Janegitz MC, Souza EA, Rosolem CA. Brachiaria as a Cover Crop to Improve Phosphorus Use Efficiency in a No-till Oxisol. Rev Bras Cienc Solo. 2016;40:e0150128.

Copyright: This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided that the original author and source are credited.

INTRODUCTION

Oxidic soils and the climate predominant in tropical and subtropical regions are prone to the formation of high energy bonds between phosphorus and soil colloids (Schroder et al., 2011). As a consequence, these soils behave as P drains and compete with plants for the nutrient, which may lead to low phosphorus use efficiency (PUE) (Syers et al., 2008). Hence, it is important to develop economical technologies to improve PUE. In addition to the choice of more efficient cultivars, tools to be explored in increasing PUE are fertilizer application in the right manner, amount, and period and the use of cover crops efficient in acquiring soil P (Roberts, 2008). Several species used as winter or spring cover crops are able to accumulate significant amounts of P. Therefore these plants can be introduced in rotation with cash crops under no-till (NT) since they may increase soil organic matter and nutrient use, decrease losses, and release nutrients for the next crop as they decay (Pavinato and Rosolem, 2008; Schoninger et al., 2013).

Species of the *Brachiaria* genus are adapted to low fertility soils and tolerate toxic Al and low soil P and Ca. These species have been widely used as cover crops during the fall/winter in Brazil. They are important in nutrient recycling because of their high efficiency in taking up soil P through mechanisms such as development of large root system and lowering soil P fixation by exuding low weight organic acids like citrate, malate, and oxalate. They have specific, high affinity P carriers, and acid phosphatase activity is increased in the *Brachiaria* rhizosphere (Nanamori et al., 2004; Calonego and Rosolem, 2013; Janegitz et al., 2013; Rosolem et al., 2014).

The benefits of NT are widely known, but there is a lack of information on fertilizer use efficiency and P dynamics in the soil profile as affected by cover crops, which demands further research with different species, rates, and P sources for a better understanding of the processes and to develop fertilizer recommendations for this particular cropping system. The adoption of no-till using ruzi grass as a cover crop, associating the benefits of the system with the particular characteristics of this grass, may decrease soil capacity in fixing the P fertilizer applied and make this nutrient available for the next crop, which would be an alternative in improving P availability and use efficiency in tropical regions.

The objective of this study was to evaluate the effects of a brachiaria species (*Urocloa ruziziensis*, R. Germ. & C.M. Edvrard, Crins; or ruzi grass) cropped as a fall/winter cover crop on soil P availability and soybean response to P fertilization sources, rates, and manners of application under NT.

MATERIALS AND METHODS

The experiment was conducted in Botucatu, São Paulo, Brazil, in 2010/2011 and 2011/2012, in a *Latossolo Vermelho Distroférrico* (Embrapa, 1999) or Rhodic Hapludox (Soil Survey Staff, 2010), sandy loam, with the following chemical characteristics (Raij et al., 2001) and particle size (Camargo et al., 1986): pH 4.9; 19.1 $mmol_c$ dm^{-3} of Ca^{2+}, 7.07 $mmol_c$ dm^{-3} of Mg^{2+}, 1.02 $mmol_c$ dm^{-3} of K^+, 30 $mmol_c$ dm^{-3} of H+Al, 48 % of base saturation, and 17 g kg^{-1} of organic matter, with 670 g kg^{-1} sand, 150 g kg^{-1} silt, and 180 g kg^{-1} clay. The experimental area had been cropped under NT for 10 years. Soybean and ruzi grass were grown in rotation with different P rates and P sources. In April 2010, 20 disturbed soil samples were taken randomly at a depth of 0.00-0.20 m.

A completely randomized block experimental design was used with split split-plots, with four replications. Soluble (triple superphosphate) and natural reactive (Arad) phosphates were broadcast on the plots at 0.0 or 80 kg ha^{-1} of P_2O_5 (as total P), and ruzi grass was grown or not in the split-plots. Rates of 0, 30, and 60 kg ha^{-1} of P_2O_5 in the form of triple superphosphate were applied in the soybean planting furrows (Table 1) for formation of split split-plots. Granulated triple superphosphate (TSP) with 41 % P_2O_5 was used as the soluble source, and Arad natural reactive rock phosphate (NRP) powder with 32 % total P_2O_5 was used as the less soluble source. This application was made only in 2010, before planting the cover crop, and in 2011, the residual effect was assessed. During the previous 10 years of cultivation, 400 kg ha^{-1} of P_2O_5 (total P) was broadcast, while P application in soybean planting furrows totaled 220, 340, and 460 kg ha^{-1} of P_2O_5 in the form of triple superphosphate. Each experimental unit was 40 m^2, but evaluations were made within 10.8 m^2.

Before planting the cover crops, in April 2010, dolomitic limestone (92 % TNP) was applied to raise the soil base saturation to 70 % (Raij et al., 1997). The soybean cv. Monsoy 5942 was planted in mid-November 2010 and 2011, one or two weeks after ruzi grass chemical desiccation. Each year ruzi grass straw samples were collected using a 0.50 × 0.50 m wooden frame and dried to constant weight in a forced air oven at 65 °C. Soil samples were taken in November, preceding soybean planting each year, from 0.00-0.05 and 0.05-0.10 m soil depths to determine available P, as in Raij et al. (2001). Six soil samples were taken per plot each year using an auger type sampler, combining them into one for laboratory analysis. Soybean yield was calculated considering a moisture content of 130 g kg^{-1}, and P was analyzed according to Malavolta et al. (1997). The agronomic PUE was determined using the formula recommended by Roberts (2008):

$$\text{PUE (kg kg}^{-1}\text{)} = (\text{GYwf} - \text{GYnf})/(\text{Pa})$$

where GYwf (kg ha^{-1}) is grain yield with P fertilizer; GYnf (kg ha^{-1}) is grain yield with no fertilizer; and Pa (kg ha^{-1}) is amount of P applied.

The results were subjected to ANOVA and means were compared using the t test (LSD, $p<0.05$).

Table 1. Available P (resin) at soybean planting and P values (p>f) at soil depths of 0.00-0.05 and 0.05-0.10 m, as affected by phosphates (soluble and reactive) broadcast in the presence or absence of ruzi grass and P rates applied to soybean seed furrows (0, 30, and 60 kg ha^{-1} of P_2O_5 as TSP). November 2010

P_2O_5 rate	Available P					
	0		NRP		TSP	
	With ruzi grass	No ruzi grass	With ruzi grass	No ruzi grass	With ruzi grass	No ruzi grass
kg ha^{-1}	mg dm^{-3}					
	0.00-0.05 m					
0	9.2 bB	14.7 aB	53.9 bB	70.2 aB	38.6 bA	61.7 aA
30	13.4 aA	14.9 aA	60.4 bA	70.8 aB	39.5 bA	67.2 aA
60	14.6 bA	18.8 aA	61.6 bA	81.3 aA	38.6 bA	65.6 aAB
	0.05-0.10 m					
0	5.9 aB	6.9 aC	13.6 aB	14.9 aB	11.3 aC	13.4 cA
30	10.8 aA	12.5 aB	16.4 aAB	16.5 aB	17.8 aB	17.4 aB
60	11.9 bA	20.8 aA	17.3 bA	20.7 aA	27.2 bA	32.9 aA

Source of variation	(p>f) 0.00-0.05 m	(p>f) 0.05-0.10 m
Broadcast P (BP)	0.000	0.000
Ruzi grass (R)	0.000	0.009
P at soybean planting (PP)	0.000	0.000
BP×PP	0.000	0.000
PP×R	0.000	0.005
PP×R	0.014	0.000
R×BP×PP	0.051	0.000

Different uppercase letters in columns and lowercase letters in lines show significant differences (LSD, $p<0.05$).

RESULTS AND DISCUSSION

Soil P availability was affected by P sources and rates in the two soil layers (Tables 2 and 3). The use of natural reactive phosphate (NRP) increased P availability in both years. However, in the first year, NRP application resulted in higher P levels in the 0.00-0.05 m layer, whereas triple superphosphate (TSP) showed superior results in the 0.05-0.10 m layer. In the second year, NRP increased P availability down to 0.10 m, and when applied in combination with furrow fertilization, increased soil available P (Tables 1 and 2) compared to TSP. Soluble phosphates, such as TSP, exhibit high reactivity and typically show a higher P release rate compared to less soluble fertilizers; they are therefore considered more efficient than natural phosphates in the short term because the efficiency concept, in this case, is directly related to solubility. However, the NRP may have a compensatory residual effect and equalize or exceed soluble phosphates and there may no longer be a correlation between efficiency and solubility as of the second crop cycle (Goedert et al., 1986; Horowitz and Meurer, 2003), as observed in this experiment. The use of TSP may have facilitated fixation reactions with soil and plant uptake (Tables 1 and 2) due to fast release of P, especially in applications at high rates, which increases the adsorption reactions and immediate build-up of soil P and decreases PUE over time (Johnston and Syers, 2009). Similar results were found by Esteves and Rosolem (2011), depending on the source of P (TSP or NRP) broadcast.

The availability of P was lower in the presence of ruzi grass with both P sources in the first year (Table 1). However, Rosolem et al. (2014) observed in a greenhouse experiment with more controlled conditions that ruzi grass can make soil P more available in the first

Table 2. Available P (resin) at soybean planting and P values (p>f) at soil depths of 0.00-0.05 and 0.05-0.10 m, as affected by phosphates (soluble and reactive) broadcast in the presence or absence of ruzi grass and P rates applied to soybean seed furrows (0, 30, and 60 kg ha^{-1} of P_2O_5 as TSP). November 2011

P_2O_5 rate	Available P					
	0		NRP		TSP	
	With ruzi grass	No ruzi grass	With ruzi grass	No ruzi grass	With ruzi grass	No ruzi grass
kg ha^{-1}	mg dm^{-3}					
	0.00-0.05 m					
0	13.8 aA	14.0 aA	57.0 aB	66.6 aAB	34.5 aB	37.2 aB
30	18.9 aA	16.7 aA	82.9 aA	63.4 bB	39.5 aB	39.3 aB
60	17.4 aA	15.3 aA	80.0 aA	73.4 aA	65.6 aA	49.4 bA
	0.05-0.10 m					
0	7.9 aB	4.5 aB	20.4 aB	15.3 bB	13.1 aB	11.1 aB
30	9.8 aA	6.7 aB	23.7 aB	14.9 bB	14.8 aAB	13.1 aB
60	13.7 aA	13.7 aA	41.3 aA	24.7 bA	17.9 Aa	19.4 aA

Source of variation	(p>f) 0.00-0.05 m	(p>f) 0.05-0.10 m
Broadcast P (BP)	0.000	0.000
Ruzi grass (R)	0.923	0.019
P at soybean planting (PP)	0.000	0.024
BP×PP	0.000	0.000
PP×R	0.020	0.000
PP×R	0.120	0.000
R×BP×PP	0.000	0.000

Different uppercase letters in columns and lowercase letters in lines show significant differences (LSD, p<0.05).

Table 3. Ruzi grass dry matter yields and P accumulation before desiccation, on November 2010 and 2011

Treatment	Dry matter	Accumulated P	Dry matter	Accumulated P
	Mg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}
	2010		2011	
No P	4.2 b	5.7 b	6.4 b	4.1 b
NRP	5.7 a	9.0 a	7.7 a	6.4 a
TSP	4.9 b	8.9 a	6.9 ab	7.2 a
Mean	4.9	7.9	7.0	5.9
p>f	0.000	0.000	0.013	0.000

Different letters in columns show significant differences (LSD, $p<0.05$).

cropping cycle. Moreover, higher accumulation of P in the plant tissue in the first year contrasted with a lower dry matter weight of ruzi grass compared to the second year (Table 3), and resulted in lower physiological efficiency of P in the 2010/2011 season, showing that weather conditions such as low rainfall and temperatures were possibly limiting the full potential for grass development.

When NRP was broadcast and associated with ruzi grass, there was a significant increase in soil available P from the first to the second year of the experiment at different depths (Tables 1 and 2), showing an interaction of the grass and nutrient solubilization in the soil. Among the mechanisms used by P efficient plants are higher root surface and root/shoot ratio, increased uptake rate per root unit, increased root exudation of phosphatases and other organic compounds, and changes in the degree of mycorrhizal associations (Verheijen et al, 2009; Schroder et al, 2011). Ruzi grass specifically shows high affinity for P carriers capable of increasing the efficiency of absorption and the dissolution of NRP in soil (Schoninger et al., 2013).

In both years, yield data show a beneficial interaction of NRP and the use of ruzi grass as a cover crop, and of STF applied to the soybean furrow in the absence of ruzi grass. These combinations ensured an increase in soybean yields of 603 kg ha^{-1} with NRP and 360 kg ha^{-1} in the treatment with TSP (Table 4). The greatest accumulation of P was observed at the highest P_2O_5 rate (60 kg ha^{-1}) applied in the soybean planting furrows together with broadcast NRP or TSP. The response in P accumulation was similar to that of grain yield (Table 5).

Field studies have shown the importance of crop residues in the use efficiency of NRP, leading to increases in soil P availability, followed by increases in P uptake and crop yield (Sharma and Prasad, 2003). The presence of plant residues on the soil surface in conservation management systems increases the flow of organic acids to the soil, increasing the competition for soil P retention sites. The increase in organic acids interferes in soil pH, facilitating the solubilization of NRP through acidification of the environment by soil microbes (Nautiyal et al., 2000; Mendes et al. 2014). According to Nautiyal et al. (2000), not only the pH, but also factors such as the amount and quality of root exudates can affect soil microbiota efficiency in phosphate solubilization.

Soybean responded up to the highest P rate applied in the seeding furrow in the two seasons, and, regardless of the presence of broadcast P or ruzi grass, this management practice resulted in higher yield at 60 kg ha^{-1} P_2O_5 in the form of TSP (Table 4). A lower soybean yield in the presence of ruzi grass in the first year (2010/2011) can be explained by P immobilization in the grass straw, since its mineralization takes longer than the period of the present study (120 days), and there is no synchronism between P release and plant demand. Moraes (2001) concluded that 183 days can

Table 4. Soybean grain yields and P values (p>f) as affected by phosphate fertilizers (soluble and reactive) broadcast in the presence and absence of ruzi grass and P rates applied to soybean seed furrows (0, 30, and 60 kg ha^{-1} of P_2O_5 in the form of TSP)

P_2O_5 rate	Grain yield					
	0		NRP		TSP	
	With ruzi grass	No ruzi grass	With ruzi grass	No ruzi grass	With ruzi grass	No ruzi grass
kg ha^{-1}	kg ha^{-1}					
	2011					
0	934.9 aC	785.8 aC	1,428.2 aC	1,527.7 aB	1,261.1 aB	1,392.9 aC
30	1,349.5 aB	1,547.3 aB	2,172.3 aB	1,611.5 bB	1,263.4 bB	2,099.1 aB
60	2,206.3 aA	1,831.3 bA	2,652.9 aA	2,435.9 aA	2,104.7 bA	2,465.0 aA
	2012					
0	1,082.3 bC	1,738.8 aB	2,549.1 aC	2,297.1 bC	2,303.7 aC	2,189.2 aC
30	2,655.7 aB	2,138.7 bA	2,721.9 aB	2,532.6 bB	2,591.4 aB	2,663.4 aB
60	2,866.9 aA	2,127.2 bA	3,357.1 aA	2,753.2 bA	2,893.2 bA	3,220.5 aA
Source of variation	(p>f) 2011			(p>f) 2012		
Broadcast P (BP)	0.001			0.000		
Ruzi grass (R)	0.258			0.009		
P at soybean planting (PP)	0.000			0.000		
BP×PP	0.005			0.000		
PP×R	0.000			0.005		
PP×R	0.000			0.000		
R×BP×PP	0.000			0.000		

Different uppercase letters in columns and lowercase letters in lines show significant differences (LSD, $p<0.05$).

Table 5. Phosphorus accumulation in soybean grains and P values (p>f) as affected by phosphate fertilizers (soluble and reactive) broadcast in the presence and absence of ruzi grass and P rates applied to soybean seed furrows (0, 30, and 60 kg ha^{-1} of P_2O_5 in the form of TSP).

P_2O_5 rate	P accumulated in soybean grains					
	0		NRP		TSP	
	With ruzi grass	No ruzi grass	With ruzi grass	No ruzi grass	With ruzi grass	No ruzi grass
kg ha^{-1}	kg ha^{-1}					
	2011					
0	3.7 aC	2.6 aB	6.6 aC	6.1 aB	5.8 aB	6.2 aB
30	5.5 aB	5.7 aA	9.9 aB	6.6 bB	5.7 bB	9.4 aA
60	9.2 aA	6.5 bA	12.2 aA	10.3 bA	12.2 aA	9.8 bA
	2012					
0	4.0 bC	9.4 aA	9.3 aB	10.4 aB	12.1 aB	11.0 aB
30	11.3 aB	8.7 bA	15.9 aA	13.6 aA	12.0 aB	14.0 aA
60	13.9 aA	10.8 bA	14.0 aA	12.9 aA	14.6 aA	15.0 aA
Source of variation	(p>f) 2011			(p>f) 2012		
Broadcast P (BP)	0.000			0.000		
Ruzi grass (R)	0.003			0.842		
P at soybean planting (PP)	0.000			0.000		
BP×PP	0.025			0.000		
PP×R	0.000			0.290		
PP×R	0.000			0.000		
R×BP×PP	0.000			0.001		

Different uppercase letters in columns and lowercase letters in lines show significant differences (LSD, $p<0.05$).

be considered as an average time for mineralization of brachiarias under similar conditions. These data demonstrate that soluble P released by the soluble source was taken up and stored in ruzi grass tissues, and it was not released and mineralized in time to meet the next crop demand, ensuring a better response to the soluble source in the absence of the cover crop. Rodrigues et al. (2009) also found that forages such as pearl millet, brachiarias, and sorghum immobilized P from TSP, decreasing its residual effect for soybeans; when grasses were fertilized with NRP, there was an increase in the residual effect, with better P use efficiency by the soybean crop grown following these cover crops.

In the presence of ruzi grass, PUE was higher in 2011/2012 for NRP and TSP, and especially for treatments without broadcast fertilization (Table 6). The PUE expresses the increase in yield per unit of nutrient applied (Roberts, 2008) and so, in this study, the use of ruzi grass as a cover crop improved the use of the P fertilizer applied, especially under conditions of low availability of this nutrient. These results are in agreement with Ramos et al. (2010), who found that previous cultivation of grasses as cover crops resulted in a higher residual effect of P by the subsequent crop when the P source was a low solubility phosphate such as NRP, especially in a sandy soil with low Fe and Al oxide content. The continuous slow mineralization of nutrients present in the cover crop residue associated with improved soil conditions resulting from no-till, plus the release of organic compounds increasing competition for adsorption sites, can explain the increase in PUE when ruzi grass was grown as a cover crop in the fall/winter season (Selles et al., 1997).

Table 6. Phosphorus use efficiency by soybeans grains and P values (p>f) as affected by phosphate fertilizers (soluble and reactive) broadcast in the presence and absence of ruzi grass and P rates applied to soybean seed furrows (0, 30, and 60 kg ha^{-1} of P_2O_5 in the form of TSP).

P_2O_5 rate	Phosphorus use efficiency					
	0		NRP		TSP	
	With ruzi grass	No ruzi grass	With ruzi grass	No ruzi grass	With ruzi grass	No ruzi grass
kg ha^{-1}	kg ha^{-1}					
	2011					
0	-	-	17.4 aB	21.2 aB	9.3 bB	17.4 aB
30	25.0 aB	21.6 aB	25.6 aA	17.1 bB	7.7 bB	27.2 aA
60	31.6 bA	39.9 aA	28.1 aA	30.4 aA	25.0 aA	21.6 aB
	2012					
0	-	-	42.0 aA	16.0 bA	34.9 aA	12.9 bB
30	120.1 aA	30.6 bA	33.9 aB	16.4 bA	31.2 aA	19.1 bA
60	68.1 aB	14.8 bB	37.2 aAB	16.6 bA	29.6 aA	24.2 aA
Source of variation	(p>f) 2011			(p>f) 2012		
Broadcast P (BP)	0.000			0.000		
Ruzi grass (R)	0.305			0.000		
P at soybean planting (PP)	0.000			0.000		
BP×PP	0.057			0.000		
PP×R	0.000			0.000		
PP×R	0.000			0.000		
R×BP×PP	0.000			0.000		

Different uppercase letters in columns and lowercase letters in lines show significant differences (LSD, p<0.05).

CONCLUSIONS

Ruzi grass (*U. ruziziensis*) can increase soil P availability and use by improving the agronomic efficiency of P use.

Broadcast Arad natural phosphate increases and maintains available P content in the soil profile over time. When this practice is associated with ruzi grass grown as a cover crop in the fall/winter season along with triple superphosphate applied in the seed rows, it results in higher phosphate use efficiency by soybeans.

ACKNOWLEDGMENT

Our thanks to the São Paulo Research Foundation (Process Nº 2010/03097-8).

REFERENCES

Calonego JC, Rosolem CA. Phosphorus and potassium balance in a corn soybean rotation under no till and chiseling. Nutr Cycl Agroecosyst. 2013;96:123-31. doi:10.1007/s10705-013-9581-x

Camargo OA, Moniz AC, Jorge JA, Valadares JMAS. Métodos de análise química, mineralógica e física de solos do Instituto Agronômico de Campinas. Campinas: Instituto Agronômico de Campinas; 1986. (Boletim técnico, 106).

Empresa Brasileira de Pesquisa Agropecuária - Embrapa. Centro Nacional de Pesquisa de Solos. Sistema brasileiro de classificação de solos. Rio de Janeiro: 1999.

Esteves JAF, Rosolem CA. Triticale, milheto e adubação fosfatada para formação de palhada em semeadura direta. Rev Bras Cienc Solo. 2011;35:981-90. doi:10.1590/S0100-06832011000300032

Goedert WJ, Sousa DMG, Lobato E. Fósforo. In: Goedert WJ, editor. Solos dos cerrados: tecnologias e estratégias de manejo. São Paulo: Nobel; 1986. p.129-66.

Horowitz N, Meurer EJ. Eficiência de dois fosfatos naturais farelados em função do tamanho da partícula. Cienc Rural. 2003;33:41-7. doi:10.1590/S0103-84782003000100007

Janegitz MC, Inoue BS, Rosolem CA. Formas de fósforo no solo após o cultivo de braquiária e tremoço branco. Cienc Rural. 2013;43:1381-6. doi:10.1080/01904169709365316

Johnston AE, Syers JK. A new approach to assessing phosphorus use efficiency in agriculture. Better Crops. 2009;93:14-6.

Malavolta E, Vitti GC, Oliveira SA. Avaliação do estado nutricional das plantas: princípios e aplicações. 2ª ed. Piracicaba: Associação Brasileira para a Pesquisa da Potassa e do Fosfato; 1997.

Mendes GO, Freitas ALM, Pereira OL, Silva IR, Vassilev NB, Costa MD. Mechanisms of phosphate solubilization by fungal isolates when exposed to different P sources. Ann Microbiol. 2014;64:239-49. doi:10.1007/s13213-013-0656-3

Moraes RNS. Decomposição das palhadas de sorgo e milheto, mineralização de nutrientes e seus efeitos no solo e na cultura do milho em plantio direto [dissertação]. Lavras: Universidade Federal de Lavras; 2001.

Nanamori M, Shinamo T, Wasaki J, Yamamura T, Rao IM, Osaki M. Low phosphorus tolerance mechanisms: phosphorus recycling and photosynthate partitioning in the tropical forage grass, brachiaria hybrid cultivar mulato compared with rice. Plant Cell Physiol. 2004;45:460-9. doi:10.1093/pcp/pch056

Nautiyal CS, Bhadauria S, Kumar P, Lal H, Mondal R, Verma D. Stress induced phosphate solubilization in bacteria isolated from alkaline soils. FEMS Microbiol Lett. 2000;182:291-6. doi:10.1111/j.1574-6968.2000.tb08910.x

Pavinato PS, Rosolem CA. Disponibilidade de nutrientes no solo - decomposição e liberação de compostos orgânicos de resíduos vegetais. Rev Bras Cienc Solo. 2008;32:911-20. doi:10.1590/S0100-06832008000300001

Raij Bvan, Andrade JC, Cantarella H, Quaggio JA. Análise química para avaliação da fertilidade de solo tropicais. Campinas: Instituto Agronômico de Campinas; 2001.

Raij Bvan, Cantarella H, Quaggio JA, Furlani AMC, organizadores. Recomendações de adubação e calagem para o Estado de São Paulo. Campinas: Instituto Agronômico/Fundação IAC; 1997. (Boletim técnico, 100).

Ramos SJ, Fanquin V, Rodrigues CR, Silva CA. Efeito residual das aplicações de fontes de fósforo em gramíneas forrageiras sobre o cultivo sucessivo da soja em vasos. Bragantia. 2010;69:149-55. doi:10.1590/S0006-87052010000100019

Roberts TL. Improving nutrient use efficiency. Turk J Agric For. 2008;32:177-82.

Rodrigues CR, Faquim V, Ávila FW, Rodrigues TM, Baliza DP, Oliveira EAB. Crescimento e acúmulo de fósforo pela soja cultivada em sucessão a diferentes gramíneas forrageiras adubadas com super fosfato triplo e fosfato reativo de Arad. Cienc Agrotec. 2009;33:1486-94. doi:10.1590/S1413-70542009000600005

Rosolem CA, Merlim A, Bull JCL. Soil phosphorus dynamics as affected by congo grass and P fertilizer. Sci Agric. 2014;71:309-15. doi:10.1590/0103-9016-2013-0345

Schoninger EL, Gatiboni LC, Ernani PR. Fertilization with rock phosphate and kinetics of phosphorus uptake by soybean and cover crops of Brazilian cerrado soils. Semina: Cienc Agrár. 2013;34:95-106. doi:10.5433/1679-0359.2013v34n1p95

Schroder JJ, Smit AL, Cordell D, Rosemarin A. Improved phosphorus use efficiency in agriculture: a key requirement for its sustainable use. Chemosphere. 2011;84:822-31. doi:10.1016/j.chemosphere.2011.01.065

Selles F, Kochhann RA, Denardin JE, Zentner RP, Faganello A. Distribution of phosphorus fractions in a Brazilian Oxisol under different tillage systems. Soil Till Res. 1997;44:23-4. doi:10.1016/S0167-1987(97)00026-3

Sharma SN, Prasad R. Yield and P uptake by rice and wheat grown in sequence as influenced by phosphate fertilization with diammonium phosphate and Mussoorie rock phosphate with or without solubilizing bacteria. J Agric Sci. 2003;141:359-69. doi:10.1017/S0021859603003678

Soil Survey Staff. Keys to soil taxonomy. 11th ed. Washington, DC: USDA/NRCS; 2010.

Syers JK, Johnston AE, Curtin D. Efficiency of soil and fertilizer phosphorus use. Rome: FAO; 2008. (FAO Fertilizer and Plant Nutrition Bulletin, 18).

Verheijen FGA, Jones RJA, Rickson RJ, Smith CJ. Tolerable versus actual soil erosion rates in Europe. Earth Sci. 2009;94:23-38. doi:10.1016/j.earscirev.2009.02.003