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Grain crops and forage yield resulting from the use of phosphates in integrated production system[1]

Rendimento de grãos e forragens devido ao uso de fosfatos em sistema integrado de produção

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ABSTRACT - The aim of this study was to assess the effects of the sources and levels of surface-applied (broadcast) phosphorus (P) when sowing the winter annual forages on phosphorus accumulation and yields of maize, soybean, black oat and annual ryegrass crops in a crop-livestock integration system over three years. The experiment was established in April 2009, in the municipality of Castro, Parana, Brazil. The treatments consisted of the broadcast application when sowing the winter forages of four doses (0, 60, 120 and 180 kg ha^{-1} year^{-1}) of total P_2O_5 as triple superphosphate (TSP), rock phosphate (RP-Arad) and magnesium termophosphate (MTP). The dry matter yields of black oat (2009 and 2011), annual ryegrass (2010), maize (2009/10 and 2011/12) and soybean (2010/11) and the accumulation of P in these crops were assessed. TSP provided the highest yield of total dry matter (TDM) and P accumulation only for black oat in the first year of cultivation. In the second year, MTP resulted in higher P accumulation than occurred with the other P sources in annual ryegrass and soybean, and both MTP and TSP provided higher P accumulation and grain export. In the third year, MTP provided a higher TDM yield and P accumulation for both the black oat and maize crops, resulting in the greatest residual effect over time.

Key words: *Zea mays* L. *Glycine max* (L.) Merril. Black oat. Annual ryegrass. Crop-livestock integration.

RESUMO - O objetivo deste trabalho foi verificar os efeitos de fontes e doses de fósforo (P), aplicados na superfície do solo, por ocasião da semeadura de forrageiras anuais de inverno, sobre o acúmulo de P e rendimento das culturas de milho, soja, aveia preta e azevém anual, em um sistema de integração lavoura-pecuária, ao longo de três anos. O experimento foi instalado em abril/2009, no município de Castro-PR, empregando-se delineamento em blocos ao acaso e esquema fatorial incompleto, com quatro repetições. Foram aplicadas doses (0; 60; 120 e 180 kg ha^{-1}) de P_2O_5 total por ocasião da semeadura da forrageira de inverno, nas formas de superfosfato triplo (SFT), fosfato natural reativo (FNR-Arad) e termofosfato magnesiano (TFM). Foram avaliados os rendimentos de massa seca de aveia preta (2009 e 2011) e azevém anual (2010), de grãos de milho (2009/10 e 2011/12) e soja (2010/11), e o acúmulo de P nestas culturas. O uso de SFT aumentou o rendimento de massa seca total (MST) e acúmulo de P apenas para a aveia preta no primeiro ano. No segundo ano, a aplicação de TFM proporcionou maior acúmulo de P para o azevém anual. Para a soja, tanto a aplicação de TFM quanto de SFT proporcionaram maior acúmulo e exportação de P nos grãos. No terceiro ano, o uso de TFM proporcionou maior rendimento de MST e acúmulo de P tanto para a aveia preta quanto para a cultura do milho, caracterizando maior efeito residual.

Palavras-chave: *Zea Mays* L. *Glycine max* (L.) Merril. Aveia preta. Azevém anual. Integração lavoura-pecuária.

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INTRODUCTION

The adoption of integrated production systems, such as the crop-livestock integration system (CLIS), which enables the cultivation of grain-producing plants in the summer and forages for grazing animals during winter has been increasingly objective of current research (BALBINOT JUNIOR *et al*., 2009). The main crops in the predominant CLIS in southern Brazil include maize (*Zea mays* L.) and soybean (*Glycine max* (L.) Merril) for grain production in the summer, and black oat (*Avena strigosa* Schreb.) and annual ryegrass (*Lolium multiflorum* L.) for animal feed and phytomass production to maintain no-tillage (NT) (MORAES *et al*., 2002). Thus, the improvement of fertility attributes becomes essential to achieve a high yield of these crops in tropical and subtropical soils.

After control the acidity, the main factor limiting for crop yields has been the low soils concentrations of available phosphorus (P) (NOVAIS; SMYTH, 1999). The supply of this nutrient in CLIS has been little studied under tropical or subtropical conditions, and the crop responses that have been differed according to the source and form of P application (CHIEN *et al*., 2011).

An increase in grain yield has been noted upon anticipated phosphate fertilization applied when sowing cover crops (BOHAC; CÂMARA; SEGATELLI, 2007). Therefore, anticipated phosphate fertilization may be applicable to the CLIS in which nutrient cycling (CARVALHO *et al*., 2010) and releasing of the organic acids (RUSSELE; FRANZLEUBBERS, 2007) are increased because of the decomposition of plant residues and animal excretions. Those acids have provided a greater soluble P availability, given the competition for adsorption sites on colloidal surfaces (PAVINATO; ROSOLEM, 2008).

Nevertheless, doubts regarding the efficacy of anticipated phosphate fertilization in CLIS persist despite being an attractive practice. The P derived from fertilizers with high solubility (in water and neutral ammonium citrate), such as triple superphosphate (TSP), may be readily transformed into forms unavailable to plants, and the fertilizer efficiency may be reduced over time (SILVA *et al*., 2009). On the other hand, the efficiencies of water-insoluble phosphate fertilizers, such as rock phosphate (RP) and magnesium termophosphate (MTP), tend to increase over time.

Another factor relevant for P management in production systems is the broadcast application of fertilizers containing this nutrient (OLIVEIRA JUNIOR; PROCHNOW; KLEPER, 2008). The broadcast application of P in NT aims to decrease the contact of phosphate ions ($H_2PO_4^-$ and HPO_4^{2-}) with the iron and aluminum oxides, which present powerful phosphate-chelating surfaces that favor high-energy reactions (RANNO *et al*., 2007). This type of P treatment over the total soil surface (on the straw) may also over time minimize the horizontal variability of this nutrient in soils. The high variability of P in NT has been one of the most important and complex issues affecting the evaluation of fertility in relation to this nutrient (SANTOS; GATIBONI; KAMINSKI, 2008).

Thus, the efficiency of broadcast applications of water-insoluble phosphates in integrated production systems (when sowing the annual winter forages) may be increased over time, benefiting the grain crops cultivated subsequently. In this paper, we aimed to assess the effect of surface-applied doses and sources of P that was broadcast when sowing the winter crops (annual forages) on the accumulation of P and on the crop yield of maize, soybean, black oat and annual ryegrass in the CLIS.

MATERIAL AND METHODS

The experiment was started in April 2009 in the municipality of Castro, Parana (24°51'49" latitude, 49°56'61" longitude and a mean elevation of 1,020 m), located in the First Parana Plateau. The predominant climate in the region according to the Köppen classification is the Cfb type, which is characterized by cool summers with frequent frosts and no dry season (CAVIGLONE *et al*., 2000). The air temperatures and average rainfall during the 36 months of the study are outlined in Table 1.

The area had been successively cultivated in NT with soybean and maize crops in the summer and black oat, annual ryegrass and wheat in the winter for eight years. The soil is a Typic Distrudept whose chemical and granulometric characteristics in the 0-20 cm layer were as follows: pH ($CaCl_2$) 4.8; exchangeable Al^{3+}, Ca^{2+}, Mg^{2+} and K^+ of 0.4; 31.2; 23.5 and 3.5 $mmol_c\ dm^{-3}$, respectively; total acidity ($H+Al^{3+}$) 92.1 $mmol_c\ dm^{-3}$; base saturation 38%; P (Mehlich-1) 4.2 mg dm^{-3}; total organic carbon (TOC) and total nitrogen (TN) of 29.6 and 2.0 g dm^{-3}, respectively; and clay, silt and sand of 605, 225 and 170 g kg^{-1}, respectively. The soil mineralogical analysis showed simple mineralogy, predominantly quartz, kaolinite and gibbsite and, subordinately, hematite and goethite. In the clay fraction, the minerals kaolinite and gibbsite were predominant, and iron oxides (mainly hematite and goethite) were less prominent.

The experimental design used for the study consisted of randomized blocks in an incomplete factorial scheme (3 x 3 + 1) with four replicates and ten treatments, namely: *Treatment 1* (*T1*) without P

Table 1 - Temperature and average rainfall (from April 2009 to April 2012) in the experimental period

Year	Month												Mean
	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	
	Average air temperature, °C												
2009/10	18.5	15.3	14.6	12.3	14.4	13.3	17.1	17.5	19.9	19.5	19.4	19.7	16.8
2010/11	19.3	16.1	14.1	12.2	13.8	14.4	17.5	16.9	19.8	20.7	20.6	18.5	17.0
2011/12	17.4	13.7	11.6	13.4	13.6	14.1	16.9	17.2	18.9	18.9	20.7	18.9	16.3
2012	17.1	-	-	-	-	-	-	-	-	-	-	-	17.1
Mean[1]	18.1	15.0	13.4	12.6	13.9	13.9	17.2	17.2	19.5	19.7	20.2	19.0	16.7
	Precipitation, mm												
2009/10	21	78	89	314	69	222	181	115	124	200	110	122	137.2
2010/11	151	113	55	75	21	53	112	109	212	214	250	75	120.0
2011/12	63	30	113	185	278	34	189	116	140	192	150	94	132.0
2012	177	-	-	-	-	-	-	-	-	-	-	-	177.0
History[2]	92	112	113	91	79	134	156	126	152	198	162	150	130.4

[1]Mean air temperature during the 36 months of study in the experimental area. [2]Historical average rainfall occurring in the experimental area during the last 40 years (FUNDAÇÃO ABC, 2012)

application (absolute control); *T2*, *T3* and *T4* consisting of the application of 60, 120 and 180 kg ha^{-1} of total P_2O_5, respectively, in the form of TSP (granulated) with 460, 380 and 130 g kg^{-1} of total P_2O_5, water-soluble P_2O_5 and calcium oxide (CaO), respectively; *T5*, *T6* and *T7* consisting of the application of 60, 120 and 180 kg ha^{-1} total P_2O_5, respectively, in the form of reactive RP (Arad) with 330, 100 and 370 g kg^{-1} of total P_2O_5, citric acid-soluble P_2O_5 and CaO, respectively; and *T8*, *T9* and *T10* consisting of the application of 60, 120 and 180 kg ha^{-1} of total P_2O_5, respectively, in the form of MTP containing 180, 165, 180, 70 and 100 g kg^{-1} of total P_2O_5, citric acid-soluble P_2O_5, CaO, magnesium oxide (MgO) and silicate (SiO_2), respectively.

The quantities of each fertilizer source used were based on the total P_2O_5 content of the fertilizers and the amounts annually broadcast-applied on the soil surface when sowing the winter forages. Each plot had a total area of 425 m^2 (17 x 25 m). Disregarding the 2.0 m guard rows, each plot had a floor area of 273 m^2. In the autumn-winter period, the area was divided into four paddocks of equal size (5,525 m²) to adopt the rotational grazing method. Fifteen Canchim, Brangus and Senepol-breed calves with a mean live weight of 300 kg were used in all years. The animals remained in each paddock from four to five days when the crop was black oat and from six to seven days when the crop was annual ryegrass. Thus, the doses of P_2O_5 applied in the forages were studied in the following crops: black oat (2009 and 2011) and annual ryegrass (2010) in rotation with maize (2009/10 and 2011/12) and soybean (2010/11) crops. The sequence of events and the cultivation of crops in the experimental period are shown in Table 2.

All nutrients except P were applied at the recommended doses according to the crop demands and soil analyze. When sowing black oat (2009), 65 kg ha^{-1} of nitrogen (N) and 59 kg ha^{-1} of potassium (K) were applied. At the end of the first grazing, 116 kg ha^{-1} of N were applied (by top-dressing). Side-dressings of 68 kg ha^{-1} of N and 73 kg ha^{-1} of K and a topdressing of 68 kg ha^{-1} N were applied at the V4 stage of maize (2009/10). The fertilization when sowing annual ryegrass (2010) was performed by side-dressing with 34 kg ha^{-1} of N and 74 kg ha^{-1} of K. Topdressing of 34 kg ha^{-1} of N was applied after the second grazing. The soybean was inoculated with strains of *Bradyrhizobium japonicum* (approximately 10^5 bacteria g^{-1} of soil), and 97 kg ha^{-1} of K was applied when sowing soybeans (2010/11). N and K were applied at the rate of 45 and 50 kg ha^{-1}, respectively, when sowing black oat (2011); 50 kg ha^{-1} of N was applied (topdressing) at the end of the second grazing. The maize (2011/12) received applications of 75 kg ha^{-1} of N and 75 kg ha^{-1} of K by side-dressing and 75 kg ha^{-1} of N by top-dressing at stage V4.

All N was applied in the form of urea [$CO(NH_2)_2$ - 450 g kg^{-1} of N], and the K was applied in the form of potassium chloride (KCl - 48.3 g kg^{-1} of K). All fertilizers were applied by broadcasting over the surface. Other agricultural practices were used when necessary (such as seed treatment and control of weeds, pests

Table 2 - Sequence of crop events during the experiment, including the sowing season, row spacing, plant density, cultivar or hybrid, overview of activities and cover (forages) or crop (grains) management

Crop	Sowing	Row spacing and seeding rate	Cultivar or hybrid	Overview of activities	Handling coverage (fodder) or crop (grain)
Black oat (2009)	April 28, 2009	0.17 m e 250 seeds m^{-2}	IAPAR-61	Early grazing with 30 cm, and total of two grazing periods	Drying[1] 21 days after removal of the animals from the area
Maize (2009/10)	September 27, 2009	0.80 m e 5 seeds m^{-1}	P30F53	-	April 14, 2010
Annual ryegrass (2010)	April 17, 2010	0.17 cm e 450 seeds m^{-2}	FABC-1 and Barjumbo	Early grazing with 25 cm, and total of two grazing periods	Drying[1] 28 days after removal of the animals from the area
Soybean (2010/11)	November 05, 2010	0.40 m e 16 seeds m^{-1}	BMX-Apolo	-	March 30, 2011
Black oat (2011)	April 04, 2011	0.17 cm e 250 seeds m^{-2}	IAPAR-61	Early grazing with 30 cm, and total of three grazing periods	Drying[1] 21 days after removal of the animals from the area
Maize (2011/12)	September 02, 2011	0.80 m e 5 seeds m^{-1}	P30F53	-	April 16, 2012

[1]The herbicide *glyphosate* was used (1,500 g ae ha^{-1})

and diseases) to enable the appropriate growth and development of the crops.

Exclusion cages (two per plot) manufactured with iron ½ inch in diameter, closed with 5.0 m mesh wire netting and measuring 0.25 m² were employed to evaluate the phytomass values pre- and postgrazing using a method adapted from Cano *et al*. (2004). The cages were placed randomly in the plots to quantify the dry matter produced by grazing (GDM). An area of 0.5 m² was randomly sampled per plot to assess the residual dry matter (RDM). All cutting of plants was manually performed 5.0 cm above the ground using a sickle.

The samples of black oat and annual ryegrass were weighed in the field to assess the green mass, and subsamples (100 g) were removed and sent to the laboratory. Those subsamples were washed in deionized water and dried in a forced-air convection oven at 60 °C until reaching a constant mass (MALAVOLTA; VITTI; OLIVEIRA, 1997). Subsequently, the subsamples were weighed to quantify the dry matter (DM), which was separated into the following categories: (i) the GDM, represented by the sum of the accumulations of the DM for the 2, 3 and 3 grazing cycles that occurred in black oat (2009), annual ryegrass (2010) and black oat (2011), respectively; (ii) the RDM relative to the accumulation of dry matter in the period between the last grazing and the use of herbicide, which occurred before sowing the summer crop in each year studied; and (iii) the total DM (TDM), corresponding to the sum of the GDM and RDM.

After weighing, all the subsamples were ground in a Wiley-type mill equipped with a 1.0 mm sieve and stored in sealed plastic containers until the quantification of the P concentrations according to methods proposed by Malavolta, Vitti and Oliveira (1997). The P concentrations in the plant tissues were assessed by molecular absorption spectrophotometry (MAS) following nitric-perchloric acid digestion of the subsample material. The accumulations of P in the forage shoots were calculated by multiplying the concentration of this nutrient in each subsample by the corresponding DM value. Thus, the accumulations of P in the GDM, RDM and TDM, represented by P-GDM, P-RDM and P-TDM, respectively, were quantified (PAULETTI, 2004).

The plants along a 1.0 m length of crop row were collected per plot to quantify the accumulations of DM and P in shoots when the maize (2009/10 and 2011/12) and soybean (2010/11) plants reached the R3 and R6 phenological stages, respectively. The plants were separated into subsamples of maize leaves, stalks and cobs and soybean leaves, stalks and pods. These subsamples were prepared, preserved and analyzed using the same procedures as described above for the annual forages. The accumulations of P (P-Ac) in the shoots of the maize and soybean plants were calculated by multiplying the concentration of this nutrient in each subsample by the corresponding DM value (PAULETTI, 2004).

Maize and soybean were harvested and threshed in the field after physiological maturation to assess the grain yield of each crop. Five 4.0 m lengths from the central rows of maize (2009/10 and 2011/12) within 16.0 m² were harvested in each plot. For the soybean crop (2011/12), six 5.0 m lengths from the central rows within 12.0 m² were harvested in each plot. The grain yield (GY) was expressed on the basis of 130 g water kg^{-1}. Grain subsamples (100 g) were collected to quantify the P levels (using the procedures previously described for the plant tissues). P export (P-Ex) by the crop was calculated based on the grain yield and the P levels in the grain subsamples (PAULETTI, 2004).

All results were submitted to univariate statistical analysis appropriate for randomized blocks in an incomplete factorial scheme. Tukey's test *(P*=0.05) was applied when the *F* values were significant (*P*<0.05) to perform comparisons between the effects of the P source and dose treatments. The effect of the predictive variables was adjusted to the response variables using the regression models for linear or quadratic orthogonal polynomials. The following were considered replicates in the absence of interaction: (i) for doses, the blocks (four) and the mean of the sources (TSP, RP and MTP); and (ii) for sources, the blocks (four) and the mean of the doses (0, 60, 120 and 180 kg ha^{-1} of total P_2O_5).

Regarding the GY of maize (2011/12), the relative efficiency of the combinations of the doses and sources of P were compared (Tukey's test, *P*=0.05) using as a reference (relative efficiency = 100%) the grain production in *T1*, the control without phosphate fertilization. All statistical analyses were performed by SAS, 2010.

RESULTS AND DISCUSSION

Dry matter and phosphorus accumulation in annual winter forages

No interaction occurred between the doses and sources of P for the GDM, RDM, TDM, P-GDM, P-RDM and P-TDM attributes in the forage crops of black oat (2009 and 2011) and annual ryegrass (2010). There was a quadratic increase in the yields of the GDM, RDM and TDM resulting from the application of the P doses (Table 3) to black oat (2009). The maximum yields of the GDM (1,210 kg ha^{-1}), RDM (2,343 kg ha^{-1}) and TDM (3,538 kg ha^{-1}) were predicted to occur when applying 98, 71 and 85 kg ha^{-1} of P_2O_5 to the black oat and ryegrass crops, respectively.

Regarding the accumulations of P in black oat (2009), quadratic increases in the amounts of P-GDM, P-RDM and P-TDM were detected (Table 3), as found for the DM yields (GDM, RDM and TDM). The maximum accumulations of P-GDM (4 kg ha^{-1}), P-RDM (9 kg ha^{-1}) and P-TDM (14 kg ha^{-1}) were predicted to occur when using 66, 64 and 87 kg ha^{-1} of P_2O_5, respectively.

The quadratic effects for the DM yields and accumulations of P (P-GDM, P-RDM and P-TDM) in black oat (2009) may be explained by the following factors: (i) the soil of the area was classified as heavy clayey with the predominance of kaolinite and aluminum hydroxides, which favors the fixation of excess P (NOVAIS; SMYTH, 1999; RAIJ, 2011); (ii) the soil acted as a drain and the applied P was not absorbed, most likely undergoing adsorption by the colloidal surfaces of iron and aluminum (PROCHNOW *et al*., 2003); (iii) the soil contained medium (4.2 mg dm^{-3} in the 0-20 cm layer) levels of P when the experiment was started and high (51 g dm^{-3}) concentrations of organic matter (OM) according to Pauletti (2004), thus favoring the greater availability of this nutrient through mineralization (BERTOL; GUADAGNIN; RITTER, 2004); (iv) the animals (through excretions) may have acted as a source of P for the system, returning approximately 85% of the nutrient ingested in the form of total P (organic P + inorganic P (RUSSELE; FRANZLEUBBERS, 2007); and (v) the doses of P that provided the maximum DM yields and accumulations of P were in equilibrium with the soil solution, promoting optimal plant growth.

There was an increase in the DM yield and P accumulation in black oat (2009) when using TSP (Figure 1). The clear effect of TSP resulted from the following: (i) the high solubility of this fertilizer; (ii) the surface application, which decreases the fertilizer contact with soil, causing less dissolution of water-insoluble sources (RP and MTP) in a short period of time (CHIEN *et al*., 2011); and (iii) the pH value (5.3) in the 0-5 cm layer, which fell within the pH range shown to favor the dissolution of the TSP granules and enable a greater P release into the solution (pH range of 5.0 to 6.2, 0.01 mol L^{-1} calcium chloride ($CaCl_2$) (RAIJ, 2011). Thus, higher yields and accumulations of P were found in the forage in the first study year when using the application of TSP, which corroborates findings by Prochnow *et al*. (2003) and Oliveira, Oliveira and Corsi (2007).

The IAPAR-61 cultivar of black oat (used in the present study) may reach yields between 4,728 and 8,358 kg ha^{-1} of TDM during a 134 days cycle under conditions of five cuts and soil cover cultivation,

Table 3 - Regression equations and significance levels for the attributes of black oat (2009 and 2011) and annual ryegrass (2010) evaluated under four doses of phosphorus (0, 60, 120 and 180 kg ha^{-1} of total P_2O_5) applied to the soil surface in crop-livestock integration system

Attributes	Equation	R^2	Significance[1]
	Black oat (2009)		
GDM [2]	$\hat{y} = 801.60 + 8.38\,x - 0.04\,x^2$	0.78	0.01
RDM [3]	$\hat{y} = 2{,}155.30 + 5.30\,x - 0.04\,x^2$	0.64	0.05
TDM [4]	$\hat{y} = 2{,}956.80 + 13.68\,x - 0.08\,x^2$	0.66	0.05
P-GDM [5]	$\hat{y} = 3.34 + 0.0265\,x - 0.0002\,x^2$	0.94	0.05
P-RDM [6]	$\hat{y} = 7.96 + 0.0256\,x - 0.0002\,x^2$	0.58	0.05
P-TDM [7]	$\hat{y} = 11.30 + 0.0521\,x - 0.0003\,x^2$	0.75	0.05
	Annual ryegrass (2010)		
GDM	$\hat{y} = \bar{y} = 5{,}979$	-	-
RDM	$\hat{y} = \bar{y} = 3{,}956$	-	-
TDM	$\hat{y} = \bar{y} = 9{,}935$	-	-
P-GDM	$\hat{y} = \bar{y} = 9$	-	-
P-RDM	$\hat{y} = \bar{y} = 10$	-	-
P-TDM	$\hat{y} = \bar{y} = 19$	-	-
	Black oat (2011)		
GDM	$\hat{y} = \bar{y} = 3{,}412$	-	-
RDM	$\hat{y} = 2{,}731.90 + 8.9116\,x - 0.0501\,x^2$	0.63	0.05
TDM	$\hat{y} = 5{,}898.30 + 14.289\,x - 0.0657\,x^2$	0.65	0.05
P-GDM	$\hat{y} = 10.286 + 0.0481\,x - 0.0002\,x^2$	0.98	0.01
P-RDM	$\hat{y} = 9.08 + 0.0492\,x - 0.0002x^2$	0.96	0.01
P-TDM	$\hat{y} = 29.40 + 0.1382\,x - 0.0005\,x^2$	0.98	0.05

[1]Significance level of the equation. [2]GDM: dry matter produced under grazing. [3]RDM: residual dry matter. [4]TDM: total dry matter. [5]P-GDM: phosphorus accumulated in GDM. [6]P-RDM: phosphorus accumulated in RDM. [7]P-TDM: phosphorus accumulated in TDM

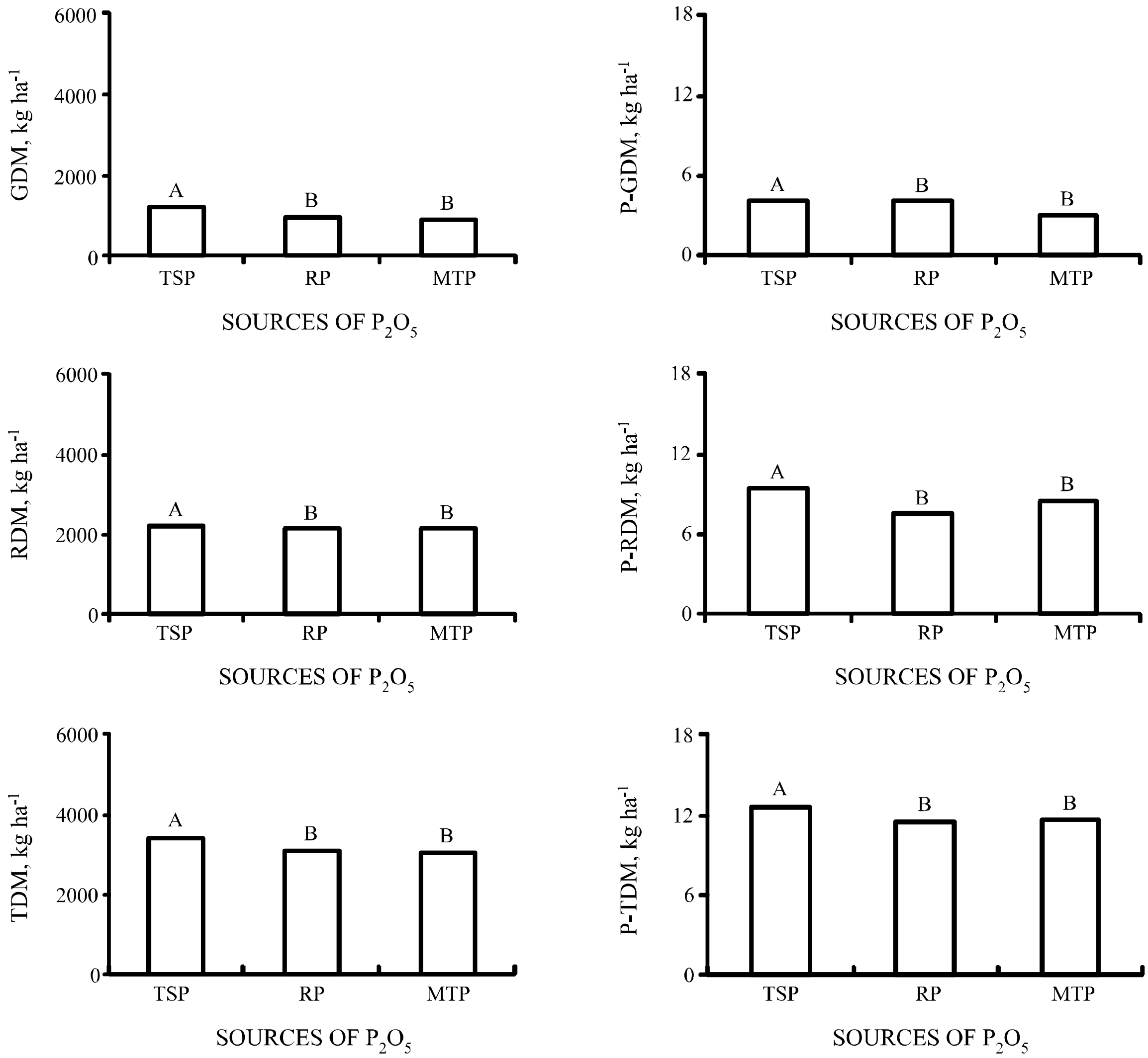
respectively (IAPAR, 2010). However, the maximum TDM production of black oat (2009) in the present study was 3,538 kg ha^{-1} (Table 3), a value below the average expected for the cultivar in question. Note that a water deficit occurred in the first 30 days of the black oat (2009) cycle (Table 1), impairing plant emergence and early growth and affecting the yield of the forage. The productive capacity of the IAPAR-61, black oat cultivar has been found to decrease in dry winters.

The treatments did not affect the DM yields (GDM, RDM and TDM) of annual ryegrass (2010) (Table 3 and Figure 2). However, the annual ryegrass showed high DM yields. At least 2,000 kg ha^{-1} of RDM are needed to maintain adequate residues in the soil and DM input for NT (ASSMANN; SOARES; ASSMANN, 2008). This level corresponds to a height of approximately 15-20 cm for oat pastures and ryegrass. Therefore, the mean RDM yield (Table 3) was higher than the recommended values for maintaining NT, even with three grazing cycles.

With four cuts, annual ryegrass may yield up to 8,472 kg ha^{-1} and 9,287 kg ha^{-1} of TDM for the FABC-1 and Barjumbo cultivars, respectively (FUNDAÇÃO ABC, 2012). Thus, the mean TDM produced by the annual ryegrass in this study was higher than that usually found for these cultivars (Table 3 and Figure 2). Annual ryegrass, when properly managed, has been found to support a high density of grazing animals while providing high forage yields throughout the cycle (FONSECA; MARTUSCELLO, 2010). Note that adequate rainfall occurred in 2010 (Table 1), even at the beginning of forage establishment, favoring plant development and growth.

The accumulation of P-GDM in annual ryegrass (2010) was not affected by the doses (Table 3) and

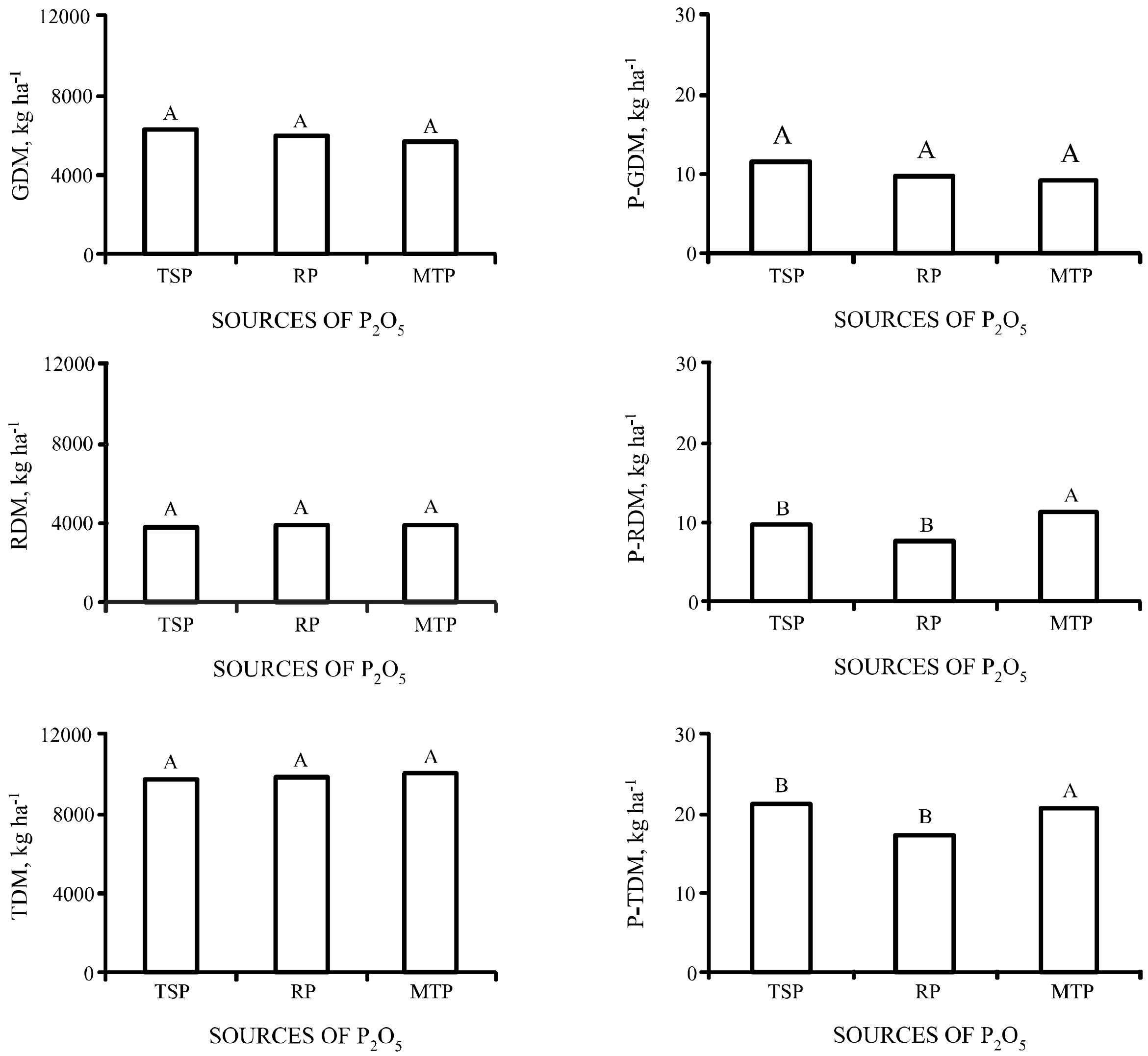
Figure 1 - Dry matter produced under grazing (GDM), residual dry matter (RDM), total dry matter (TDM) and phosphorus accumulated in the GDM (P-GDM), RDM (P-RDM) and TDM (P-TDM) of black oat (2009) following surface application of different sources of phosphorus in crop-livestock integration system. TSP is triple superphosphate, RP is rock phosphate and MTP is magnesium termophosphate. Means followed by the same letters do not differ from each other according to Tukey's test (*P*=0.05)



sources (Figure 2) of the phosphates. The accumulations of P-RDM and P-TDM in annual ryegrass (2010) were also unaffected by the P doses (Table 3) but increased when MTP was applied (Figure 2). This response pattern may be explained by the following factors: (i) the MTP product releases P more slowly than does the TSP product, decreasing the likelihood of P adsorption onto soil colloids (BEDIN *et al*., 2003); (ii) MTP is water-insoluble, although it has higher solubility in citric acid than RP, and proportionately more P may be dissolved (RESENDE *et al*., 2006), particularly in systems with animals; (iii) MTP contains magnesium (Mg), which acts as a plant P loader, promoting the plant phosphate nutrition; (iv) the presence in MTP of silicon (Si), which has the ability to decrease the specific adsorption of phosphate ions, leaving P more available to plants (RAIJ, 2011); and (v) the residual effect of the fertilizer applied in previous years.

Excluding the GDM, there was a quadratic increase in the RDM and TDM yields and the accumulations of P (P-GDM, P-RDM and P-TDM) in black oat (2011) resulting from the application of the P doses (Table 3). The maximum yields of RDM (3,128 kg ha^{-1}) and TDM (6,675 kg ha^{-1}) were predicted to occur when using 89 and 108 kg ha^{-1} of P_2O_5, respectively, and the maximum accumulations of P-GDM (12 kg ha^{-1}), P-RDM (13 kg ha^{-1}) and P-

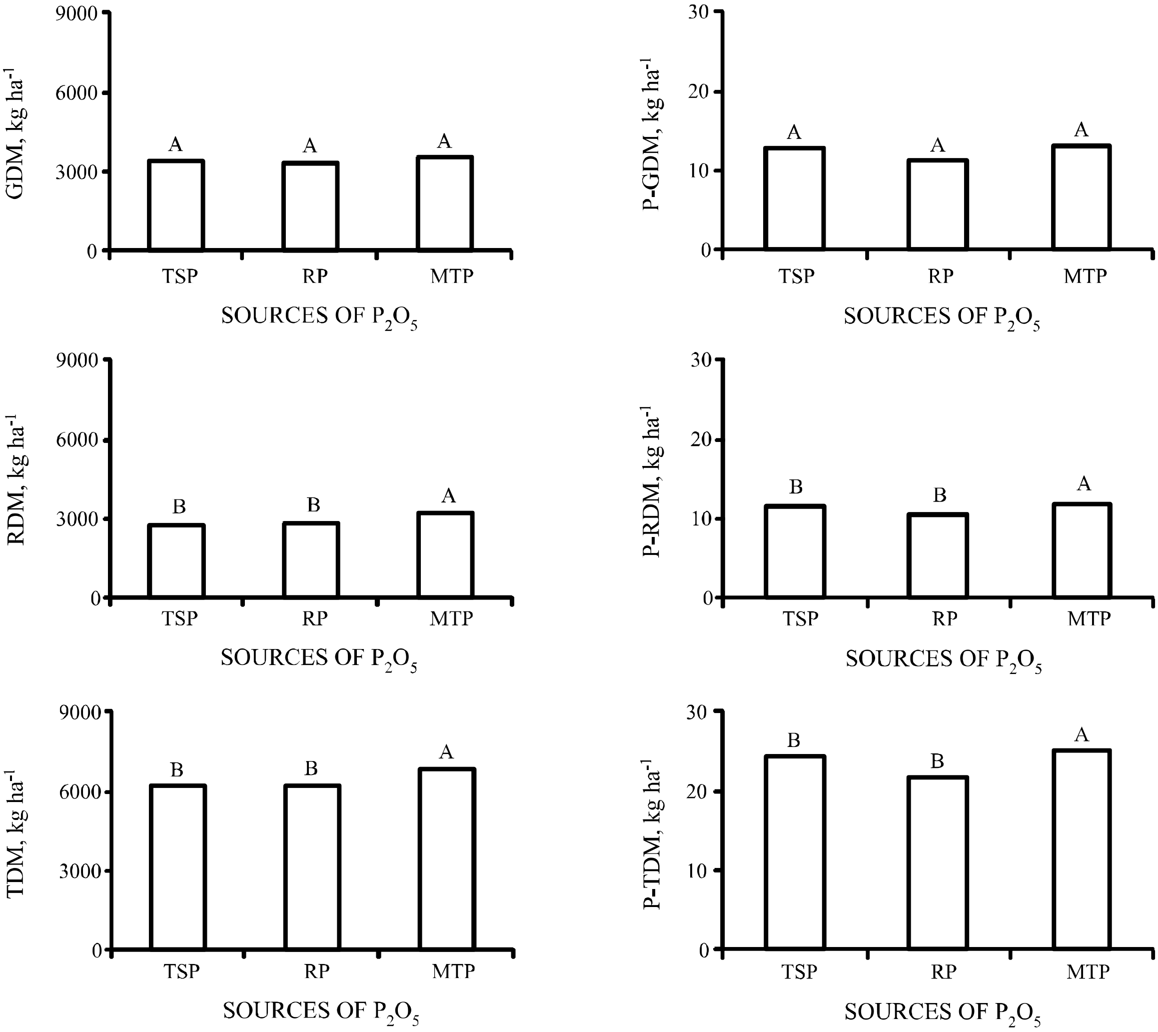
Figure 2 - Dry matter produced under grazing (GDM), residual dry matter (RDM), total dry matter (TDM) and phosphorus accumulated in the GDM (P-GDM), RDM (P-RDM) and TDM (P-TDM) of annual ryegrass (2010) following surface application of different sources of phosphorus in crop-livestock integration system. TSP is triple superphosphate, RP is rock phosphate and MTP is magnesium termophosphate. Means followed by the same letters do not differ from each other according to Tukey's test (P=0.05)



TDM (39 kg ha^{-1}) were predicted at doses of 121, 123 and 138 kg ha^{-1} of P_2O_5, respectively. The quadratic effects may be assigned as previously performed for black oat (2009), especially to the balance between the maximum DM yields and the P accumulations provided by the P doses and the soil solution.

In black oat (2011), MTP provided a greater increase than the other P sources in the RDM and TDM yields and in the accumulations of P-RDM and P-TDM but not in the GDM yields and the P-GDM accumulations (Figure 3). The forages submitted to grazing responded with permanent resprouting resulting from the defoliation. Upon defoliation, roots have shown more accelerated growth than other organs, releasing higher amounts of organic acid exudates (CARVALHO *et al.*, 2010). The low molecular weight organic acids (citric, malic, oxalic and tartaric) in the root exudates are also found in animal manure (BAZIRAMAKENGA; SIMARD, 1998) and may have promoted the solubilization of the P derived from MTP. Organic acids have been shown to compete for P adsorption sites, favoring the availability of this nutrient in the soil solution (PAVINATO; ROSOLEM, 2008). Furthermore, the Si present in MTP may be involved in the increased production of DM in shoots (KORNDÖRFER *et al.*, 2010) because Si promotes a

Figure 3 - Dry matter produced under grazing (GDM), residual dry matter (RDM), total dry matter (TDM) and phosphorus accumulated in the GDM (P-GDM), RDM (P-RDM) and TDM (P-TDM) of black oat (2011) following surface application of different sources of phosphorus in crop-livestock integration system. TSP is triple superphosphate, RP is rock phosphate and MTP is magnesium termophosphate. Means followed by the same letters do not differ from each other according to Tukey's test (P=0.05)



greater photosynthetic capacity by encouraging a more erect leaf arrangement (AGARIE *et al*., 1998).

The GDM yield of black oat (2011) was not affected by the P sources (Figure 3), most likely due to the uneven forage intake by the animals and resulting high variability between treatments. Furthermore, the soil of the area contained high and medium levels of OM (51 g dm^{-3}) and P (4.2 mg dm^{-3}), respectively, at the time the experiment was installed, favoring the mineralization of organic P (BERTOL; GUADAGNIN; RITTER, 2004). Note that in 2010, the yield of GDM was also not affected by the P sources (Figure 2). A comparison between ungrazed and grazed pastures has shown that the presence of animals changes the pattern of nutrient distribution in the soil through the deposition of manure, thereby altering nutrient recycling (BALBINOT JUNIOR *et al*., 2009). Furthermore, approximately 90% of the P consumed from forages may return to the soil, primarily through feces (WILLIAMS; HAYNES, 1990).

The animals distribute their excretions randomly through the pasture; therefore, the development of the forages may have been differentially affected by the grazing cycles because only two cycles were conducted in 2009, compared with three cycles in 2010 and 2011. Russele and Franzleubbers (2007) found that feces cause greater grazing rejection than urine, causing intake unevenness across the grazed area. The authors observed the relationship between the waste supply and the time of grazing and noted that the rejection of waste-contaminated areas might last up to 16 months with feces but only one cycle of rotational grazing (approximately four weeks) with urine.

In contrast to 2009, the rainfall conditions were adequate for black oat in 2011 (Table 1), when the IAPAR-61 cultivar reached a satisfactory TDM yield (6,675 kg ha^{-1}) compared with the expected yield between 4,728 and 8,358 kg ha^{-1} (Table 3 and Figure 3). Black oat has been shown to be less demanding than annual ryegrass regarding fertility (FONSECA; MARTUSCELLO, 2011). However, in the present study, the IAPAR-61 cultivar was more responsive than the annual ryegrass to the phosphate fertilization.

Black oat has been shown to extract nutrients from the deepest soil layers through the root system and to make them available at the surface following the cutting of shoots and after decomposition by the action of microorganisms (MELO *et al*., 2011). Borkert *et al*. (2003) verified that the P is recycled by black oat in relatively small amounts, which range from 8 to 12 kg ha^{-1}, in the class interval ranging from 5,000 to 10,000 kg ha^{-1} of TDM. However, note that the maximum P-TDM accumulations in the present study, which for black oat (2009) and (2011) were 14 and 39 kg ha^{-1}, respectively, exceeded those found in the literature (Table 3).

The accumulation of P does not indicate that plants are more or less efficient because certain plant cultivars may develop and grow well (through genetic adaptations) with a comparatively low amount of this nutrient (FERNANDES; MURAOKA, 2002). However, it has been reported that the greater amounts of P accumulated and concentrated is grass residues (P-RDM) provide higher returns of this nutrient for the system and the following crop through straw decomposition (MURUNGU *et al*., 2011).

In general, the high TDM yields produced by the annual ryegrass (2010) and black oat (2011) may be related to the following factors: (i) P is the nutrient responsible for plant tillering, thus increasing the DM production of forages (GUEDES *et al*., 2009); (ii) grazed plants have high levels of root exudates and release high-quality components into the soil, which would stimulate microbiological activity, thereby accelerating the cycling of applied phosphorus (CARVALHO *et al*., 2010); (iii) organic acids derived from the decomposition of organic matter (roots and feces) have the ability to form complexes with iron and aluminum oxides, avoiding P fixation (PAVINATO; ROSOLEM, 2008); (iv) forage resprouting may have been affected by the soil OM reserves (SOUZA *et al*., 2008) because these reserves showed high levels in the present study (51 g dm^{-3} in the 0-20 cm layer); (vii) the presence of indole acetic acid in the urine of cattle, which is a known plant growth stimulant (CESAR *et al*., 2007); and (viii) the moderate grazing intensity used in the present experiment, favoring adequate plant growth (CARAVALHO *et al*., 2010).

Grain yield and phosphorus accumulation and export in maize and soybean crops

No interaction for the GY, P-Ac and P-Ex maize (2009/10) and soybean (2010/11) attributes (Table 4) was found between the P sources and doses, except for

Table 4 - Regression equations and significance levels for the attributes of maize (2009/10 and 2011/12) and soybean (2010/11) evaluated under different (anticipated) doses of phosphorus (0, 60, 120 and 180 kg ha^{-1} of total P_2O_5) applied to the soil surface in crop-livestock integration system

Attributes	Equation	R^2	Significance[1]
	Maize (2009/10)		
GY[2]	$\hat{y} = \bar{y} = 11,908$	-	-
P-Ac[3]	$\hat{y} = \bar{y} = 60$	-	-
P-Ex[4]	$\hat{y} = \bar{y} = 52$	-	-
	Soybean (2010/11)		
GY	$\hat{y} = \bar{y} = 5,067$	-	-
P-Ac	$\hat{y} = 71.992 + 0.0995\ x$	0.92	0.01
P-Ex	$\hat{y} = 45.671 + 0.0444\ x$	0.57	0.05
	Maize (2011/12)		
P-Ac	$\hat{y} = 36.722 + 0.3853\ x - 0.0014\ x^2$	0.98	0.01
P-Ex	$\hat{y} = 32.483 + 0.4808\ x - 0.002\ x^2$	0.98	0.01

[1]Significance level of the equation. [2]GY: grain yield. [3]P-Ac: phosphorus accumulated in shoots. [4]P-Ex: phosphorus exported by grains

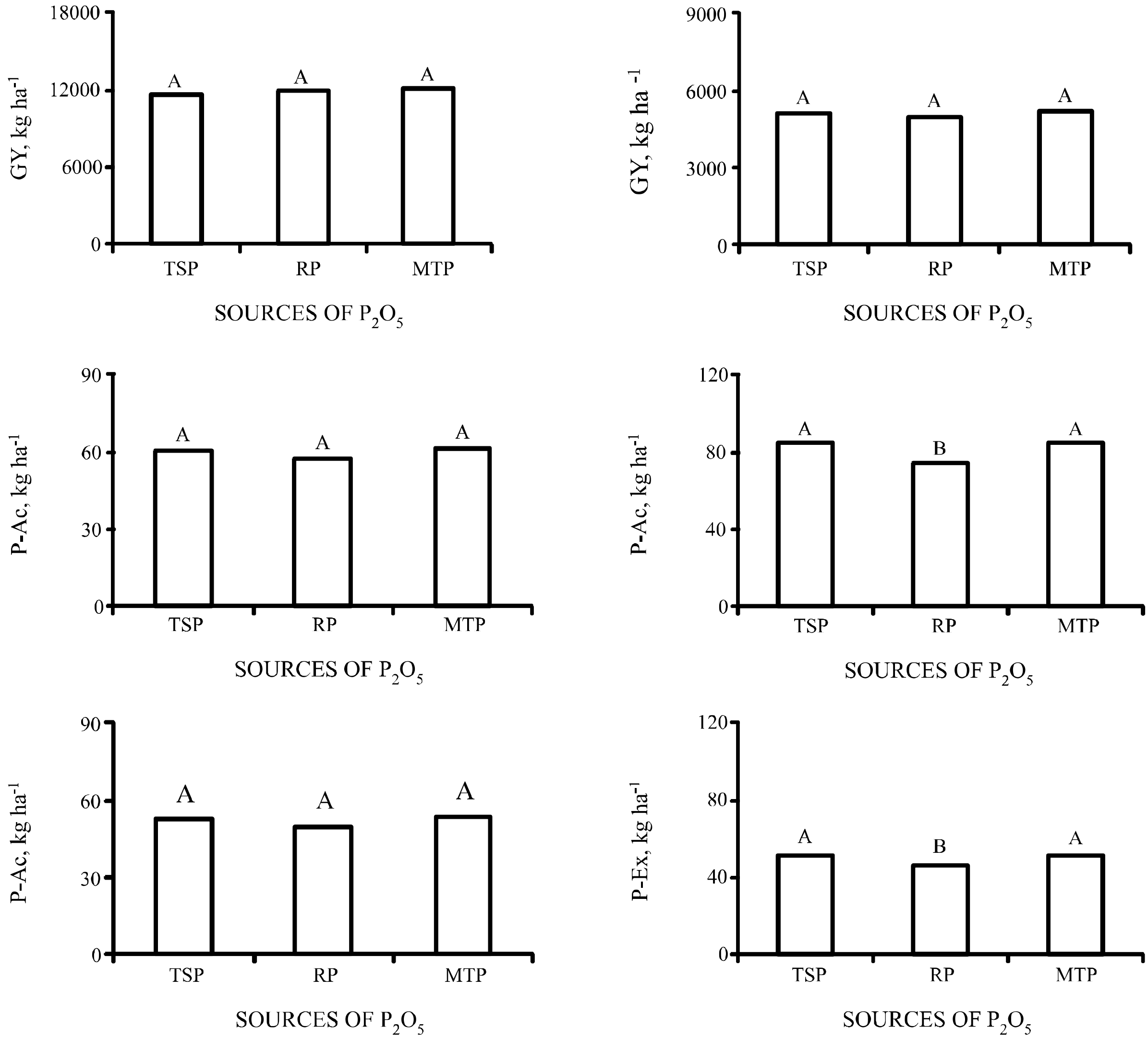
an interaction term for the maize (2011/12) GY (F=2.98, P<0.05). The GY, P-Ac and P-Ex attributes of maize (2009/10) were not affected by the anticipated surface-applied P doses (Table 4) and sources (Figure 4) that were used when sowing the winter crops.

These results most likely resulted from the following factors: (i) the short study period; (ii) the adequate rainfall throughout the entire crop cycle (Table 1); (iii) the high soil concentrations of OM (51 g dm^{-3}) and implied satisfactory soil reserve of organic P, which may have been mineralized (RESENDE *et al*., 2006); and (iv) the increased nutrient cycling observed in CLIS (CARVALHO *et al*., 2010).

No difference in the soybean (2010/11) GYs was found among the treatments (Table 4 and Figure 4). However, the P-Ac and P-Ex linearly increased as the P dose increased (Table 4), reaching greater accumulations because of the TSP and MTP applications (Figure 4). These results may be characterized by the excellent intake by the plant because there was no response in the GY. This fact is most likely linked to the physiological process of nitrogen fixation (biological nitrogen fixation, BNF), which requires large amounts of energy (and P in the form of ATP) (TAIZ; ZEIGER, 2004).

When studying the P absorption capacity and BNF of soybeans, Miao *et al*. (2007) and Rotaru and

Figure 4 - Grain yield (GY), phosphorus accumulated in shoots (P-Ac) and exported phosphorus (P-Ex) in maize (2009/10) and soybean (2010/11) following surface application of different sources of phosphorus in crop-livestock integration system. TSP is triple superphosphate, RP is rock phosphate and MTP is magnesium termophosphate. Means followed by the same letters do not differ from each other according to Tukey's test (P=0.05)

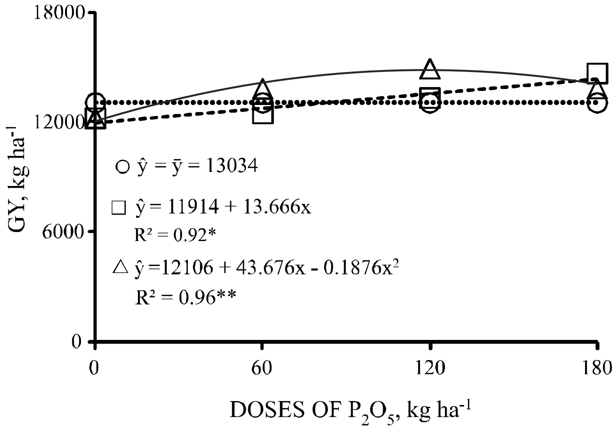


Sinclair (2009) found that P deficiency has been one of the factors that most affects legume production in various types of soils. These authors noted a linear and positive correlation between P absorption and node formation, indicating that higher doses of P would stimulate BNF because plants stored greater amounts of P. The relatively small increases in the P-Ac and P-Ex in the RP treatments were plausible (Figure 4) because annual crops have been shown to have a high demand for P in a short period of time, and the P effects have been observed in medium- to long-term studies (NOVAIS; SMYTH, 1999; RESENDE *et al*., 2006).

An interaction occurred between the P doses and sources for the GY (Figure 5) of maize (2011/12). A GY increase resulted from the (anticipated) MTP and RP doses, although no difference was found with TSP (Figure 5). The results predicted a maximum GY (14,649 kg ha^{-1}) when using 116 kg ha^{-1} of P_2O_5 in the form of MTP, and the effect was linear for RP.

The lack of an effect on the maize (2011/12) yield from the anticipated TSP application may be assigned to the following: (i) the high solubility of this fertilizer and resulting immediate availability of P to the system, which favors greater absorption by forage plants and/or adsorption by soil colloids soon after its application (ONO *et al*., 2009); (ii) the lower DM yields and accumulations of P produced in this crop by the TSP compared with the MTP applications to the black oat (2011) crop preceding maize 2011/12 (Figure 3), resulting in a reduced P return to the system; and (iii) the lower effect of TSP than has been observed and proven in medium to long term studies (PROCHNOW *et al*., 2003; RESENDE *et al*., FRANZINI *et al*., 2009).

Figure 5 - Grain yield (GY) of maize (2011/12) following an anticipated surface application of different sources of phosphorus in crop-livestock integration system. The sources are indicated as follows: ○ triple superphosphate (TSP), □ rock phosphate (RP) and Δ magnesium termophosphate (MTP). Points are means of four replicates (**P<0.01 and *P<0.05)



Although RP is a water-insoluble product with low solubility in citric acid, its efficiency when estimated in periods longer than two crop cycles has been shown to match that of soluble phosphates (MOREIRA; MALAVOLTA; MORAES, 2002). Therefore, in this study, the dissolution of RP was certainly favored because of the following factors: (i) the high soil levels of OM (51 g dm^{-1}) in the 0-20 cm layer, which decreased the likelihood of P adsorption; (ii) the longer duration of fertilizer contact with the soil, given the fertilizations in previous years; and (iii) the supply of protons (H^+) likely generated by

Table 5 - Relative maize (2011/12) yield efficiency by the doses and sources of phosphorus applied when sowing black oat (2011) in crop-livestock integration system

Sources of Phosphorus	Doses of P_2O_5	Relative Efficiency
	---------------- kg ha^{-1} ----------------	------------------ % ------------------
Triple superphosphate	60	105 C
Rock phosphate	60	104 C
Magnesium termophosphate	60	113 B
Triple superphosphate	120	107 C
Rock phosphate	120	109 B
Magnesium termophosphate	120	123 A
Triple superphosphate	180	108 C
Rock phosphate	180	119 A
Magnesium termophosphate	180	113 B
Control[1]	0	100 D

[1]Control (control treatment): 100%. Means followed by the same letters do not differ from each other according to Tukey test (P=0.05)

the acidification of the rhizosphere and enhanced by the presence of animals in the system (SOUZA *et al*., 2008).

However, the highest maize (2011/12) GY was found when using MTP because an increase from 14 to 44 kg of maize produced was predicted to occur for each kilogram of P applied to the soil in the form of RP and MTP, respectively (Figure 5). Doses of 180 kg ha^{-1} RP and 120 kg ha^{-1} MTP were predicted to yield the greatest relative increases in production, at 19 and 23%, respectively, when compared with the control (Table 5).

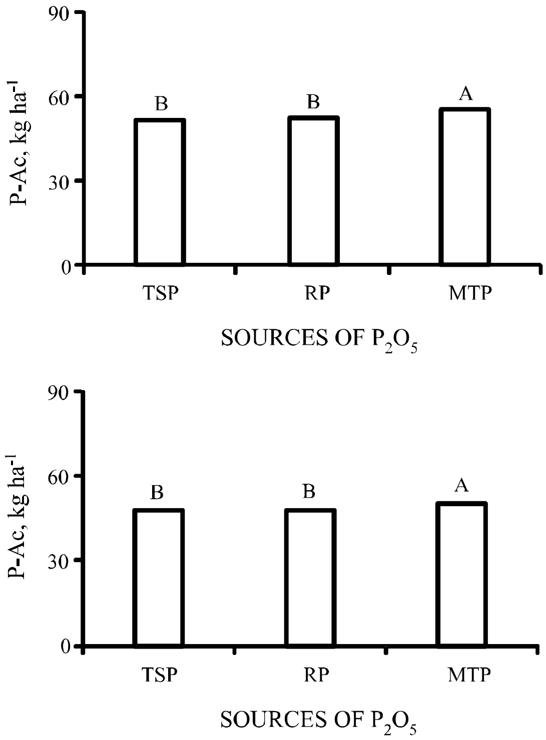
This shows the high efficiency of silicophosphates in plants because the same relative efficiency could be obtained with a lower dose of MTP than RP. The relative efficiency of the grains was also noticeably unaffected by the TSP doses, demonstrating the lower residual effect of this fertilizer in soils.

There was a quadratic effect on the P-Ac and P-Ex resulting from the application of the P doses (Table 4) and an increase in these attributes when using MTP (Figure 6). The greatest P-Ac (63 kg ha^{-1}) and P-Ex (61 kg ha^{-1}) values were predicted in maize (2011/12) at doses of 138 and 120 kg ha^{-1} of P_2O_5, respectively. The quadratic effect on these attributes may be related to the following factors: (i) the high soil concentration of P, most likely resulting from a decrease in the plant concentration of zinc (Zn), which has been the factor most limiting for maize, given the competitive inhibition of P against Zn (ARAÚJO *et al*., 2004); (ii) the dose yielding the maximum GY was in equilibrium with the soil solution, characterizing the plant absorption limit between the soil drainage and soil source (NOVAIS; SMYTH, 1999); and (iii) the maximum production capacity of the P30F53 hybrid was reached and was inclusively higher than values that have been recorded for the average production in the State of Parana, Brazil - ranging from 13,000 to 13,500 kg ha^{-1} (SANDINI *et al*., 2011).

The average rainfall values for the spring-summer harvest in the months of January and February were adequate for the maize (2009/10 and 2011/12) and soybean (2010/11) crop development (Table 1). This fact should be emphasized because the crops were found to require an adequate amount of water precisely during that period (flowering and grain filling) because of the greater demand for nutrients (BERGAMASCHI *et al*., 2004).

The mean production from the last harvest in Paraná was 7,873 kg ha^{-1} of maize and 3,360 kg ha^{-1} of soybean (CONAB, 2011). Therefore, the GYs of both maize and soybean (even in the absence of an effect) were high in all years of this study. High grain yields have been observed in CLIS resulting from the increase in nutrient cycling provided by grazing animals (CARVALHO *et al*., 2010; SILVA *et al*., 2012).

Figure 6 - Phosphorus accumulated in shoots (P-Ac) and exported phosphorus (P-Ex) in maize (2011/12) following an anticipated surface application of different sources of phosphorus in crop-livestock integration system. TSP is triple superphosphate, RP is rock phosphate and MTP is magnesium termophosphate. Means followed by the same letters do not differ from each other according to Tukey's test (P=0.05)



CONCLUSIONS

1. The use of triple superphosphate provided a higher yield of total dry matter and accumulation of phosphorus only for black oat in the first year of cultivation;
2. In the second year, the application of magnesium termophosphate caused a greater accumulation of phosphorus in annual ryegrass and soybeans, and the application of both magnesium termophosphate and triple superphosphate provided a greater phosphorus accumulation and exportation by grains;
3. In the third year, the use of magnesium termophosphate provided a higher total dry matter yield and accumulation of phosphorus for both black oat and maize;
4. The application of water-insoluble sources, especially magnesium termophosphate, achieved greater residual effects and provided higher forage and maize yields after 36 months of study.

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