v. 3, n. 18, 2023

Journal of
Agricultural
Sciences
Research

AGRONOMIC EFFICIENCY OF ROCK PHOSPHATES USED ALONE OR ASSOCIATED WITH SOLUBLE SOURCE OF PHOSPHORUS FOR CORN AND COMMON BEAN CROPS CULTIVATED IN SUCCESSION UNDER NO-TILLAGE AND IRRIGATED SYSTEM

Antônio Marcos Coelho
Embrapa Milho e Sorgo

Álvaro Vilela de Resende
Embrapa Milho e Sorgo

Abstract: Tropical soils present a high adsorption capacity in the dynamics of the applied P, thus reducing their initial efficiency of use by the plants. Within this approach, sources of P with lower solubility, such as natural rock phosphates with different degrees of reactivity (slow release), could be an alternative for fertilization of these soils, in relation to soluble phosphates. In order to evaluate this possibility, experiments with maize and bean crops were conducted in Sete Lagoas-MG, in a "Latossolo Vermelho" (Oxisol) clayey texture. The experimental design was in a randomized block design, with four replications, with the treatments arranged in subplots, with phosphorus sources in the plots, and in the subplots the doses of P applied annually. The treatments consisted of phosphorus sources: Phosphorite (18 % P_2O_5 total), Bayóvar (29 % P_2O_5 total) and Triple Superphosphate (45 % P_2O_5 total), broadcast applied and incorporated in soil 0-10 cm depth, at a dose of 200 kg of P_2O_5 ha^{-1}, calculated on basis of total P_2O_5 content of the sources. A control treatment, without applying phosphate fertilization was included. As maintenance fertilization, for each source and control treatment, doses of 0, 50 and 100 kg of P_2O_5 ha^{-1}, applied annually in the furrow at sowing time of corn, in the form of Triple Superphosphate. The corn was sowing in the spring/summer in six successive crops in the period 2012 to 2018. The bean was sowing in the autumn/winter, in four successive crops, in the period of 2013 to 2016. The initial application of a high dose of P as a corrective fertilizer, using sources varying in reactivity, was ineffective in terms of increasing the productivity of corn and beans, both for immediate and residual effect, when compared to the annual application of doses of P as maintenance fertilizer. The highest grain yields obtained with the annual application of 100 kg of P_2O_5 ha^{-1} as Triple Superphosphate. However, corn was less responsive than beans, an indication of the greater efficiency of this crop in using the soil's P reserve. The corn genotypes used presented in relation to the old results, reported in the literature, marked reduction in the concentration of P in the grains, which was not verified for the beans. The efficiency in the use of P, calculated by the balance method, indicated for the production system used, it can be reached 100%, without reduction in productivity and maintaining in the soil an adequate content of P "available" (10 mg dm^{-3} - Mehlich1), above of recommended critical level. Above this efficiency value (>100%), there was a marked reduction in grain yield and in the P "available" content in the soil to values below the critical level.

Index terms: Zea mays, phaseolus vulgaris, rock phosphate, P use efficiency, P-balance.

INTRODUCTION

In the state of Minas Gerais, Brazil, the area irrigated by center pivots, occupy 452,190 hectares (30 % of total irrigated area in Brazil) with the largest spatial concentration in the municipalities of Unai (65,930ha), Paracatu (65,555 ha), Rio Paranaíba (15,170 ha) and João Pinheiro (14,052 ha) (ANA, 2019) and, are located mainly in the cerrado region. In these areas, the cropping system corn and common bean are important and competitive crops (SILVEIRA et al., 2011) used for production of seeds, grain, forage and green corn. The cropping system is characterize by adoption of high technological level, such as correcting soil acidity (limestone and gypsum), high doses of fertilizers, no tillage soil management, modern genotypes, crop management (reduced row space, high plant density, crop-livestock system) and, disease and pest control. Thus, these cropping systems rely on fertilizer inputs to supplement soil nutrient levels to help maximize crop yield. While in many agricultural areas, the lack of available nutrients limits crop yields, in others fertilizers are being over-used and misapplied (i.e. non-optimal crop uptake due to misplacement in location and/or timing). Overuse of nitrogen (N) and phosphate (P_2O_5) fertilizers can cause significant environmental degradation and pollution through a wide array of inter-related physical, chemical and biological pathways (e.g., soil acidification, leaching into surface and ground water).

The productivity of cropping systems is dependent on the use of phosphorus (P) as fertilizer and growing consumption of inorganic phosphorus (P) fertilizers derived from mining of nonrenewable phosphate rock has contributed to major increases in crop yields since the 1950s (TILMAN et al., 2002). This scenario was also observed in Brazil, where total annual use of P fertilizers increased from an average of 40,000 tons in 1960 to 2.2 million tons in 2016. This rapid rise in P fertilizer use has contributed substantially to the green revolution in Brazil (WITHERS et al., 2018). Likewise, the use of phosphorus fertilizers in the Cerrado region for the cropping systems has also changed considerably since the first areas were reclaimed from the natural savanna vegetation and cultivated for agriculture. For example, initial fertilizer inputs to increase P availability to critical levels in Cerrado soils can range from 26 to 122 kg P ha^{-1} (60 to 280 kg P_2O_5 ha^{-1}) for sandy to clayey soils, respectively (SOUZA e LOBATO, 2004). Typical rates are now 44–87 kg P ha^{-1} $year^{-1}$ (100–200 kg P_2O_5 ha^{-1}) in the first year of cultivation and 26–35 kg P ha^{-1} $year^{-1}$ (60–80 kg P_2O_5 ha^{-1}) once the cropping system has become established (RODRIGUES et al., 2016).

Nowadays, the fertilization of cropping systems is an innovative technology that aims to fertilize the production system as a whole. It consists of intensive fertilization of more responsive crops and use of residual fertilization for less responsive crops (ALTMANN, 2012). Also, the total nutrients uptake and exported from the field by crops should be taken in consideration. This concept is important for those nutrients that present residual effect such as phosphorus. For example, where P is added to soil in fertilizers or manures, there can be a large P residue, which may increase the yields of subsequent crops for a number of years (JOHNSTON et al., 2014; COELHO et al., 2021a; COELHO et al., 2021b).

Although corn and bean crops are responsive to P fertilization, they present great difference in the use efficiency. Cunha et al. (2018) reporting data about the nutrient balance in Brazilian agriculture from 2013 to 2016, found that for corn and bean crops the consumption factor of P (relationship between consumption and crop demand) of 1.2 and 2.6, respectively, and the fertilizer use rate (% exported in relation to consumption) of 80 % and 38 %, respectively, for corn and bean crops. These results are an indicator that the average rate of P actually applied for corn is only 20 % above of their necessity and for bean 62 % more than their necessity, an indicator of low use efficiency. Improving the efficiency of P use in Brazils' cropping systems and reducing dependence on high rates of fertilizer requires a better understanding of how soil, crop and fertilizer management practices influence long-term P availability in soils, and requires access to long-term experiments (ROWE et al., 2015). Several factors can influence both the rate and the amount of P taken up by roots and thus estimates of P-use efficiency, not only that of a single application of P fertilizer but also that of P reserves accumulated in the soil from past additions of P as fertilizer and manure (JOHNSTON et al., 2014).

Currently, Brazil's phosphate rock (PR) mines supply only limited amounts of P due to the igneous rock's low P solubility and high processing costs, and about 60% of inorganic P fertilizer used in Brazilian agriculture is imported (ANDA, 2017). More recent geological prospecting has identified several other PR reserves in Brazil, including those of sedimentary origin with higher P solubility (OGASAWARA et al., 2010; FIANCO, 2011)). The main sources of phosphorus used in Brazil are soluble, such as single superphosphate (SSP), triple superphosphate (TSP) and ammonium phosphates (MAP and DAP), which provide the nutrient readily available, rapidly increasing the concentration of phosphorus in the soil solution. However, these sources come from non-renewable resources phosphate rocks, which can compromise the sustainability of production systems. According to Cunha et al. (2018), in the period of 2013 to 2016 the average consumption of phosphate fertilizers in Brazilian agriculture was of 12 million tons (37 % of total fertilizers marketed). The mainly sources and respective participation in the market were SSP (45.55 %), MAP (32.18 %), TSP (15.15 %), DAP (4.91 %), phosphate rocks (1.62 %) and thermophosphate (0.54%).

Unavailability of phosphorus (P) from slightly reactive PR may be one of the reasons for low crop yields on P-deficient soils fertilized with PR. The addition of small amounts of soluble phosphates to act as a starter dose, until nutrients from the PR becomes available has been shown to increase the effectiveness of these rocks (MENON and SHIEN, 1990). A mixture of North Carolina PR and TSP at a P ratio of 50:50 has been showed to be as effective as TSP at equal total P applied to a limed soil with a pH 6.2 (CHIEN et al., 1987a). Likewise, mixing Mussoorie PR from India with TSP at 50:50 ratio on a P base has been reported to give the same or higher yields of maize and wheat as compared with application of TSP at similar total P rate (TIWARI, 1979).

The main objective of this research was to evaluate use of rock phosphates of sedimentary origin in corrective fertilization in combination with soluble phosphates in maintenance fertilization with phosphorus in maize and bean production systems. Factors such as relative phosphate efficiency in crops productivity, residual effect of sources, nutritional status of crops, P balance (input-output), and change of P availability in soil, are presented and discussed.

MATERIALS AND METHODS

The experiments were carried out over a period of 6 years (from 2012 to 2018), at the agronomic research station of Embrapa Milho e Sorgo, located in Sete Lagoas, MG, Brazil (19° 28' S, 44° 15' W and 732 m above sea level) in a P phenotyping site (COELHO et al., 2004). The soil classified as "Latossolo Vermelho" clayey texture (Oxisol), under savannah vegetation ("cerrado"). In the period of 2003 until 2006, the site was used for experiments with inbred lines and hybrids of corn for study of P efficiency, without P fertilizer application, under conventional tillage (PARENTONI et al. 2010). In the years of 2006 and 2007, because buried solid-set sprinkler irrigation fixed system was building in the experimental field, no crops were sowing. In the summer season of 2006 - 2007, the area was cultivated with pear millet as cover crop, without fertilizers applications. After that (2007- 2012), the area was fallow, under natural pasture of brachiaria. In the Table 1, are show the results of soil chemical analyses, of samples taking in September of 2012, from of experimental field and adjacent area, under natural "cerrado" vegetation. According to results of these analysis (Table 1), the indicators of the soil fertility of experimental field were similar (except for P and K) to the obtained for soil under natural vegetation.

Prior to the experiments begin, dolomitic limestone (43 % CaO, 14 % MgO, CCE 80 %)

and gypsum (Ca 17%, S 14 %), were broadcast and incorporated into the top 20 cm of soil (plough depth) at rate of 5.0 and 1.0 Mg ha^{-1}, respectively, in October of 2012, thirty-five days before planting. To obtain a better and uniform distribution of limestone in depth, the dose was split in 2 applications, 50 % before plowing (moldboard plow) and 50 % after and before soil level surface with harrowing (disk).

The experimental design was a randomized complete block with four replications. The treatments design was in split plot. The main plots (15.4 x 6.0 m) were sources of P and the split-plot (4.2 x 6.0 m) factor consisted of the doses of P applied annually. The treatments consisted of three sources of phosphorus: one soluble and two reactive rocks phosphates. The soluble source used was the triple superphosphate (TSP) contend 45 % total P_2O_5 (granulated) The reactive rocks phosphate were phosphorite (Campos Belos, GO, Brazil) contend 18 % total P_2O_5 of which 4.8 % soluble in citric acid 2% (powder) and bayóvar (Sechura Desert, Peru) contend 28 % total P_2O_5 of which 13 % soluble in citric acid 2 % (branny). Itafós Mining Company markets the phosphorite in Brazil as Itafós and Heringer Fertilizers Company markets the bayóvar in Brazil, imported from Peru.

The sources of phosphate, at dose of 200 kg ha^{-1} of P_2O_5 (87.34 kg ha^{-1} of P), calculated with base in the total P_2O_5 of each source, were applied only in the first year (November 2012), broadcast on the soil surface and incorporated into the soil at 10 cm depth. One treatment control (named source zero), without P broadcasted application, was also included. For each source and control, three doses of P (0, 50 and 100 kg ha^{-1} of P_2O_5), were annually applied (except in 2015) by hand, only for corn crop, banded in the furrows, using a soluble source of P (TSP). Bean crop did not receive P fertilizer, to enable assessment of the uptake of the residual P left by the preceding summer corn crop. Thus, in five years, were applied a total of 87.34, 196.51 and 305.68 kg ha^{-1} of P, included P broadcasted and banded as maintenance.

The crop system used was corn sowed during spring-summer and bean sowed during autumn-winter growing seasons, under no tillage soil management (after 1[a] corn crop) and irrigation. Corn and bean were sowed mechanically, in rows spaced of 70 cm and 50 cm apart and density of 5 and 12 seeds per meter, respectively. In the Table 4 are described the transgenic single hybrids of corn and variety of bean used in the experiments. The data of sowing times and doses of nutrients as fertilizer (N-K 20-00-20, urea, ammonium sulfate, potassium chloride and FTE-fritted trace elements), applied at sowing and on side dress, are showing in the Table 2.

In January of 2013, corresponding to three and two months, respectively, after application of limestone plus gypsum and the sources of P, soil samples were taking at 20 cm depth, in the main plots (15.4 x 6.0 m). To avoid doses of P banded-applied in the furrows, samples were taking from between rows of corn. In addition, the top 20 cm of soil was sampled in the years of 2014 (May 14) and 2017 (October 27) after crop establishment. Soil samples were taking in the sub-plot (4.2 x 6.0 m), in the rows and between rows of crops and analyzed for chemical characteristics as described by Silva (2009). Since the minimum (zero) - tillage was the soil management used, there is not a mixed soil P.

Before the planting of experiments and during the development of crops, cultural and phytosanitary treatments were performed according to the recommended for corn and bean crops, when necessary. To control of the weeds in corn crop, herbicides glyphosate and atrazine plus nicosulfuron were applied in pre and post planting, respectively. For bean, glyphosate applied in pre-planting and hand weeding were used in the weeds control. To the control of pests and disease, appropriated insecticide and fungicide were applied in the seeds and foliar spray at vegetative stage.

Corn and bean grain yields were determined by hand harvesting four adjacent 4.0 m and 6.0 m long rows (appropriately bordered), respectively, and reported based on a moisture content of 130 g kg^{-1}. In addition, were reported the yield components such as number of plants, years and pods. After each harvest, were collected samples of plant and grain, dried in forced circulation oven at 65ºC temperature, and analyzed for total contend of macro (N, S, P, K, Ca and Mg) and micronutrients (Zn, Cu, B, Fe and Mn) as described by Silva (2009).

The balance method, i.e. the total P removed in corn and bean grain divided by the total P applied (TPR/TPA) expressed as a percentage, was used to calculate the recovery of the applied P by corn and bean crops. Thus, can be measured P-use efficiency (PUE_B) by expressing total P removal in grain crop as a percentage of the total P applied. This method is adaptation from Syers et al. (2008), which considers P uptake (shoot and grain) relative to the amount of P applied. In addition, these authors advocated the use of the balance method over the difference method, mainly due to residual effect of P, which can be beneficial for improve yields in subsequent years.

Statistical analysis was made using SAS (version 9.4) software. A factorial procedure was used with sources of P (main plots) as main factor and P banded in the furrows applied annually as maintenance (sub plots) as second factor. The effect isolated and interactions of treatments were accept as statistical significance when *P* values fall in the range of 0.01 to ≤ 0.05 levels. When treatments effects were significant, the differences among means were compared by tukey test at level of 0.05.

RESULTS AND DISCUSSION

SOIL FERTILITY BUILD-UP (SOIL CHEMICAL CHARACTERISTIC)

In the Table 3 are showing the results of soil chemical characteristics after limestone, gypsum and the sources of phosphorus, had been broadcasted and incorporated in the soil. In general, compared to the original soil, under natural vegetation (Table 1), the soil fertility status was improved for all parameters, with values in the range suitable for growth of corn and beans crops and which characterize a soil with high yield potential. In addition, the micronutrients contend, Zn, Cu, Fe and Mn, were also in adequate levels, with values of 2.16, 0.73, 38 and 35 mg dm^{-3}, respectively. Except to the available P, the parameters such as pH, organic matter (O.M.), exchangeable cations, effective CEC and micronutrients (data not show), were not affected by sources of P (Table 3).

Although the extractable soil phosphorus (available P) by the extractor Mehlich1 had been significantly ($P \leq 0.05$) affected by sources of P, the significant differences (tukey 0.05) only were observed between the means values of sources and control. Thus, the available P extracted was similar among the sources of P and higher than the control (Table 3). However, the interpretation these results, should be carefully since that, the sources of P used present different solubility and the extractor Mehlich-1, an acid extractor, excessively extract the P from the soils that have received application of natural rock phosphates, and that portion of the element maybe is not available for the plants (SILVA, 2009). In fact, this was verified when the results obtained for P extracted by Mehlich-3 extractor, with values of 15.2, 13.0, 10.5 and 8.5 mg P dm^{-3}, respectively for TSP, RRP bayóvar, RP phosphorite and control treatments, were compared with the results obtained by Mehlich-1 extractor (Table 3). According to Novais and Smyth (1999), in the first year after application, the Mehlich-1 extractor overestimate the availability of P, as they solubilize part of the not dissolved fertilizer in the soil, resulting in higher levels. This problem disappears when dissolution is complete, which occurs as of the second or at most third year after application of these products, with incorporation, in soils with a pH of 6.0 or less.

YIELD COMPONENTS

The yield components, number of plants and years for corn and number of plants for bean, were not affected significantly ($P \leq 0.05$) by the applied treatments (sources, doses and interaction). Thus, in the Table 4, are presented the means data for these parameters obtained at harvest time for each growing season and crops. The number of plants ha^{-1} measured in each growing season is in the recommended range, for the corn hybrids and variety of bean used in the experiments. In addition, the observed variations among growing seasons for these parameters were small as indicated by confidence interval and coefficient of variation (Table 4).

For bean, the sources of P broadcasted and doses of P banded, affected significantly ($P \leq 0.05$) the number of pods per plant (data not shown), with high values (15 pods $plant^{-1}$) for TSP and RRP bayóvar and lower values for RRP phosphorite and control (11 pods $plant^{-1}$). For the band-applied P treatments, the values were 15, 13 and 12 pods per plant for residual effect of doses of 100, 50 and 0 kg P_2O_5 ha^{-1}, respectively.

TOTAL ACCUMULATED GRAIN YIELD OF CORN AND BEAN CROPS

Independent of applied treatments (sources and doses of phosphorus), the annual corn grain yields to six cultivated crops, range from 6.36 to 12.73 Mg ha^{-1} with average of 10 Mg ha^{-1} and, for bean to four cultivated crops, the grain yields range from 1.83 to 3.95 Mg ha^{-1} with average of 2.82 Mg ha^{-1} (data not shown).

The sources used are characterized by great differences in reactivity and solubility, which affect soil phosphorus dynamic in soil and consequently their efficiency, mainly when is evaluated the residual effect as observed by Chien and Hammond (1978). According these authors, the response of bean to the residual P from TSP decreased substantially relative to the residual response to the phosphate rock sources. However, in this research corn and bean grain yields obtained in the treatment with TSP applied without the combination with doses of P banded as maintenance, was never less than that obtained with the rock phosphate sources (Table 5). On the other hand, the control treatment not show a yield decline when P fertilizer was withheld, although STP falls below critical agronomic levels. However, STP is not always a reliable guide to the adequacy of soil P supply, because it does not take account of soil P buffering capacity, defined as the ability of a soil to maintain Pi in the soil solution as Pi is removed by crops (HOLFORD, 1980; NOVAIS, SMYTH, 1999).

Thus, accumulated total grain yield of corn and bean crops, were used as an indicator of responses to applied treatments of sources of P broadcasted an doses of P banded in the furrows applied annually for corn. In the Table 6, are showing the total accumulated grain yields obtained for six corn and four beans crops, cultivated in the period from 2012 to 2018.

The analysis of variance (ANOVA)

revealed that the sources of P broadcast do not have significant effect ($P \leq 0.05$) in the total grain yield of corn. Also, the interaction between sources of P broadcast and the doses of P banded in the furrow, which could be an important information for agronomic P management practice, was not significant ($P \leq 0.05$), an indicator that within each source, the doses of P banded had similar effect. With regard to the relationship between the sources, without annual application of P banded and corn responses to residual P (Table 6), the total corn grain yield obtained with TSP was higher than RRP bayóvar, RP phosphorite and control treatments. On the other hand, the annual application of doses of P banded in the furrow effected significantly ($P \leq 0.05$) the total corn grain yield, with the maximum obtained with dose of 100 kg P_2O_5 ha^{-1} (43.67 kg of P ha^{-1}) applied annually (Table 6).

Results of experiments with the same sources and similar doses of P used in this work, were conducted by Santos et al. (2014) in a Latossolo amarelo, clayey texture, and poor in P (P-Mehlich1 - 2 mg dm^{-3}) and by Sousa et al. (2014) in a Cambissolo eutrofico, clayey texture, and poor in P (P-Mehlich1 - 1.39 mg dm^{-3}). In these experiments, the applications of rock phosphates (Phosphorite and Bayòvar) as corrective fertilization, improved significantly the grain yields of corn (~7.0 Mg ha^{-1}) as compared to the control (~3.5 Mg ha^{-1}).

For bean crop, the analysis of variance (ANOVA) revealed significantly effect ($P \leq 0.05$) of sources of P broadcasted and doses of P banded in the furrow in the total grain yield (Table 6), but not for the interaction between sources and P banded ($P \leq 0.05$). Among the sources, TSP and RRP bayóvar presented similar total grain yield and higher than RP phosphorite and control treatments (Table 6). With regard to the relationship between the sources, without annual application of P banded and bean responses to residual P (Table 6), the total bean grain yield obtained with TSP and RRP bayóvar was higher than RP phosphorite and control treatments. For P banded, high grain yield was obtained with residual effect of the dose of 100 kg P_2O_5 ha^{-1} applied annually for corn. These results could be explained to the fact that the bean crops were cultivated without application of P banded in the furrows, using the residual of effect of the P applied for corn crop.

These results indicated that for this soil with available P (Mehlich-1) of 4.82 mg dm^{-3} (Table 1), the application of high dose of P as corrective to buildup soil P, would not be necessary as practical management. Cumulative effects of repeated P additions on acid tropical soils are often more economical than single, large doses, primarily because of increasing in the relative and agronomic efficiency (CASSMAN et al., 1993). On soils with low P and/or high fixation capacity, capital investments are required to build-up soil nutrients to levels until the system becomes profitable and sustainable. This needs to be accompany by other soil and crop improvement measures to ensure profitability.

PHOSPHORUS EXTRACTED AND EXPORTED BY CORN AND BEAN CROPS

Analysis of Variance (ANOVA) for total accumulated dry matter grain yield, P grain concentration (mean values of six corn and four bean crops) and P removal in the grain, at harvest by corn and bean crops, resulted in significant difference ($P \leq 0.05$) of sources and doses of P banded (Table 7). However, the interaction sources of P broadcasted and doses of P banded, were not significantly ($P \leq 0.05$), an indicator that within each source, the doses of P banded had similar effect. According to mean separation tukey's method ($\alpha=0.05$) the sources of P, TSP and RRP bayóvar, presented similar results for dry matter grain yield, P concentration and P removal by corn and bean crops and were higher than RP phosphorite and control treatments (Table 6). For the treatment P banded, the dose of 100 kg of P_2O_5 ha^{-1} applied annually, presented for the measured parameters values significantly (tukey 0.05) more high as compared with doses of 0 and 50 kg of P_2O_5 ha^{-1} (Table 7). Thus, based in these results, the two crops with different nutritional requirements and yield potential, presented similar response to the applied treatments, sources and doses of P banded (Table 7). However, it is important to emphasize that the bean crop was cultivated taking advantage of residual P applied for corn crop.

In agricultural production systems, which annually harvest only grain, the grain quantity (yield) and grain nutrient concentration determine nutrient removal and collectively estimate annual maintenance fertilizer rates. In this study (Table 7), for corn crop average P concentration and removal values, were of 1.66 kg P Mg^{-1} grain (3.80 kg P_2O_5 Mg^{-1} grain) and 91.42 kg P ha^{-1} (209 kg P_2O_5 ha^{-1}), respectively. Working with three of the same transgenic hybrids used in this research, Silva et al. (2018) found an average P concentration in grain of 1.83 Kg Mg^{-1} (4.2 kg P_2O_5 Mg^{-1}) for similar grain yield potential (11 Mg ha^{-1}) obtained in this research.

When the P concentration e removal in corn grain obtained in this research are compared with others data reported in the literature, the value are substantially lower than those reported by Resende et al. (2012) from Brazilian publications with average of 3.10 kg P Mg^{-1} grain (7.10 kg P_2O_5 Mg^{-1}). Also, Coelho e Alves (2004) and Bender et al. (2013) found higher export ratios of P_2O_5, between 7.5 and 9.5 kg Mg^{-1} (3.30 and 4.15 kg P Mg^{-1}), than that of the present study. Similar results were reported by Binford (2010) analyzing the P concentration of 668 corn grain samples, found values ranged from 1.9 to 5.2 kg Mg^{-1} with a mean of 3.1 kg Mg^{-1} (grain yield range from 3.2 to 17.9 Mg ha^{-1}, with a mean of 10.9 Mg ha^{-1}). Duarte et al. (2017) studied nutrient concentrations in maize grains in 197 samples from 41 genotypes from different producing regions of Brazil, and verified that the reference values are overestimating the concentration and, consequently, the export of P and others nutrients in maize. They suggested a reduction in phosphorus values from 9.2 to 6.0 kg of P_2O_5 per mega gram of grains.

For bean crop (Table 7) the average P concentration and removal values, were of 3.40 kg Mg^{-1} (7.78 kg P_2O_5 Mg^{-1}) and 35.07 kg ha^{-1} (80.31 kg P_2O_5 ha^{-1}), respectively.

The average P removal values in this study are within the range of others (FAGERIA et al. 2007; SORATO et al. 2013), which were found to vary depending on agronomic management practices, yield level, and grain nutrient concentration. These authors found values of 3.60 – 3.80 kg P Mg^{-1} (8.24 – 8.70 kg P_2O_5 Mg^{-1}) for a grain yield potential around of 3.90 Mg ha^{-1}. Although the P concentrations in bean grain were two times more than that observed for corn grain, the total P exported by corn was much higher due to the different in yield potential between the two crops (Table 7). The average values of total P off take from system were respectively of 91.42 and 35.07 kg ha^{-1} for corn and bean crops (Table 7). The great differences in the values of P off take between corn and bean should be taking in consideration in the fertilization program of these two crops when cultivated successively.

For corn crop, the productivity and mainly P concentration and exported in grain reported here, could reflect efficiency gains in P use, as compared with others results reported in the literature. For bean crop this improve in P use efficiency was not clear in this research. This improve in efficiency could be explained with the advances in crop breeding, crop and soil management systems and irrigation practices. Lowering grain P content in cereals by breeding crops with reduced capacity to translocate P to the developing grains is another approach to improve P use efficiency based on the hypothesis that not all of the P that is stored in plants is metabolically necessary for yield (WITHERS et al. 2014). Possible reductions in seed P requirements of up to 25 % have been suggest but concerns over seedling vigor and human health remain to be resolved before this approach will gain wider acceptance (ROSE et al. 2013).

The importance of P in harvested products is highlighted by calculations showing that the total P removed annually in grain equates to 80 % and 38 % of fertilizer P applied to crops of corn and bean, respectively (CUNHA et al., 2018). The high P removal rate in harvested grains drives the need to replace soil P by fertilizer application or leads to P mining where fertilizer application rates are low. Developing crop varieties that translocate less P to developing grains may offer one option to balance P budgets in agriculture at reduced fertilizer requirements.

However, it is important to mention that environmental conditions, cropping rotations, fertilization rates, cultivar background, and trait packages, have all been showed to influence grain nutrient concentrations, a crucial component of nutrient removal (HECKMAN et al., 2003; BELOW et al., 2010; MALLARINO et al., 2011). Thus, large variation across fields and years in the grain nutrient concentrations suggest a need for better understanding of factors that affect grain nutrient concentrations in order to improve removal estimates.

THE RECOVERY OF ADDED PHOSPHORUS BY CORN AND COMMON BEAN CROPS YIELDS: BALANCE METHOD

In the Table 8, are presented the data of total P applied (TPA), total dry matter grain yield of corn and bean (TGY), total P removed in corn and bean grains (TPR), P balance (PUE_B) and P soil extracted by Mehlich1 (PM1). The ANOVA for these parameters, except for P balance, indicated significantly effect ($P \leq 0.05$) of sources and doses of P banded in the furrow, without significantly effect for interaction between these treatments ($P \leq 0.05$). For P balance, the significant effect obtained for interaction between P source and P banded, could be due by the fate that the treatments with RPP and control, corn and bean extracted less P in the grains as compared with the treatments with TSP and RRPB, affecting the P efficiency use as calculated by balance method (Table 8).

Phosphorus removal via corn and bean grains quantitatively expressed maintenance fertilizer application rates used to replace exported nutrient (Table 8, Figure1). For all sources applied at dose of 87.34 kg of P ha^{-1} (200 kg P_2O_5 ha^{-1}), in the begin of experiments (build-up), without annually maintenance, the total P removed by corn and bean of 121.78, 114.46 and 89.30 kg ha^{-1} for TSP, RRPB and RPP, respectively, exceed the dose of P applied (Table 8). However, when doses of P (50 and 100 kg of P_2O_5 ha^{-1}) were applied annually for corn as maintenance, associated with the sources of P, the values of total P removed by corn and bean are less than total P applied and consequently left in soil a significantly part of this nutrient (Table 8, Figure 1).

Thus, where the values of recovery determined by the balance method exceeds 100 %, this implies that the added P has not replaced all the P removed in the harvested grain crop and that are being depleted P soil reserves. This can be view in Figure 1, where the values of recovery of P ranging from 43 to 139 %. For all sources, the lowest PUE_B (43 to 51 %) was obtained with the dose of 100 kg P_2O_5 ha^{-1}, applied annually as maintenance and the highest (102 to 139 %) without additional maintenance. Roberts and Johnston (2015) stated that PUE calculated by balance method often exceeds 80 %. They further interpreted results obtained from the balance method where a PUE_B of 100 % implied little or no change in plant available P, less than 100 % meant that fertilizer input was more than removal and greater than 100 % suggest nutrient mining.

According to Syers et al. (2008), another approach to estimating the recovery or efficiency of P added in fertilizers is to use soil analysis to assess whether P residues have remained in soil P pools from which they can be recovery by crops. In the Figure 2, the values of availability P in soil, extracted by Mehlich1 (STP), from soil samples taking in 2017 are well correlate with the data of P use efficiency (PUE_B). When the values of PUE_B improve, the values of STP decrease or vice-versa as show by linear equation ($STP = 22.65 - 0.122PUE_B$ $R^2 = 0.76$ $P = 0.0005$). A moderate but not significant correlation was found between STP and total dry matter grain yield ($STP = 80.10 - 0.093$ TGY $R^2 = 0.27$ $P = 0.10$) (Figure 2). Both sets of results (PUE_B and STP), suggest that there is an advantage to be gain from maintaining soils at an adequate level of readily "available" soil P, to achieve maximum efficiency of applied fertilizer P as revealed by yield potential of corn and bean crops obtained in these experiments (Figure2).

The relative agronomic effectiveness {RAE = (total yield of PR) – (total yield of check) ÷ (total yield of TSP) – (total yield of check) x100} of the rock phosphates associated or not with soluble phosphate in the crop system corn and bean are presented in the Table 9. When applied alone, as corrective fertilization, the RAE of rocks phosphate were quite different. The bayóvar, a reactive rock phosphate, presented relative effectiveness of 71.5%, and to the phosphorite, a not reactive rock phosphate, the relative effectiveness was 0.0% (Table 9). However, the RAE of these rocks phosphate were improved when associated with a soluble source of P such as TSP (Table 9). On the other hand, Souza et al. (2014) conducted experiments for two years, using the same sources of rock phosphates and applied at the same dose in a "Cambissolo eutrófico vertissólico" (Inceptisol), with pH 6.0 and high content of Ca and poor in P (Ca -13.5 $cmol_c$ dm^{-3}, P - Mehlich1-1.39 mg dm^{-3}). On this conditions, the results indicated that when applied as corrective fertilization (without maintenance), at rate of 200 kg P_2O_5 ha^{-1}, the relative agronomic effectiveness (RAE) of rock phosphates were 72.0% and 82.3% (average 77.2%) for bayóvar and 43.8% and 47.4% (average 45.6%) for phosphorite (Itafós), respectively, for the growing seasons of 2011 and 2012 (SOUSA et al., 2014). Thus, when the results obtained on this research, are compared with the results obtained By Souza et al. (2014), the relative agronomic effectiveness (RAE) of the rocks phosphate are more dependent of the availability of P in soils than the acidity (pH).

CONCLUSIONS

In a long term of experiments with system of corn and bean crops, cultivated in succession under irrigation, in a soil with high yield potential and initial soil "available" P of 4.82 mg dm^{-3} (Mehlich1). The application of high doses of P (200 kg P_2O_5 ha^{-1}) as corrective, to buildup soil "available" P, using sources with different degree of reactivity, was less effective than annual application of doses of P, banded in the furrows as maintained, using soluble source (TSP). The crops responses to P management were different, with corn was less responsive than bean, an indicator than corn is more efficient in the use of soil P reserves of soil. These results maybe are an indicator that in this crop system, could be more interesting to apply P for bean and corn been cultivated take advantage of the effect residual of applied P fertilizer and soil P reserves. This could be a subject for future research. The higher accumulated grain yields for both crops, were obtained with the annual application of dose of 100 kg of P_2O_5 ha^{-1}, as TSP, banded in the furrow at sowing time of corn, obtained 64.26 Mg ha^{-1} for corn and 12.97 Mg ha^{-1} for bean. The accumulated grain yields for the control treatment were 56.19 Mg ha^{-1} and 8.20 Mg ha^{-1}, respectively, for corn and bean. When compared to oldest data of literature, the lower values of P concentrations in corn grain, could be an indicator of improve in the efficiency of use of P. This can be associated to modern corn genotypes, but also the no-till soil management used, with high content of organic matter and the use of irrigation. For bean this improvement was not observed, confirmed a low gain in improve efficiency in the use of phosphorus. The use efficiency, calculated by balance method, indicated that when the values exceed 100%, occurred mining of P soil "available", less than 10.0 mg of P (extractor Mehlich1) and with accentuated reduction in total grain yields of the corn and bean crops. In this situation, the application of P according to the removed in the harvest grain was necessary for proper maintenance of "availability" of soil P for higher grain yield.

ACKNOWLEDGEMENTS – FINANCIAL SUPPORT

This research was supported by the Empresa Brasileira de Pesquisa Agropecuária - Embrapa (Grant number 01.13.05.001.02.00) National network of field trials for agronomic evaluation and validation of new fertilizers. Portfolio "Nutrients for Brazilian Agriculture".

REFERENCES

ANA-Agência Nacional das Águas (Brasil). Levantamento da agricultura irrigada por pivôs centrais no Brasil. Agência Nacional das Águas, Embrapa Milho e Sorgo – 2ed. Brasília: ANA, 2019, 47p.

ANDA - Associação Nacional para a Difusão de Adubos. Estatísticas Indicadores: Principais Indicadores do Sector de Fertilizantes.

BENDER, R.R., HAEGELE, J.W., RUFFO, M.L., BELOW, F.E. Nutrient partitioning and remobilization in modern transgenic insect-protected maize hybrids. **Agronomy Journal**, 105:161-170, 2013.

CASSMAN, K.G., SINGLETON P.W.; LINQUIST B.A. Input/output analysis of the cumulative soybean response to phosphorus on an Ultisol. **Field Crops Research**, 34: 23-36. 1993.

CHIEN, S. H; ADAMS, F; KHASAWNEH, F. E. and HENAO, J. Effects of combination of TSP and a reactive phosphate rock on yield and phosphorus uptake by corn. Soil Sci. Soc. Am. J. 51, 1656-1658, 1987.

COELHO, A. M.; PARENTONI, S. N.; SOUZA, F. A. de; MARRIEL, I. E. **Tecnologias e estratégias para aumentar a eficiência de uso de reservas de fósforo acumuladas em Latossolo Vermelho no bioma Cerrado**. Sete Lagoas: Embrapa Milho e Sorgo, 2021a. 47 p. (Embrapa Milho e Sorgo. Boletim de Pesquisa e Desenvolvimento, 230).

COELHO, A.M.; PARENTONI, S.N.; GAMA, E.E.G.; SCHAFFERT, R.E. Planning of test areas based on soil spatial variability to evaluate abiotic stresses in crops. In: From Partnership to Community: The Arc of Change in the CCRP, 2004, Valls, The Netherlands. The McKnight Foundation Collaborative Crop Research Program, 2004.

COELHO, A. M.; SOUZA, F. A. de; RESENDE, A. V. de; OLIVEIRA, A. C. de. Maize and brachiaria intercropping system efficiency in the use of soil phosphorus reserves and fresh fertilizer. In: WORLD CONGRESS ON INTEGRATED CROP-LIVESTOCK-FORESTRY SYSTEMS, 2., 2021. Proceedings reference... Brasília, DF: Embrapa, 2021b. p. 591-596. WCCLF. Evento online.

DUARTE, A.P.; CANTARELLA, H.; KAPPES, C. Adubação de sistemas produtivos: milho safrinha e soja. In: PAES, M.C. (Ed.). Construindo sistemas de produção sustentáveis e rentáveis: palestra do XIV Seminário Nacional de Milho Safrinha, 2017. Sete Lagoas: ABMS, 2017, p.173-195.

FIANCO, C. B. Métodos geofísicos aplicados à prospecção de fosforitos na região nordeste do Estado de Goiás. Dissertação de Mestrado, Instituto de Geociências, Universidade de Brasília, Brasília. 110p. 2011.

FREITAS, I. F. de, NOVAIS, R. F., VILLANI, E. M. A., NOVAIS, S. V. Phosphorus extracted by ion Exchange resins and Mehlich-1 from oxisols (latosols) treated with different phosphorus rate and sources for varied soil-source contact periods. **Revista Brasileira de Ciência do Solo**, 37: 667-677, 2013.

HECKMAN, J.R., SIMS, J.T., BEEGLE, D.B., HERBERT, S.J., BRUULSEMA, T.W., BAMKA, W.J. Nutrient removal by corn grain harvest. **Agronomy Journal**, 95: 587-591. 2003.

HOLFORD, I.C.R. Effects of phosphate buffer capacity on critical levels and relationships between soil tests and labile phosphate in wheat-growing soils. Aust. J. Soil Res. 18, 405–414. 1980.

KARLEN, D.L., FLANNERY R.L., SADLER, E. J. Aerial accumulation and partitioning of nutrients by corn. **Agronomy Journal**, 80: 232-242, 1988.

MONTEIRO, C.M. Fosforitos do Grupo Bambuí na região de Campos Belos (GO)/Arraias (TO), na borda oeste do Cráton São Francisco. Brasília, Universidade de Brasília, 2009. 129p.

MENON, R. G., CHIEN S. H. Phosphorus availability to maize from partially acidulated phosphate rocks and phosphate rocks compacted with triple superphosphate. Plant Soil 127:123-128, 1990.

NOVAIS, R. F.; SMYTH, T. J. **Fósforo em solo e planta em condições tropicais**. Viçosa, MG: Universidade Federal de Viçosa, 1999. 399 p.

NUNES, R.S. **Eficiência de uso do fósforo em sistemas de manejo do solo e adubação fosfatada por um longo período.** Brasília: Faculdade de Agronomia e Medicina Veterinária, Universidade de Brasília, 2014, 150 p. Tese de Doutorado.

OGASAWARA, E. S.; KULAIF, Y.; FERNANDES, F. R. C. A indústria brasileira de fertilizantes (cadeia NPK, enxofre, rocha fosfática e potássio) - Projeções de 2010 a 2030. In: Fernandes et al. (Eds.), Agrominerais para o Brasil. Rio de Janeiro: Centro de Tecnologia Mineral - CETEM/MCT, 2010. Cap.8, p.145-168. http://anda.org.br/index.php?mpg=03.00.00 (23 November 2017) (2017).

PARENTONI, S. N.; SOUZA JUNIOR, C. L. de; ALVES, V. M. C.; GAMA, E. E. G. e; COELHO, A. M.; OLIVEIRA, A. C. de; GUIMARAES, C. T.; VASCONCELOS, M. J.

V. de; PACHECO, C. A. P.; MEIRELLES, W. F.; MAGALHAES, J. V. de; GUIMARAES, L. J. M.; SILVA, A. R. da; MENDES, F. F.; SCHAFFERT, R. E. Inheritance and breeding strategies for phosphorus efficiency in tropical maize (Zea mays L.). Maydica, Bergamo, v. 55, n. 1, p. 1-15, 2010.

RESENDE, A.V. de; COELHO, A.M.; SANTOS, F.C. dos; LACERDA, J.J. de J. **Fertilidade do solo e manejo da adubação NPK para alta produtividade de milho no Brasil Central**. Sete Lagoas: Embrapa Milho e Sorgo, 2012. 12p. (Embrapa Milho e Sorgo. Circular técnica, 181).

RODRIGUES, M., PAVINATO, P. S., WITHERS, P. J. A., TELES, A. P. B., HERRERA, W. F. B. Legacy phosphorus and no tillage agriculture in tropical oxisols of the Brazilian savanna. **Science of the Total Environment**, 542:1050-1061. 2016.

ROBERTS, T.L., JOHNSTON, A.E. Phosphorus use efficiency and management in agriculture. **Resources, Conservation and Recycling**, 105:275-281. 2015.

SANTOS, D.G. dos; BRASIL, E.C.; JUNIOR, A.O.; HUNGRIA, L.C. da; DANTAS, R.C.R.; VIEIRA, M.E. Residual effects of reactive phosphates associated to soluble phosphorus source to corn production in the third agricultural cycle. World Fertilizer Congress of CIEC, 16th. Rio de Janeiro, October, 20-24th 2014, p.314-315.

SANTOS, H. G. dos; JACOMINE, P. K. T.; ANJOS, L. H. C. dos; OLIVEIRA, V. A. de; LUMBRERAS, J. F.; COELHO, M. R.; ALMEIDA, J. A. de; CUNHA, T. J. F.; OLIVEIRA, J. B. de. **Sistema brasileiro de classificação de solos.** 3. ed. rev. e ampl. Brasília, DF: Embrapa, 2013. 353 p.

SILVA, F.C. da (Ed.). **Manual de análises químicas de solos, plantas e fertilizantes**. 2.ed. rev. e ampl. Brasília: Embrapa Informação Tecnológica, 2009. 627p.

SILVA, C.G.M., REZENDE, A. V.; GUTIÉRREZ, A.M.; MOREIRA, S.G.; BORGHI, E.; ALMEIDA, G.O. Macronutrient uptake and exported in transgenic corn under two levels of fertilization. **Pesquisa Agropecuária Brasileira**, Brasília, v.53, n.12, p.1363-1372, Dec. 2018.

SILVEIRA, P.M. da, SILVA, J. H. da, JUNIOR, M. L., CUNHA, P. C. R. da. Atributos do solo e produtividade do milho e do feijoeiro irrigado sob sistema de integração lavoura-pecuária. **Pesquisa Agropecuária Brasileira**, Brasília, v.46, n.10, p.1170-1175, Out. 2011.

SOUSA, D. M. G. de; LOBATO, E. (Eds.). Cerrado: correção do solo e adubação. 2.ed. Brasília, DF: Embrapa Informação Tecnológica. 2004.

SYERS J.K., JOHNSTON A.E., and CURTIN D. Efficiency of soil and fertilizer phosphorus use: reconciling changing concepts of soil phosphorus behavior with agronomic information. FAO FERTILIZER AND PLANT NUTRITION BULLETIN, 18, **FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS,** Rome, 2008, 108 p.

TILMAN, D., CASSMAN, K. G., MATSON, P. A. NAYLOR, R. and POLASKY, S. Agricultural sustainability and intensive production practices. **Nature**, v.418, n. 6898, p.671-677, Ago. 2002. https://doi.org/10.1038/nature01014 (accessed 11 Jun. 2019).

TIWARI, K. N. Efficiency of Mussoorie rock phosphate, pyrites, and their mixtures in some soils of UE. Bulletin No. 12, Indian Soc. of Soil Sci. 519-526, 1979.

WITHERS, P. J. A., et al. Transitions to sustainable management of phosphorus in brazilian agriculture. Scientific Report, 8: 2537 2018, https://www.nature.com/scientificreports DOI:10.1038/s41598-018-20887-z 1 (acessado 11 Jun. 2019).

Soil depth	pH	Mehlich1 P	OM	Exchangeable cations				Effective CEC	Al^{3+} Sat
				Ca^{2+}	Mg^{2+}	K^+	Al^{3+}		
cm	H2O	mg dm-3	g dm-3	---------------- cmolc dm-3 -----------------					%
Soil experimental field									
0 - 20	5.40	4.82	36	1.95	0.16	0.17	0.69	2.97	24
20 - 40	5.20	3.45	31	1.33	0.07	0.17	1.01	2.59	39
Soil natural “cerrado”									
0 - 20	5.40	2.88	33	1.96	0.18	0.06	0.52	2.72	20
20 - 40	5.20	1.67	28	0.95	0.10	0.04	0.79	1.88	43

Table 1-Soil chemical characteristic (means of seven replicates).

OM - organic matter, CEC - effective cation exchange capacity at soil natural pH, Al^{3+} sat - aluminum saturation of the effective CEC.

Growing seasons	Sowing times	Applied at sowing time[1]			Applied on side dress[2]		
		N	K_2O	FTE[3]	N	S	K_2O
- - - - - - - - - - - - - - - -					kg		ha^{-1}
			Corn crop				
2012-13	11/22/12	45	90	50	147	0	80
2013-14	11/20/13	45	90	50	167	24	80
2014-15	01/07/15	45	90	0	155	36	80
2015-16	12/02/15	45	60	0	165	36	0
2016-17	11/22/16	45	90	0	165	36	0
2017-18	11/29/17	45	90	0	165	36	0
			Bean crop				
2013	06/19/13	50	50	0	67	0	0
2014	05/14/14	50	50	0	67	0	0
2015	06/09/15	25	25	0	67	30	0
2016	05/12/16	50	50	0	54	24	0

Table 2-Growing seasons, sowing times and rates of nutrients used in the sowing time and on side dress for corn and common bean crops.

[1]Fertilizers applied banded in the furrow at sowing time. [2]Fertilizers applied side dress at the V5 leaves corn stage and V4 3[th] trifoliate bean stage. [3]FTE-fritted trace elements content: Zn 9.0%, B 1.6%, Cu 0.8%, Fe 3.0%, Mn 2.6% and Mo 0.1%.

Sources of P[1/]	pH	Mehlich1 P	O.M.	Exchangeable cations				Effective CEC
				Ca^{2+}	Mg^{2+}	K^{+}	Al^{3+}	
		PPP						
		P						
	H_2O	mg dm^{-3}	g dm^{-3}	---------- $cmol_c$ dm^{-3} ----------				
TSP	5.8a	16.2a	46.6a	3.7a	0.9a	0.24a	0.0	4.8a
RRPB	5.8a	21.1a	46.7a	3.5a	0.8a	0.29a	0.0	4.0a
RPP	5.8a	17.7a	45.6a	3.2a	0.8a	0.26a	0.0	4.2a
Control	5.9a	6.8b	46.9a	3.7a	0.9a	0.26a	0.0	4.8a
Mean	5.8	15.5	46.5	3.5	0.8	0.26	0.0	4.6
CV %	2	21	4	10	10	11	-	10

Table 3-Soil chemical characteristics after limestone, gypsum and sources of phosphorus, had been broadcasted and incorporated in the soil (Means of four replicates).

[1/]Sources of phosphorus broadcasted on the soil surface at rate of 87.34 kg of P ha^{-1} (200 kg of P_2O_5 ha^{-1}), and incorporated in the soil 10 cm depth, in the first year, 2012; TSP – triple super phosphate; RRPB – reactive rock phosphate bayóvar; RPP – rock phosphate phosphorite. [2/]Means in the column with the same letter are not different by tukey test 0.05.

Growing seasons	Hybrids/ variety	Nº Plants 1,000/ha	CI[1] 1,000/ha	CV[2] %	Nº Years 1,000/ha	CI[1] 1,000/ha	CV[2] %
			Corn crop				
2012-13	P30F53	77.03	±1.14	6.28	79.39	±1.05	5.62
2013-14	AG8088	65.28	±1.13	4.78	65.23	±0.73	4.75
2014-15	P30F53	76.07	±0.98	5.45	74.34	±1.20	6.48
2015-16	DKB390	66.55	±1.04	6.64	70.96	±1.07	6.42
2016-17	AG8088	64.15	±0.90	5.94	67.25	±1.83	6.46
2017-18	RK9006	58.03	±0.78	5.68	60.15	±0.91	6.44
			Bean crop				
2013	BRS-Estilo	205.57	±4.19	8.66	-	-	-
2014	BRS-Estilo	211.87	±6.07	12.17	-	-	-
2015	BRS-Estilo	185.77	±6.24	14.26	-	-	-

Table 4-Number of plants and years at harvest time obtained from of the experiments conducted in the period from 2012 to 2018.

[1]Confidence Intervals at 90 % of probability. [2]Coefficient variation.

Growing season	Sources of phosphorus[1/] TSP	RRPB	RPP	Control	Average
	Corn grain yield (Mg ha^{-1}) (CV = 13 %)				
2012-13	9.51	9.54	8.51	9.24	9.20bc
2013-14	7.59	6.96	6.36	6.36	6.82d
2014-15	10.91	10.80	8.84	9.77	10.08ab
2015-16	8.88	8.66	7.42	8.63	8.40c
2016-17	11.64	11.03	9.61	10.61	10.72a
2017-18	9.54	9.10	7.29	8.47	8.60c
Average	9.68a	9.35a	8.00b	8.85ab	8.97
	Bean grain yield (Mg ha^{-1}) (CV = 20 %)				
2013	3.10	2.48	1.83	1.94	2.34a
2014	2.63	3.38	2.11	1.83	2.49a
2015	2.81	2.62	2.16	2.29	2.47a
2016	2.29	2.20	2.04	2.14	2.17a
Average	2.71a	2.67a	2.04b	2.05b	2.37

Table 5-Corn and bean grain yields in each growing season as affected by sources of phosphorus without annual application of P banded in the furrow as maintenance.

[1/]Sources broadcasted on the soil surface at rate of 87.34 kg of P ha^{-1} (200 kg of P_2O_5 ha^{-1}), and incorporated in the soil 10 cm depth in the first year, 2012; TSP – triple super phosphate; RRPB – reactive rock phosphate bayóvar; RPP – rock phosphate phosphorite. Means in the same column and line with the same letter are not different by tukey test 0.05.

Sources of P broadcasted[1/]	P banded in the furrows as TSP (kg P_2O_5 ha^{-1})			Average
	0	50	100	
	Corn grain yield (Mg ha^{-1}) (CV = 4.83 %)			
TSP	60.88	61.74	65.37	62.67a
RRPB	58.37	64.34	65.98	62.89a
RPP	50.45	58.50	61.22	56.72a
Control	56.19	59.61	64.45	60.08a
Average	56.47c	61.05b	64.26a	60.59
	Bean grain yield (Mg ha^{-1}) (CV = 8.71 %)			
TSP	10.83	12.77	13.94	12.52a
RRPB	10.67	12.28	14.05	12.34a
RPP	8.14	9.78	11.39	9.77b
Control	8.20	11.10	12.48	10.59b
Average	9.46c	11.48b	12.97a	11.30

Table 6-Total accumulated grain yield of corn (six crops) and bean (four crops) adjusted to 130 g kg^{-1} moisture, as affected by sources and annual application of phosphorus as maintenance.

[1/]Sources broadcasted on the soil surface at rate of 87.34 kg of P ha^{-1} (200 kg of P_2O_5 ha^{-1}), and incorporated in the soil 10 cm depth, in the first year, 2012; TSP – triple super phosphate; RRPB – reactive rock phosphate bayóvar; RPP – rock phosphate phosphorite. Means in the same column and line with the same letter are not different by tukey test 0.05.

Sources of P broadcast[1/]	P-banded as TSP (P_2O_5 kg ha^{-1})	Grain yield (Mgha-1)	P-grain2/ (kgMg-1)	P-grain (kg ha-1)
TSP		56.76a	1.74a	98.59a
RRPB		56.88a	1.66ab	94.87ab
RPP		51.67b	1.60b	83.05c
Control		54.46ab	1.63b	89.18bc
	100	59.68a	1.73a	103.18a
	50	55.65b	1.68b	93.34b
	0	49.50c	1.56c	77.75c
Average		54.94	1.66	91.42
CV (%)		4.97	4.12	6.48
		Bean (four crops – 2013 to 2016)		
TSP		11.33a	3.57a	40.62a
RRPB		11.18a	3.44a	38.58a
RPP		8.85b	3.38ab	30.04b
Control		9.60b	3.21b	31.04b
	100	11.75a	3.51a	41.34a
	50	10.40b	3.43ab	35.73b
	0	8.57c	3.26b	28.14c
Average		10.24	3.40	35.07
CV (%)		8.70	6.36	11.57

Table 7-Total accumulated dry matter of grain yield, P concentration and extracted in the grain of corn and bean in successive cultivation under irrigation.

[1/]Sources broadcasted on the soil sur face at rate of 87.34 kg of P ha^{-1} (200 k g of P_2O_5 ha^{-1}), and incorporated in the soil 10 cm depth in the first year, 2012; TSP – triple super phosphate; RRPB – reactive rock phosphate bayóvar; RPP – rock phosphate phosphorite. [2/]Mean values of six corn and four bean crops. Values followed by same letter in columns, are not significantly different by tukey test 0.05.

Sources of P[1/]	P-banded-TSP kg P_2O_5 ha^{-1}	TPA kg P ha^{-1}	TGY Mg ha^{-1}	TPR kg ha^{-1}	PUE_B %	PM1 mg dm^{-3}
	0	87.34	63.21	121.78	139.44	5.28
TSP	50	196.51	68.16	139.85	71,17	8.81
	100	305.68	72.90	155.98	51.03	17.07
	0	87.34	61.26	114.46	131.06	10.03
RRPB	50	196.51	69.46	136.98	69.71	14.58
	100	305.68	73.48	148.91	48.71	19.39
	0	87.34	51.47	89.30	102.25	8.64
RPP	50	196.51	62.15	119.09	60.60	17.29
	100	305.68	67.94	130.89	42.81	17.37
	0	0.00	56.37	98.00	0.00	3.84
Control	50	109.17	64.39	120.37	110.25	7.96
	100	218.34	71.41	142.31	65.18	13.66
TSP			68.09a	139.21a	87.22a	10.39b
RRPB			68.07a	133.45ab	83.16a	14.67a
RPP			60.52b	113.09c	68.55b	14.43a
Control			64.05ab	120.23bc	58.47b	8.49b
	100		71.43a	144.52a	51.94c	16.87a
	50		66.04b	129.07b	77.93b	12.16b
	0		58.08c	105.89c	93.19a	6.96c
Average			65.18	126.49	74.35	12.00
CV (%)			4.87	6.41	11.36	27.25

Table 8-Total P applied (TPA), total dry matter grain yield (TGY), total P removal in grain (TPR), P use efficiency (PUE_B) and P-Mehlich1 (PM1) for corn and bean crops in successive cultivation under irrigation practice.

[1/]Sources broadcasted on the soil surface at rate of 87.34 kg of P ha^{-1} (200 kg of P_2O_5 ha^{-1}), and incorporated in the soil 10 cm depth, in the first year, 2012. P-Mehlich1-2017. TSP – triple super phosphate; RRPB – reactive rock phosphate bayóvar; RPP – rock phosphate phosphorite. [2/]Values followed by same letter in columns, are not significantly different by tukey test 0.05.

Source of P	Total P applied (kg ha-1)		RAE2 (%)
	Corrective	Maintenance[1]	
		0	71.50
RPB (reactive)	87.34 (200)	109.17 (250)	117.80
		218.34 (500)	103.51
		0	0.00
RPP (non-reactive)	87.34 (200)	109.17 (250)	49.00
		218.34 (500)	70.00

Table 9-Relative agronomic effectiveness (RAE) of rock phosphates associated or not with soluble phosphate in the crop system corn and bean.

[1]Doses of P supplied as TSP (50 and 100 kg of P_2O_5 ha^{-1} applied annually for corn, total 5-crops). [2]RAE = (total yield of PR) – (total yield of check) ÷ (total yield of TSP) – (total yield of check) x100. Numbers between parentheses are in kg of P_2O_5 ha^{-1}.

Journal of Agricultural Sciences Research ISSN 2764-0973 DOI 10.22533/at.ed.9733182309111

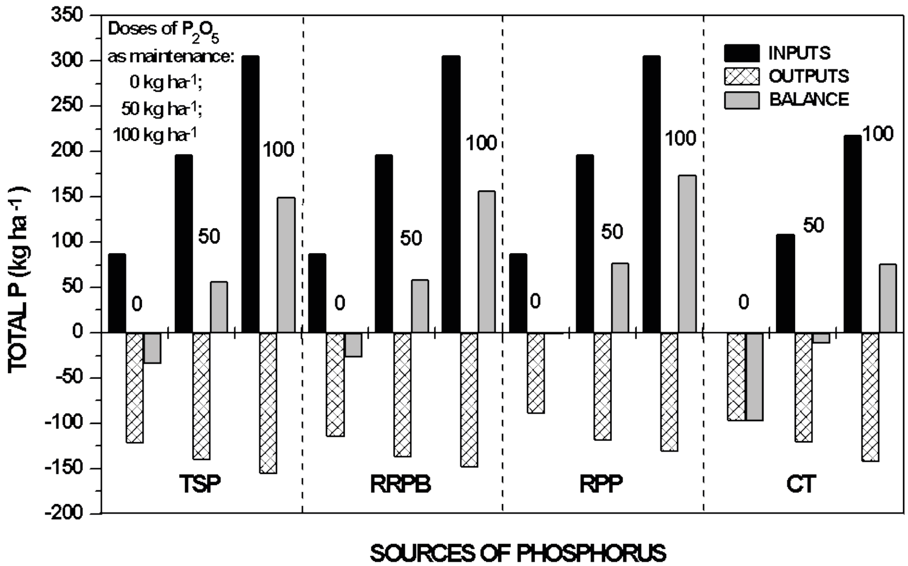

Figure 1. Phosphorus inputs, outputs and balance in the irrigated crop system corn and bean fertilized with sources of P as corrective and doses of maintenance as TSP.

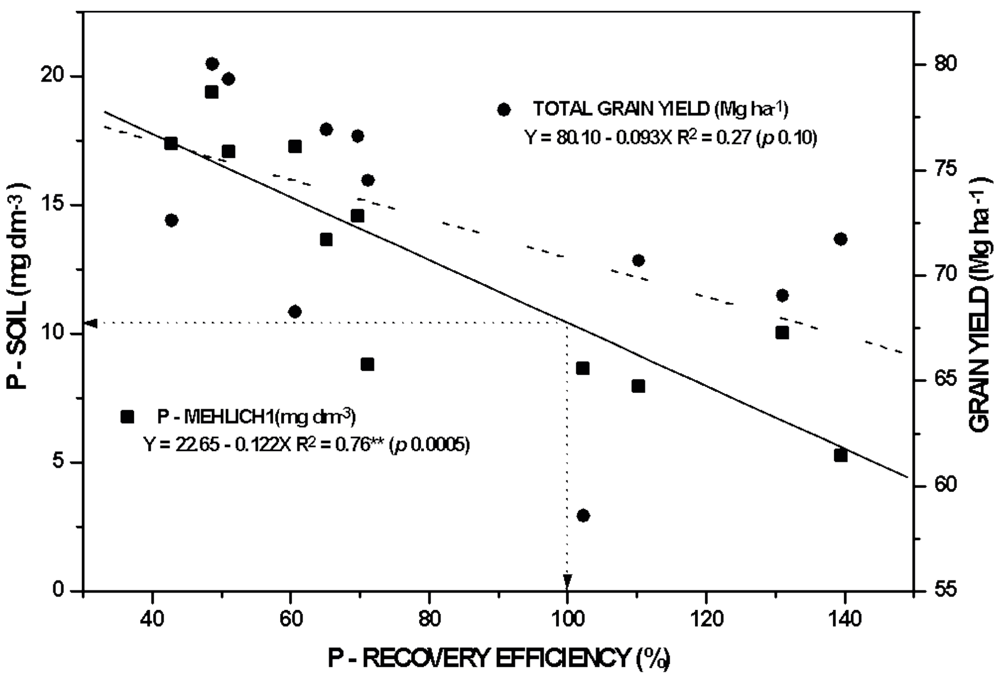

Figure 2. Relations among P use efficiency (balance method), P availability in soil and total grain yield of corn and bean.