

Phosphorus use in soybean in integrated production system under anticipation of phosphate fertilization¹

Uso de fósforo na soja em sistema integrado de produção sob antecipação de adubação fosfatada

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ABSTRACT - Conservation agriculture practices, such as integrated crop-livestock system (ICLS), can result in efficiency of phosphorus use and, economic and environmental benefits. The higher nutrient cycling, deposited crop and animal residues in the soil surface can promote the maintenance of soil fertility. Thus, the anticipated of phosphate fertilization may be a viable strategy of fertilization for soybean crop, in this system. The objective of this work was to determine the yield, accumulation of P and phosphorus use efficiency (PUE) on the dry biomass and grains of the soybean crop, in an integrated crop-livestock system (ICLS) due to anticipated fertilization of sources and doses phosphates annually applied in the soil surface. The experiment was conducted over a period of five years, in Castro-PR, under a Typic Dystrudept, using a randomized block design, in an incomplete factorial scheme (3×3+1), with four replications. The treatments consisted of three doses (60, 120 and 180 kg ha⁻¹ of total P₂O₅) plus absolute control, and three sources (triple superphosphate, rock phosphate – Arad and magnesium thermophosphate) of P. The different sources no influenced and there were no interactions between P sources and doses for the attributes: grain yield (GY), shoot dry mass (SDM), weight of thousand seeds (WTS), P accumulation in soybean (PAS), P concentration in soybean grains (PCSG), PUE and P in residual dry mass (PRDM). Linear increases were observed in GY, SDM, WTS, PCSG and PRDM and quadratic increases in PAS and PUE.

Key words: Anticipated fertilization. Sustainable intensification. *Glycine max* (L.) Merr.

RESUMO - Práticas de agricultura conservacionista, como o sistema integrado de produção agropecuária (SIPA), podem resultar em eficiência no uso de P e em benefícios econômicos e ambientais. A maior ciclagem de nutrientes e a deposição de resíduos vegetais e animais na superfície do solo podem promover a manutenção da fertilidade do solo. Assim, a antecipação da adubação fosfatada pode ser uma estratégia viável de adubação para a cultura da soja, neste sistema. O objetivo deste trabalho foi determinar o rendimento, eficiência de uso de P (EUP) e acúmulo deste nutriente na biomassa seca e nos grãos da cultura da soja, em SIPA devido à adubação antecipada de fontes e doses fosfatos aplicados anualmente na superfície do solo. O experimento foi conduzido durante cinco anos, em Castro-PR, sob um Cambissolo Háplico, em delineamento de blocos ao acaso, em esquema fatorial incompleto (3×3+1), com quatro repetições. Os tratamentos consistiram de três doses (60, 120 e 180 kg ha⁻¹ de P₂O₅ total), mais um controle absoluto, e três fontes (superfosfato triplo, fosfato natural reativo - Arad e termofosfato magnésiano) de P. As diferentes fontes não influenciaram e não houve interação entre fontes e doses de P para os atributos: rendimento de grãos (RG), massa seca da parte aérea (MSPA), peso de mil sementes (PMS), acúmulo de P na soja (APS), concentração de P nos grãos de soja (CPGS), EUP e P na massa seca residual (PMSR). Aumentos lineares foram observados em PG, MSPA, PMS, CPGS e PMSR e aumentos quadráticos em APS e EUP.

Palavras-chave: Adubação antecipada. Intensificação sustentável. *Glycine max* (L.) Merr.

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INTRODUCTION

The integrated crop-livestock systems (ICLS) has been growing in importance around the world (ASSMANN *et al.*, 2017; BONETTI *et al.*, 2019; CARVALHO *et al.*, 2010; HENDRICKSON; COLAZO, 2019; MORAES *et al.*, 2014). These crop-livestock systems employ a diverse range of integrated ecological, biophysical and socio-economic conditions (FOOD AND AGRICULTURE ORGANIZATION, 2013), that can reduce environmental risks (LEMAIRE *et al.*, 2014), improve soil fertility and increase the crop yield with reducing the use of unrenovable resources (CARVALHO *et al.*, 2010; HENDRICKSON; COLAZO, 2019; MORAES *et al.*, 2014).

In these systems, cattle grazing alters direction, magnitude and composition of nutrient fluxes, affecting residue decomposition and nutrient release rates (KUNRATH *et al.*, 2015). Thus, deposition of organic residues in the soil, accumulation of C in the soil and maximization of above- and below-ground plant development will promote higher nutrient cycling in soil solution. Moreover, increase in the soil organic matter resulting from this production system, helps to reduce adsorption of anions on the surfaces of colloids, such as phosphates, over time, and can maximize efficient use of P (CARVALHO *et al.*, 2010; HENDRICKSON; COLAZO, 2019).

The soybean (*Glycine max* L. Merrill), the most important oilseed in the world, provides vegetable protein for millions of people and ingredients for hundreds of chemicals (BEGUM *et al.*, 2015; KHANAM *et al.*, 2016). In Brazil, production is estimated at 124.2 million tons, a record in the historical series, mainly due to better weather conditions. Southern Brazil is responsible for approximately 26% of national production (COMPANHIA NACIONAL DE ABASTECIMENTO, 2020). In this region, although the benefits of ICLS are clear, only 6% (2,553,310 ha) is grown in the soybean-cattle system (MORAES *et al.*, 2017). Thus, further discussions on the development of soybean crops are needed from the perspective of this production system, especially in different types of soils, such as Typic Dystrudept.

In the Brazilian subtropics, after the soil acidity correction, the low available phosphorus (P) content is one of the main nutritional factors limiting the development of plants (NOVAIS; SMYTH, 1999). In addition, P use efficiency (PUE)- which corresponds to dry matter (DM) produced as a function of the number of nutrients of the applied units (FAGERIA *et al.*, 2010) - depends of factors as (i) P source and dose, (ii) type of soil and type of crop (PANG *et al.*, 2018); (iii) association with mycorrhizal

fungi (BÜNEMANN; CONDRON, 2007) and (iv) production system employed (RAIJ, 2011).

Furthermore, soil P management also involves the strategy adopted in the application of fertilizers. P sources that provide higher solubility, such as triple superphosphate (TSP) and magnesium thermophosphate (MTP), present a better performance in relation to sources of lower solubility, such as rock phosphate (RP), since the latter last guarantee release the gradual of P for the cultures (GALETTO *et al.*, 2014).

However, anticipated fertilization [a strategy that provides for total or partial application of recommended doses of fertilizer of the summer crop, at the time of sowing of the winter crop, in an incorporated form or at the soil surface (FRANCISCO; CÂMARA; SEGATELLI, 2007)], can be the interesting strategy in production systems such as ICLS, because it would improve P recycling, especially in the medium and/or long term and ensure a better time and operational efficiency in sowing summer crop (GALETTO *et al.*, 2014). However, scientific information on the strategy of anticipated fertilization with different sources and doses of phosphates is still scarce, especially in the medium and/or long term in ICLS.

The objective of this study was to determine the yield, accumulation of P and phosphorus use efficiency (PUE) on the dry biomass and grains of the soybean crop, submitted to doses and sources of phosphates, applied annually on soil surface, at the time of sowing of the winter crop.

MATERIAL AND METHODS

The experiment was conducted over a period of five years (April 2009 to April 2014) in the municipality of Castro-PR (24°51'49" S, 49°56'61" W, 1,020 m). The predominant climate in the region, according to the Köppen classification, which the Cfb type, with a temperature of 16 °C, and an average annual precipitation of 1,087 mm. The area was cultivated under the no-tillage system for eight years.

The soil is Typic Dystrudept (605, 225 and 170 g kg⁻¹ of clay, silt and sand, respectively). Quartz, kaolinite and gibbsite are the predominant minerals in a clay fraction. Soil chemical attributes, at the beginning of the experiment, in the layer of 0-20 cm was: pH (CaCl₂) 4.8; exchangeable Al³⁺ concentrations, Ca²⁺, Mg²⁺ and K⁺ de 0.4; 31.2; 23.5 and 3.5 mmol_c dm⁻³, respectively; total acidity (H+Al) 92.1 mmol_c dm⁻³; base saturation 38%; P (Mehlich-1) concentrations, sulphur (S), total organic carbon (TOC) and total nitrogen (TN) 4.2 and 12.8 mg dm⁻³, 29.6 and 2.0 g dm⁻³, respectively.

The experimental design was a randomized complete blocks in an incomplete factorial scheme (3x3+1), with four replications. Treatments consisted of different sources [triple superphosphate (TSP), rock phosphate - Arad (RP) and magnesium thermophosphate (MTP)] and doses [absolute control (0 kg ha⁻¹ of total P₂O₅), 60, 120 and 180 kg ha⁻¹ of total P₂O₅] of P, applied annually in the soil surface, at the time of winter crop sowing (anticipated fertilization). Chemical composition of different phosphate sources used were equivalent to: 460, 380 and 130 g kg⁻¹ of total P₂O₅, water-soluble P₂O₅ and CaO, respectively, for TSP; 330, 100 and 370 g kg⁻¹ of total P₂O₅, P₂O₅ soluble in citric acid (20 g L⁻¹) and CaO, respectively, for RP and; 180, 165, 180, 70 and 100 g kg⁻¹ of total P₂O₅, P₂O₅ soluble in citric acid (20 g L⁻¹), CaO, MgO and SiO₂, respectively, for MTP. Quantities utilized from each source were calculated based on the total P₂O₅ content of fertilizers and applied annually at soil surface at the time of winter forage sowing.

In the spring-summer period, during cultivation of grain crops, the experimental area was divided into plots (52 experimental units) corresponding to a manageable area of 273 m², for each plot. Crops rotation that was followed during the experimental period in ICLS were as follows: (i) black oat (*Avena strigosa* Schreb.) (2009, 2011 and 2013); (ii) maize (*Zea mays* L.) (2009/10, 2011/12 and 2013/14); (iii) ryegrass (*Lolium multiflorum* L.) (2010 and 2012) and (iv) soybean (*Glycine max* L.) (2010/11 and 2012/13).

In the autumn-winter period, the rotational grazing system was adopted, in which the experimental area was divided into paddock (totaling 4 paddocks with 5525 m² each). Cattle used in the grazing period correspond to 21 heifers of the Dutch dairy cattle, with an average weight of 250 kg, equivalent to 5.2 animal units (U.A.). These remained in each paddock for 4-7 days depending on forage species, also taking into account heights of the entrances (20 cm) and exits (10 cm) for the cattle.

The soybean crop (2012/2013) implementation was carried out through sowing and inoculation with *Bradyrhizobium japonicum* strains and potassium (K₂O) was applied in the form of potassium chloride (KCl) (SOCIEDADE BRASILEIRA DE CIÊNCIA DO SOLO, 2017). P accumulation in the soybean crop was evaluated, by removing 1.0 m linear soybean plants in the R6 stage. The soybean plant samples were separated into leaves, stem and pods. After the maturation stage, the soybean was harvested and the grain yield (GY) determined as expressed in 130 g kg⁻¹ humidity. For each plot, six 5.0 m long central lines were harvested, totaling a 13.2 m² area.

All the vegetable tissue samples were put in paper bags and sent to the laboratory for washing, drying,

grinding and analytical determinations, using the methods suggested by Malavolta, Vitti and Oliveira (1997). After washed with deionized water, the samples were dried at 65 °C with air forced flow until constant matter was obtained, ground in a "Wiley" mill equipped with 0.85 mm mesh and stored in sealed plastic containers until the chemical analyses were carried out. After chemical analyses determinations in order to obtain the nutrient concentration in the phytomass, P accumulation in soybean (PAS), P concentration in soybean grains (PCSG), P accumulation in residual dry mass (PRDM), weight of thousand seeds (WTS), and the shoot dry mass (SDM) were quantified. Also, the P use efficiency (PUE) was calculated according to Fageria *et al.* (2010), upon phytomass and soybean grains yield (GY).

All results were submitted to statistical analysis in randomized blocks in an incomplete factorial scheme (3x3+1). When P factors were significant (P<0.05), the Tukey test ($\alpha = 0.05$) was applied to compare the P source effects. The predictive variable (P doses) effect was adjusted to the response variables (plant attributes), using linear or quadratic orthogonal polynomial regression models. When there was no interaction, these were considered replications: (i) for doses – blocks (four) and the sources average (TSP, RP and MTP); for sources – blocks (four) and the doses average (0, 60, 120, 180 kg ha⁻¹ total P₂O₅). All statistical analyses were performed using SAS Version 9.2 program (SAS Institute Inc. 9.1.2).

RESULT AND DISCUSSION

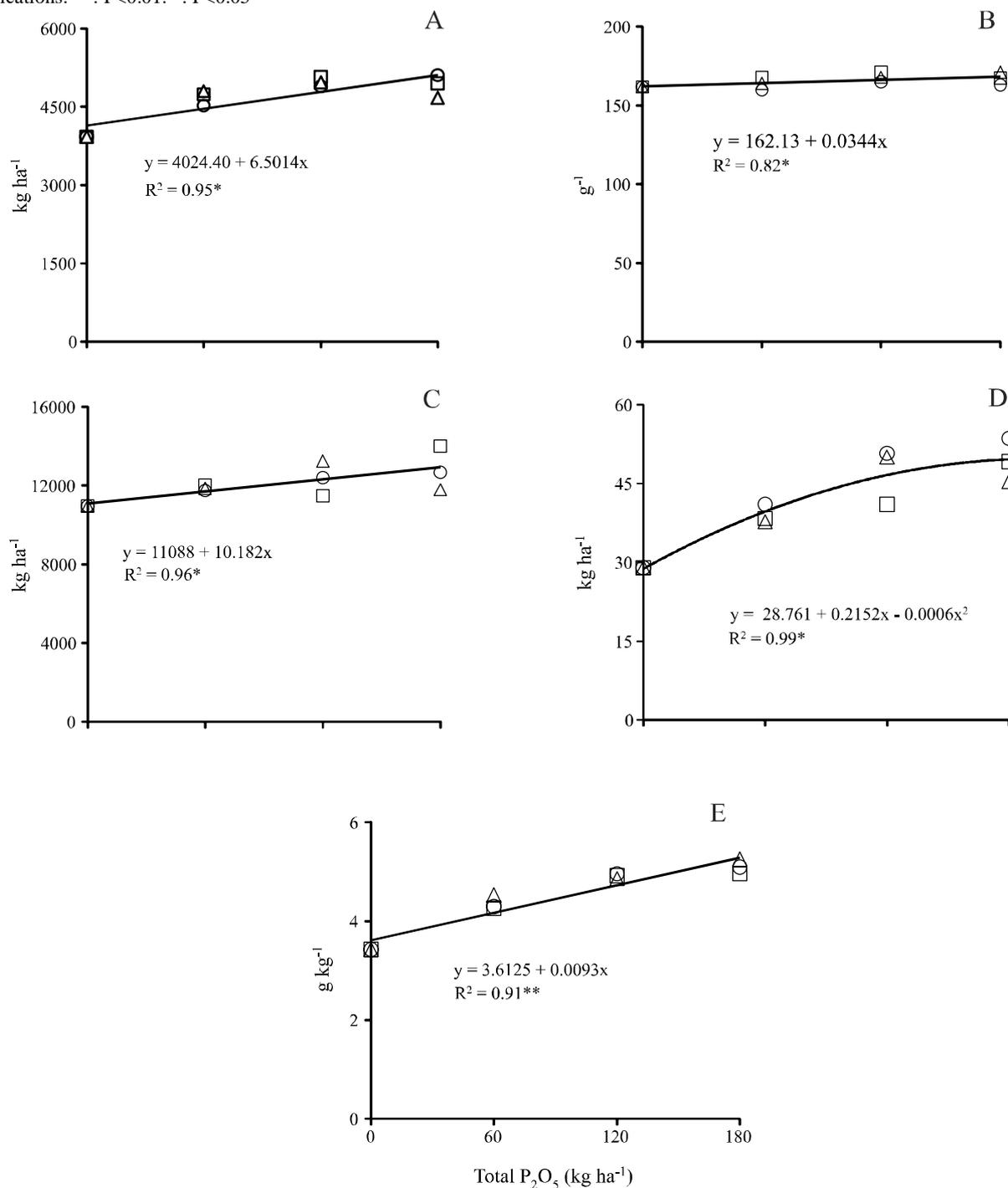
The different phosphates applied in the soil surface no influenced and, there were no interactions between P sources and doses for the components evaluated of the soybean crop. There were linear increase GY (Figure 1A), WTS (Figure 1B), SDM (Figure 1C), PCSG (Figure 1E) and PRDM (Figure 2B) due to anticipated annual application of doses of total P₂O₅. In short-term research, the application of phosphates increased soybean yield independently of the phosphate source used, when compared to the control (DEVI *et al.*, 2012). In our study, there was increase of up to 25% in GY (Figure 1A), and for each kg P₂O₅ applied.

In addition, the increase in GY due to the P doses may be related to the other factors as: (i) ICLS under no-tillage, with absence of erosion (CARVALHO *et al.*, 2010; HENDRICKSON; COLAZO, 2019); (ii) high carbon concentration in the soil, favoring the use of P by plants (BÜNEMANN; CONDRON, 2007); (iii) presence of animals, which increases the nutrient cycling in this system (ASSMANN *et al.*, 2017; CARVALHO *et al.*, 2010; HENDRICKSON; COLAZO, 2019; KUNRATH *et al.*, 2015).

The increase in soybean yield due to the application of P resulted from increased WTS and SDM. The WTS represents only one of the components of soybean crop production that can influence GY, due to the application

of P, as observed by other authors (BEGUM *et al.*, 2015; KHANAM *et al.*, 2016). The P available from the application of phosphates may have favored the accumulation of phytic acid (main form of stored P) in the

Figure 1 - Grain yield (A), weight of thousand seeds (B), shoot dry mass (C), phosphorus accumulation in soybean (D) and phosphorus concentration in soybean grain (E) after the annually application of doses of phosphates in soil surface in an integrated crop-livestock system. ○: triple superphosphate (TSP). □: rock phosphate (RP). △: magnesium thermophosphate (MTP). Points are the average of four replications. **: P<0.01. *: P<0.05



grains and which influenced their weight. In this system, the nutrient cycling is maximized by the presence of the animals (CARVALHO *et al.*, 2010) that deposit manure (source of P) and stimulate the activity of the plants to release P in the soil by grazing.

The linear increase was also observed in the soybean crop SDM due to P doses (Figure 1C). This SDM increase resulted, also, from GY increase (which represented 35.9 to 40.2 of SDM percentage) Therefore, P supply might have favored growth and development of the root system and shoot, energy transfer and, consequently, grain filling (HAWKESFORD *et al.*, 2012).

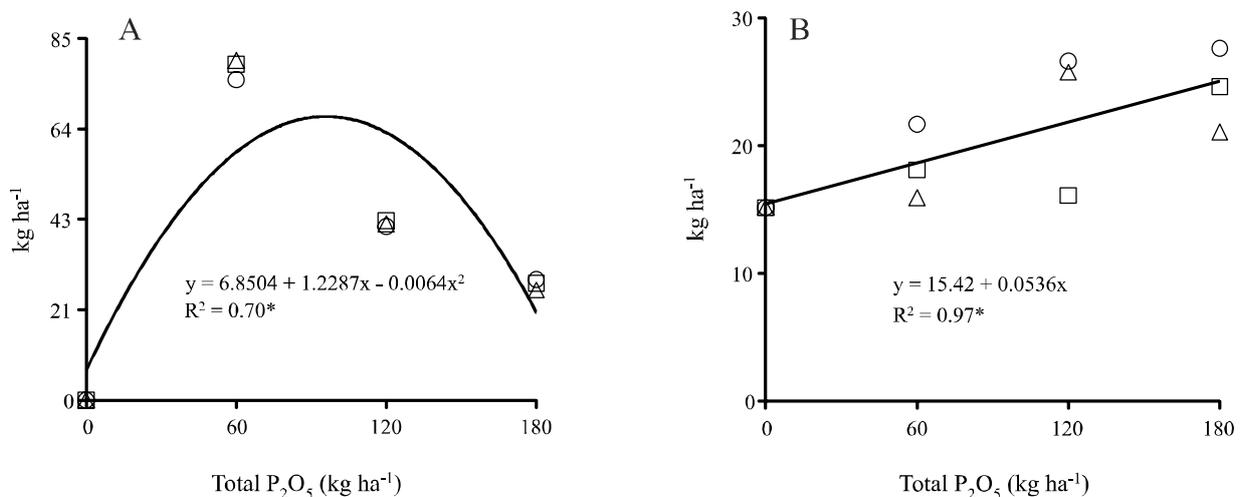
The use of different phosphate sources (TSP, RP, and MTP) did not alter the GY (Figure 1A), WTS (Figure 1B) and SDM (Figure 1C) components in the soybean crop. The experimental period may have been the main factor for the solubilization of P from the water-insoluble sources (RP and MTP) and subsequent use by the plants. For the same experimental conditions, the accumulation and export of P by soybean grains in the first years were lower with the application of RP to the soil surface. However, after the third year, RP had the supply of P maximized for both fodder and grain yield harvest (GALETTO *et al.*, 2014). The solubility of water-insoluble sources, such as RP and MTP, occurs gradually and provide P throughout the crop cycles. After the third year of experimentation, these sources can be equated to the water-soluble sources (TSP) for the efficiency of releasing P, maintaining the GY, WTS and SDM indexes.

Quadratic effects were observed in PAS (Figure 1D) and PUE (Figure 2A), due to P doses application.

The highest values of PAS occurred with the application of 179 kg ha⁻¹ total P₂O₅. Maximum PUE (65 kg soybean grains per kg P₂O₅) occurred with the use of 96 kg ha⁻¹ total P₂O₅ (Figure 2A). The PUE is related to several internal and external mechanisms such as root morphology aspects, rhizosphere chemical alterations, alterations in the physiological characteristics of absorption kinetics, genetic variability, interactions with microorganisms that live in the soil and the use of P sources (BÜNEMANN; CONDRON, 2007). Therefore, doses above 96 kg ha⁻¹ total P₂O₅ would result in PUE reduction, due to the excess consumption of this nutrient (FAGERIA *et al.*, 2010), since GY was not negatively affected by the excess phosphate fertilization (Figure 1a). Superior plants in general, tend to absorb and store from 85 to 95% of P (total) in inorganic form within their cell vacuoles (HAWKESFORD *et al.*, 2012). This allows the plant to absorb and accumulate great amounts of P (excess consumption) much higher than those needed by their metabolism, as an energy supply strategy along their cycle.

The linear increase in PCSG (Figure 1E) and PRDM (Figure 2B) were direct positive effects of phosphate fertilization. The PCSG values were adequate for the culture [2.6 to 5.0 g kg⁻¹ (MALAVOLTA, 2004)], with no negative effect on GY. The observed PRDM values represented an important factor in this supply of nutrients to the system, since they provided additional 15.4 to 25 kg ha⁻¹ of P in the subsequent crop. As P has structural function in plants, there is a close relationship between the decomposition of the vegetal residue and the release of this nutrient in the soil (HAWKESFORD *et al.*, 2012). The mineralization of P found in soybean straw can be considered one of the main factors of nutrient

Figure 2 - Phosphorus use efficiency (A) and phosphorus in residual dry mass (B) after the annually application of doses of phosphates in soil surface in an integrated crop-livestock system. ○: triple superphosphate (TSP). □: rock phosphate (RP). △: magnesium thermophosphate (MTP). Points are the average of four replications. **: P<0.01. *: P<0.05



availability for successive crops, which can benefit from annual winter forages (black oat and ryegrass) in the ICLS (GALETTO *et al.*, 2014).

The application to the soil surface of different phosphates did not change PAS (Figure 1D), PCSG (Figure 1E), PUE (Figure 2A) and PRDM (Figure 2B). This fact may be due to the period of field experimentation (four years), which favored the solubilization of water-insoluble phosphate and the use of P applied in previous years. The water-soluble sources (TSP) present better results for GY in the first years of application. However, this effect decreases along the crop cycle due to the solubilization of the water-insoluble phosphate particles, which has a slow P release to the soil solution (GALETTO *et al.*, 2014). Thus, the mixing of these sources (soluble and water-insoluble) in ratios that meet crop requirements may be an interesting combination to rapidly provide P (TSP) and maintain over time (RP and MTP) the levels of P in the production system (OLIVEIRA JUNIOR; PROCHNOW; KLEPKER, 2008).

CONCLUSION

All evaluated soybean crop components were influenced by the total P₂O₅ doses applied annually to the soil surface in an integrated crop-livestock system, with no difference between the phosphates sources used. Water-insoluble phosphates (rock phosphate - Arad and magnesium thermophosphate) provided grain yield similar to water-soluble phosphate (triple superphosphate) in this production agriculture system. However, the accumulation of phosphorus in soybean plants was higher when using high solubility phosphate.

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