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Decanted phosphate: effects on soil fertility and production of Marandu grass depending on soil acidity

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ABSTRACT

Decanted phosphate (DP) is a by-product of wastewater treatment with phosphoric acid (H_3PO_4), used as phosphate fertilizer in pastures. This experiment was conducted in a greenhouse using a sandy clay loam Typic Haplustox to evaluate the potential effects of DP on soil fertility, and production and nutrition of the Marandu grass during three growths periods in the presence or absence of lime. The experiment was conducted in a completely randomized experimental design with three replications in a 6 × 2 × 2 factorial arrangement: six doses of phosphorus (P), two sources of P, and presence (P/L) or absence (A/L) of lime. We used 0, 30, 60, 90, 120, and 150 mg kg^{-1} of P, applied as DP or triple superphosphate (TS). Lime was applied to the soil to raise the base saturation to 60%. The DP can be recommended for fertilization in pastures because of its residual supply of P to plants and its ability to decrease the soil acidity and increase the calcium (Ca) content in soil and uptake by plants. The supply of P to the soil by DP is higher under low soil acidity. The use of DP did not alter the contents of zinc (Zn), manganese (Mn), and copper (Cu) in shoots of the Marandu grass.

Key words: *Brachiaria brizantha*; by-product; liming; micronutrients; phosphorus

Fosfato decantado: efeitos na fertilidade do solo e na produção do capim-marandu dependendo da acidez do solo

RESUMO

O fosfato decantado (FD) é um subproduto do tratamento de efluentes da produção de ácido fosfórico (H_3PO_4) utilizado como fertilizante fosfatado em pastagens. Nesse sentido, conduziu-se esse experimento em casa de vegetação utilizando-se Latossolo Vermelho distrófico textura média (LVd) com objetivo de avaliar o potencial de uso do FD pelos seus efeitos na fertilidade solo e na produção e nutrição de capim-marandu durante três crescimentos na presença e ausência de calcário. O experimento foi conduzido em delineamento inteiramente casualizado com três repetições em esquema fatorial 6 x 2 x 2 [seis doses de fósforo (P); duas fontes de P; presença (C/C) e ausência de calcário (S/C)]. As doses de P foram 0, 30, 60, 90, 120 e 150 mg kg^{-1} de P. As fontes de P: o FD e o superfosfato triplo (ST). O calcário foi aplicado ao solo a fim de elevar a saturação por bases a 60%. O FD pode ser indicado para adubação em implantação de pastagens devido ao seu efeito residual fornecer P às plantas; diminuir a acidez do solo e aumentar os teores de cálcio (Ca) no solo e nas plantas. O fornecimento de P ao solo pelo FD é favorecido pela menor acidez do solo. Os teores de zinco (Zn), manganês (Mn) e cobre (Cu) na parte aérea do capim-marandu não foram alterados pelo uso de FD.

Palavras-chave: *Brachiaria brizantha*; subproduto; calagem; micronutrientes, fósforo

Introduction

Phosphate is a non-renewable resource, and its improved use efficiency in agriculture can decrease the depletion of its reserves. As such, the reuse of wastes from fertilizer industries can be a good alternative and can help to avoid contamination of the watercourses (Shepherd et al., 2016; Valle et al., 2016). When sulfuric and phosphoric acids are applied to phosphate rocks, they generate some by-products. One of these by-products is decanted phosphate (DP), which is also produced in wastewater treatment with phosphoric acid (H_3PO_4). The DP is obtained by the reaction of the calcium hydroxide or lime with the diluted H_3PO_4, resulting in a precipitate (decanted calcium phosphate). This by-product is considered an environmental liability. It is marketed as phosphate fertilizer in powder form with the immediate and gradual release of P and has been recommended in pastures to correct the low levels of P in soils due to the reduced cost compared to the more water-soluble sources.

The deficiency of P in soil is one of the main causes of degradation in pastures (Martins et al., 2014), which is strongly related to the adsorption of this nutrient to oxides and hydroxides of iron (Fe) and aluminum (Al) (Chien et al., 2011). Phosphorus is associated with the generation and storage of energy and cell division and expansion. Phosphorus fertilization and liming are high-cost practices during pasture implantation (Silva et al., 2013). Studies that explore the relationship between P use efficiency and acidity of soils are very important (Guedes et al., 2012; Sandim et al., 2014; Teixeira et al., 2016). Changes in soil pH increase or decrease the adsorption of P, and intensify the formation of low solubility compounds with Al and Fe in acidic soils and with Ca in basic soils (Chien et al., 2011). Also, the chemical composition, solubility, and accompanying cations also interfere with the solubilization of phosphates (Olatuyi et al., 2009). According to Queiroz et al. (2009), soil attributes such as acidity, texture, mineralogy, and organic matter can also affect the efficiency of phosphate fertilizers.

Moreover, studies on phosphate fertilizer should also evaluate its initial and residual effects, because different forms of P may be more or less available for plants over time. Although water-soluble phosphates have a higher initial P supply, P sources with lower solubility can compensate their higher residual effect (Guedes et al., 2009; Lima et al., 2007a). However, these fertilizers need a specific soil acidity level to improve their solubilization (Lima et al., 2007b).

The main hypothesis of this study was that soil pH alters P solubility of DP, and that the residual effect of DP is higher than soluble phosphates due to the increase of the H protonation in the course of growth period of Marandu grass. As the behavior and relationship of DP with soil acidity are unknown, the objective of this study was to evaluate the effects of DP on soil fertility, and production and nutrition of Marandu grass during three growths in the presence or absence of lime.

Materials and Methods

The experiment was conducted in a greenhouse at Sao Paulo State University (Unesp/FCAV), Jaboticabal, São Paulo, Brazil, from October 2012 to January 2013, in pots containing the sandy clay loam Typic Haplustox (Embrapa, 2013). The soil was collected in the municipality of Jaboticabal-SP in a degraded pasture land of *Brachiaria decumbens*, from the topsoil from 0 to 0.20 m depth. The soil was air-dried, passed through a 6-mm sieve, and stored. The chemical attributes relating to the fertility of the soil were determined using the methods described by Raij et al. (2001). The soil pH ($CaCl_2$) was 4.1; organic matter (OM), 23 g dm^{-3}; P (resin), 4 mg dm^{-3}; potassium (K), 0.4 $mmol_c$ dm^{-3}; calcium (C), 7 $mmol_c$ dm^{-3}; magnesium (Mg), 3 $mmol_c$ dm^{-3}; sulfur (S), 4 mg dm^{-3}; boron (B), 0.36 mg dm^{-3}; copper (Cu), 0.7 mg dm^{-3}; manganese (Mn), 5.5 mg dm^{-3}; zinc (Zn), 0.5 mg dm^{-3}; H + Al, 58 $mmol_c$ dm^{-3}; cation exchange capacity (CEC), 68 $mmol_c$ dm^{-3}; and base saturation (BS), 15%. The soil had the following granulometric characteristics: clay = 260 g kg^{-1}; silt = 30 g kg^{-1}, and sand = 710 g kg^{-1}. The plant species used was Marandu grass (*Brachiaria brizantha* Stapf. 'Marandu').

The experiment was completely randomized with three replications and a 6 × 2 × 2 factorial design [i.e., six P doses; two P sources; presence (P/L) or absence of lime (A/L)], totaling 72 experimental units. The units consisted of ceramic pots (0.22 m diameter × 0.20 m height), internally coated with a plastic bag and filled with 2.8 kg of soil. The P doses were: 0, 30, 60, 90, 120, and 150 mg kg^{-1} of P, applied as DP [17% total P_2O_5; 9% P_2O_5 soluble in neutral ammonium citrate (NAC) + water and 12% P_2O_5 soluble in citric acid; Ca = 18%; and neutralizing power (NP) = 10.49% $ECaCO_3$]. Triple superphosphate, which was used as the reference source, has the following composition: total P_2O_5 = 45%; P_2O_5 soluble in water = 37%; P_2O_5 soluble in NAC + water = 43%; Ca = 14%, and NP < 0.01% $ECaCO_3$). The soil samples with the acidity correction treatment received a lime application (CaO = 43%; MgO = 9%; PRNT = 95%) at an application rate required to raise the base saturation of the soil to 60%, as suggested by Werner et al. (1996). The two phosphate fertilizers were applied in powder form, and the total P content of the fertilizers was the dose rate.

Soil acidity correction was performed by mixing the soil of each pot, followed by the addition of distilled water until the soil reached approximately 80% of the maximum water retention capacity. After that, the soil was incubated for 20 days. After incubation, the soil in each pot was air dried, followed by the application of phosphate fertilizers and basal fertilizer, by mixing the fertilizer with the total volume of soil in each pot. Basal fertilization was performed in all experimental units using an aqueous solution, with the fertilizer consisting of N, S (ammonium sulfate), K (potassium chloride), and Zn (zinc sulfate), applied at the rates of 30, 36, 120, and 3 mg kg^{-1}, respectively. After that, distilled water was added to soil to achieve 80% of the maximum water retention capacity. Phosphorus fertilization was done just before sowing.

The Marandu grass was seeded after soil preparation, at the rate of 30 seeds per pot. After seven days from plant emergence, thinning was performed, leaving four plants per pot. Then 20 days after plant emergence, the grass was cut at 0.10 m ground level in the pot to standardize them. At this moment, the first surface soil sampling was made by collecting

100 grams of soil per pot. After that, the fertilization with N (ammonium sulfate) was performed at the rate of 120 mg kg^{-1} of N. After the standardization cut, the grass was cut at intervals of 30 days, with a total of three cuts of the shoots of the forage, at 0.10 m height from the soil surface. After each cut, fertilization with N (ammonium nitrate) and K (potassium chloride) was performed at the rates of 150 and 80 mg kg^{-1} of N and K, respectively.

Also, daily weighing and watering using distilled water were performed during the experimental period, leaving the soil of the pots containing approximately 80% of the maximum water retention capacity. The shoots removed at each of the three cuts were washed in a diluted detergent solution plus water, rinsed in tap water, and then in distilled water. Later, they were packed in paper bags to dry in a forced-air oven at 65°C. The dried plant material was weighed to determine the dry weight of shoots, and then the samples were ground in a Wiley mill. Then the concentrations of P, K, Ca, Mg, Cu, Fe, Mn, and Zn were determined (Bataglia et al., 1983). After the first and second cuttings, surface soil samples were collected (70 g/pot). These samples were used to determine the soil pH values in $CaCl_2$ and the P, K, Ca, Mg, and H + Al contents (Raij et al., 2001). Tillering was evaluated using a marking technique with a colored wire in the pots after each shoot cutting, with each existing tiller identified with a different colored wire.

The results were analyzed statistically by performing the analysis of variance. When the F-value was significant, the average Tukey test at 5% of probability and/or the polynomial regression analysis (linear or quadratic) were performed.

Results and Discussion

Soil nutrient content

At the three sampling points, the P concentrations in the soil were linearly enhanced with the increase of doses of P, regardless of the P source applied (Figure 1A). However, at

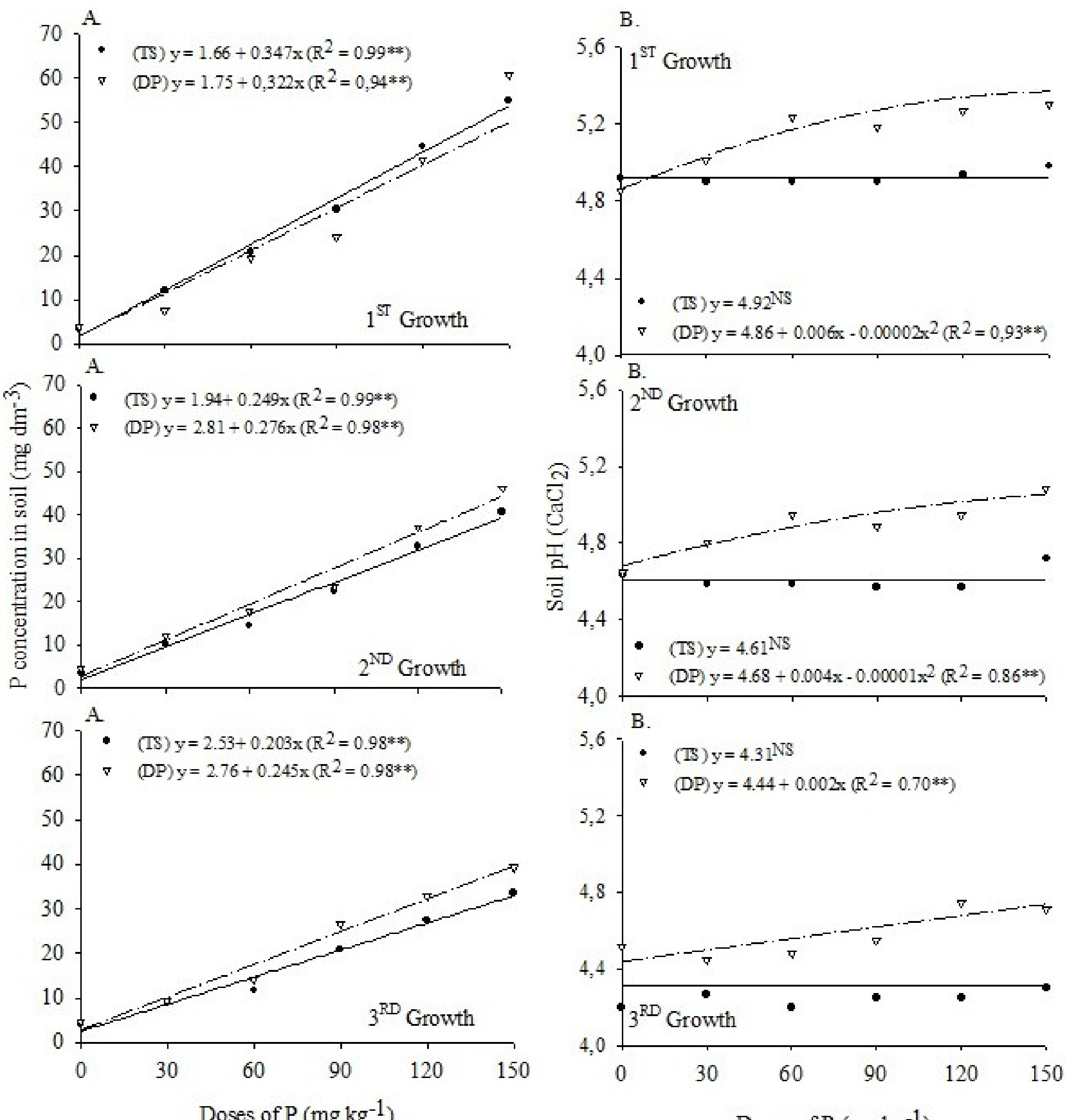


Figure 1. Effects of sources and doses of P on P content (A) and pH value (B) in the soil during three growth periods.

the first soil sampling, the P sources had different behaviors depending on the liming as evidenced by the significant interaction between the sources and liming (S × L) (Table 1). In the absence of limestone, the P sources did not differ in the levels of this nutrient in the soil. However, when lime was applied, compared to DP, the TS was superior in releasing P into the soil for plants. At the second and third soil sampling points, the DP provided more significant increases in P concentrations in soil, regardless of lime application. Also, at the first sampling, the soil corrective measure resulted in increased P availability in the soil with TS application, while there were no significant differences in the P levels when the soil corrective measure was applied with DP application. Furthermore, there was no effect of liming on P content in the soil at the second and third sampling points (Table 2).

Triple superphosphate increased P content in soil at the first sampling due to its high solubility in water and neutral ammonium citrate. The superiority of TS in supplying this nutrient during the first sampling period, when lime was applied, may be related to two processes: a) increased availability of P from TS provided by acidity correction, that reduces P absorption by Fe and Al oxides (Chien et al., 2011); b) the decreased efficiency of DP under these conditions, which needs a certain acidity in the soil solution in order to promote the initial solubilization of P. This is in line with Lima et al. (2007b) who emphasized that less soluble phosphates have a direct proportional relationship between the efficiency of partially acidulated phosphate and the acidification rate (molar ratio H^{+}/P_2O_5), which may have occurred in this experiment since the DP was significantly higher than TS in supplying P

Table 1. Analysis of variance and average values (Tukey test) for P sources (S) and liming (L) during three growth periods of Marandu grass.

	Growth stage	TS	DP	F	P/L	A/L	F	S × L
P concentration in soil (mg dm $^{-3}$)	1^{ST}	28 a	26 a	1.17^{NS}	26 a	28 a	0.84^{NS}	4.25*
	2^{ND}	21 b	24 a	5.12*	21 a	23 a	3.84^{NS}	0.04^{NS}
	3^{RD}	18 b	21 a	8.89**	19 a	19 a	0.01^{NS}	2.83^{NS}
Soil pH ($CaCl_2$)	1^{ST}	4.9 b	5,1 a	47.64**	4.5 b	5.6 a	1179.00**	5.56*
	2^{ND}	4.6 b	4,9 a	90.91**	4.3 b	5.2 a	919.31**	24.58**
	3^{RD}	4.3 b	4,6 a	58.22**	4.1 b	4.8 a	432.78**	0.06^{NS}
H + Al in soil ($mmol_c$ dm^{-3})	1^{ST}	26 a	23 b	68.03**	34 a	15 b	2857.08**	29.09**
	2^{ND}	38 a	32 b	73.09**	41 a	29 b	291.08**	15.63**
	3^{RD}	41 a	38 b	33.22**	46 a	32 b	446.06**	3.50**
Ca concentration in soil ($mmol_c$ dm^{-3})	1^{ST}	17 b	24 a	36.7**	8 b	32 a	491.80*	0.07^{NS}
	2^{ND}	21 a	24 a	1.46^{NS}	7 b	37 a	127.49**	0.79^{NS}
	3^{RD}	15 b	22 a	17.47**	7 b	30 a	180.50**	3.23*
Mg concentration in soil ($mmol_c$ dm^{-3})	1^{ST}	5 a	5 a	2.90^{NS}	2 b	8 a	2108.90**	0.32^{NS}
	2^{ND}	4 b	5 a	6.28*	2 b	8 a	296.53**	0.32^{NS}
	3^{RD}	2 a	2 a	1.84^{NS}	2 b	3 a	34.77**	1.85^{NS}
K concentration in soil ($mmol_c$ dm^{-3})	1^{ST}	1.8 a	1.8 a	0.29^{NS}	1.8 a	1.8 a	0.12^{NS}	0.11^{NS}
	2^{ND}	1.0 a	1.0 a	0.01^{NS}	1.1 a	1.1 a	0.07^{NS}	0.07^{NS}
	3^{RD}	1.0 a	1.0 a	0.27^{NS}	1.0 a	0.9 a	1.22^{NS}	0.63^{NS}
P content in plant shoots (g kg $^{-1}$)	1^{ST}	1.9a	1.7b	9.60**	1.5 b	2.1 a	48.40**	0.01^{NS}
	2^{ND}	1.3 a	1.2 a	0.70^{NS}	1.2 a	1.2 a	1.22^{NS}	0.09^{NS}
	3^{RD}	0.9 a	0.9 a	0.31^{NS}	0.9 a	0.9 a	2.82^{NS}	0.96^{NS}
Ca content in plant shoots (g kg $^{-1}$)	1^{ST}	3.2 b	3.9 a	35.92**	2.7 b	4.4 b	210.87**	0.30^{NS}
	2^{ND}	2.7 b	3.5 a	48.31**	2.0 b	4.2 a	331.05**	10.87**
	3^{RD}	2.4 b	2.7 a	5.51*	1.6 b	3.5 a	181.64**	2.89^{NS}
Mg content in plant shoots (g kg $^{-1}$)	1^{ST}	3.4 a	3.4 a	0.01^{NS}	2.8 b	4.0 a	36.66**	0.10^{NS}
	2^{ND}	2.7 a	2.7 a	0.02^{NS}	1.4 b	3.9 a	172.50**	0.01^{NS}
	3^{RD}	2.2 a	2.2 a	0.02^{NS}	1.3 b	3.1 a	301.33**	0.09^{NS}
K content in plant shoots (g kg $^{-1}$)	1^{ST}	32.6 a	33.0 a	0.06^{NS}	33.0 a	32.6 a	0.03^{NS}	0.01^{NS}
	2^{ND}	26.3 a	26.9 a	0.14^{NS}	26.7 a	26.5 a	0.07^{NS}	0.01^{NS}
	3^{RD}	26.9 a	27.4 a	0.19^{NS}	27.2 a	27.1 a	0.03^{NS}	0.01^{NS}
S content in plant shoots (g kg^{-1})	1^{ST}	2.8 a	2.9 a	0.19^{NS}	2.9 a	2.9 a	0.01^{NS}	0.02^{NS}
	2^{ND}	1.4 a	1.4 a	0.31^{NS}	1.4 a	1.4 a	0.11^{NS}	0.06^{NS}
	3^{RD}	1.8 a	1.8 a	0.05^{NS}	1.8 a	1.8 a	0.05^{NS}	0.05^{NS}
Cu content in plant shoots (mg kg $^{-1}$)	1^{ST}	12 a	12 a	0.03^{NS}	12 a	12 a	0.06^{NS}	0.03^{NS}
	2^{ND}	8 a	8 a	0.01^{NS}	8 a	8 a	0.01^{NS}	0.04^{NS}
	3^{RD}	8 a	8 a	0.03^{NS}	8 a	8 a	0.06^{NS}	0.01^{NS}
Mn content in plant shoots (mg kg $^{-1}$)	1^{ST}	103 a	100 a	0.13^{NS}	132 a	70 b	41.40**	0.11^{NS}
	2^{ND}	93 a	93 a	0.01^{NS}	126 a	60 b	242.01**	0.03^{NS}
	3^{RD}	122 a	126 a	0.41^{NS}	136 a	112 b	16.43**	0.02^{NS}
Zn content in plant shoots (mg kg $^{-1}$)	1^{ST}	121 a	122 a	0.03^{NS}	127 a	116 a	1.83^{NS}	0.01^{NS}
	2^{ND}	66 a	65 a	0.07^{NS}	79 b	51 a	91.13**	0.05^{NS}
	3^{RD}	66 a	65 a	0.28^{NS}	78 a	52 b	70.56**	0.01^{NS}
Number of tillers per pot	1^{ST}	14 a	12 b	28.03**	15 a	11 b	56.69**	0.22^{NS}
	2^{ND}	4 a	4 a	0.65^{NS}	4 a	4 a	2.25^{NS}	21.26**
	3^{RD}	7 a	7 a	0.52^{NS}	8 a	7 a	1.56^{NS}	0.04^{NS}
	Sum	26 a	23 b	12.89**	27 a	22 b	49.96**	6.41*
Shoot dry mass (g/pot)	1^{ST}	4.2 a	3.6 b	7.00*	5.3 a	2.5 b	133.43*	8.17**
	2^{ND}	8.3 a	8.0 a	1.26^{NS}	8.0 a	8.2 a	0.46^{NS}	4.81*
	3^{RD}	4.3 a	4.1 a	1.34^{NS}	3.9 a	4.4 a	3.17^{NS}	18.95**
	Sum	16.8 a	15.7 b	6.08*	17.2 a	15.1 b	19.72**	22.44**

Average values followed by the same lower case letter for line indicate that they do not differ according to Tukey test ($p < 0.05$).

Table 2. Significant interactions of P source and liming (S × L) on the pH values, P content, and H + Al content in the soil at three growth stages of Marandu grass.

P source	1ST growth stage		2ND growth stage		3RD growth stage	
	A/L	P/L	A/L	P/L	A/L	P/L
			P content in soil (mg dm $^{-3}$)			
TS	26 aB	30 aA	19 bA	22 bA	19 bA	17 bA
DP	27 aA	25 bA	22 aA	24 aA	20 aA	22 aA
			Soil pH ($CaCl_2$)			
TS	4.3 bB	5.5 bA	4.1 bB	5.1 bA	4.0 aA	4.7 aA
DP	4.6 aB	5.7 aA	4.5 aB	5.3 aA	4.2 aA	4.9 aA
			H + Al concentration in soil (mmol$_c$ dm^{-3})			
TS	36 aA	15 aB	46 aA	30 aB	49 aA	33 aB
DP	31 bA	14 bB	37 bA	27 bB	44 bA	32 aB

Average values followed by the same letter, lower case in the column and capital letter in the row, indicate that they do not differ by Tukey test ($p < 0.05$).

into soil after the first soil sampling when the pH values were reduced due to soil acidification by nitrogen fertilization.

Moreover, the DP increased the soil pH with increasing doses of P during the three Marandu grass growth periods. On the other hand, the use of TS did not change the soil pH regardless of the P doses applied (Figure 1B). Consequently, H + Al content decreased with application of DP during all sampling periods (Table 1). The increases in the soil pH and the reduction of the H + Al contents with application of DP may have occurred because when fertilizer was applied, the calcium hydroxide or lime reacted with the diluted phosphoric acid, resulting in a precipitate (decanted calcium phosphate), which is subsequently dried and sold. Thus, the hydroxyl or carbonate anions can be released in the soil solution, which removes hydrogen ions and increases the soil pH. The possible presence of these anions is confirmed by the NP value of 10.49% $ECaCO_3$ in this fertilizer. For TS, despite the fertilizer containing Ca in its composition, the companion anion did not neutralize the acidity, as evidenced by the NP value below the method detection limit (<0.01% $ECaCO_3$).

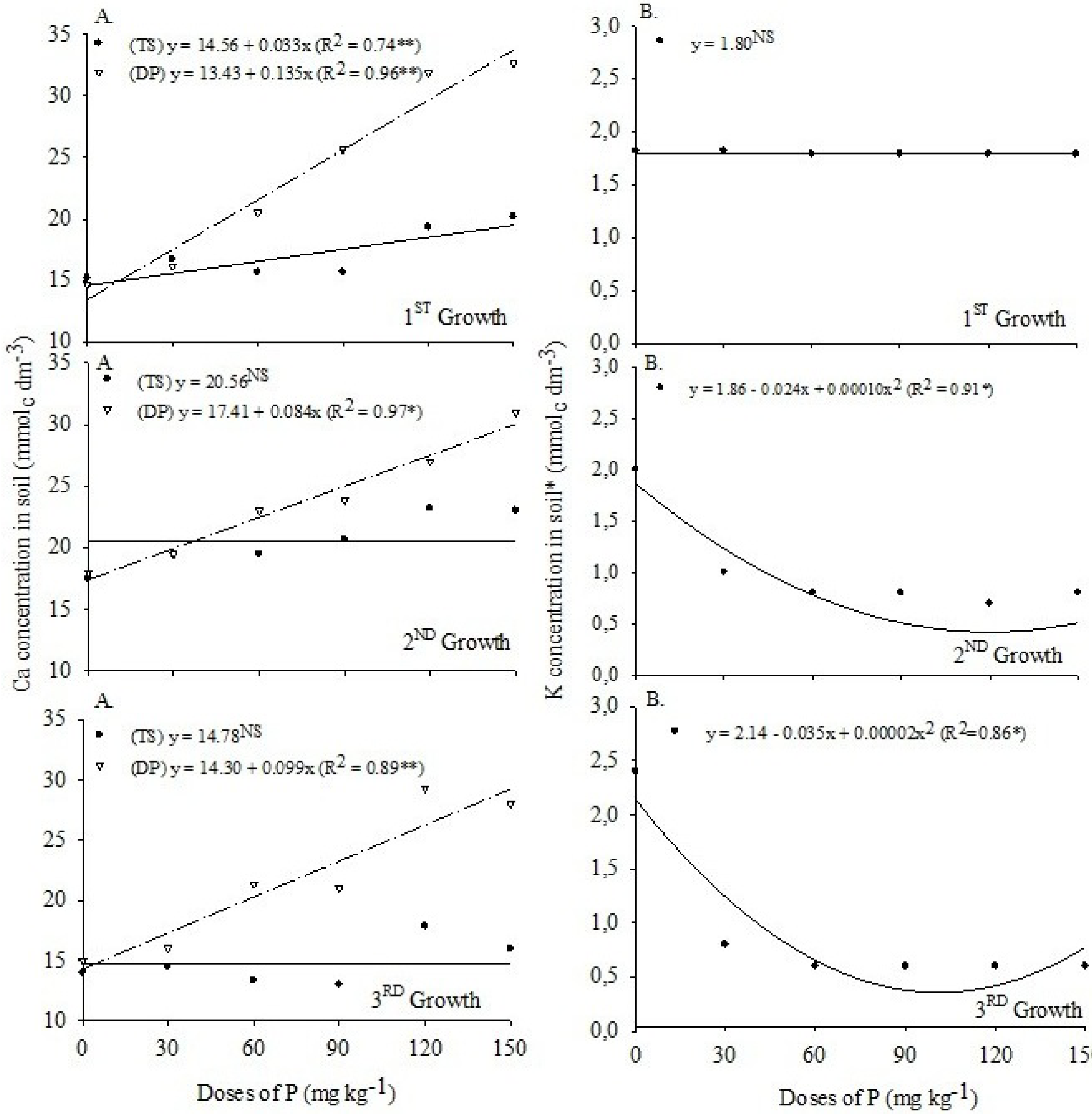
Furthermore, it was observed that the supply of Ca in soil was higher with DP application compared with TS application at the three sampling points (Figure 2A). This amount of Ca in the first soil sample increased linearly with the P doses applied but showed more pronounced effect with DP application. For the second and third soil samples, the Ca levels in the soil showed linear increases with P doses applied as DP, and remained constant with increasing P doses employed in the form of TS. The most significant increments in Ca content in soil caused by DP application are related to higher concentrations of this nutrient in the fertilizer applied compared to TS (DP = 18% of Ca; TS = 14% of Ca). The Mg content in the soil did not differ between the two P sources used during the first and third growth periods, but not during the second growth period when DP (5 mmol$_c$ dm^{-3}) slightly increased Mg content in soil compared to TS (4 mmol$_c$ dm^{-3}) (Table 1). These results may indicate a possible presence of a very small amount of Mg in the composition DP. For K in the soil, only a significant reduction of the levels of this nutrient was observed in the soil samples after the first growth period (Figure 2B), showing no significant influence of liming and P sources on K content in the soil. However, this effect caused by the P doses should be attributed to the low growth rate of plants without P, leading to the extraction of a small amount of K in the soil, which is associated with potassium fertilization performed after each cut.

Shoots of the Marandu grass

In the chemical evaluation of the shoots of Marandu grass, unfolding significant interaction between the sources and doses of P (S × D) was observed: P content in the shoots of the plant increased with P doses at the three growth stages (Figure 3A). In this case, the DP was lower than TS in providing this nutrient to plants at the first growth stage, especially from the 60 mg dm^{-3} dose of P, when the difference between the fertilizers in P content in the shoots of the plant was increased. After the first growth stage, there was no significant difference between the P sources in the levels of this nutrient in the shoots of Marandu grass.

At the first growth stage, the P content in the soil was lower with DP application than with TS application, with a similar behavior observed for P content in the shoots of the plants, but P contents increased after the first growth stage. Therefore, for the second and third growth stages, the highest P supply from DP to the soil compared to TS did not result in higher nutrient extraction by plants. This can be related to the fact that, during the first growth period, the higher values of P in soil and plants provided by TS possibly allowed the root system of Marandu grass to develop more than that during the treatment with DP, thereby increasing the root-soil contact and facilitating the absorption of this nutrient by roots via diffusion and interception. Although the main driving mechanism for P absorption is diffusion, interception of P by roots can also contribute to P absorption, mainly with extensive root growth about the aerial part of the plant (Lambers et al., 2006), making the root system to explore a larger volume of soil. Moreover, the increases in the initial P concentration in the soil solution and the root growth rate can also improve the absorption of this nutrient by plants. Salas et al. (2006) found that the use of a soluble source of P promoted the early growth of roots, promoting greater use of available P.

The P content in the soil and shoots of the plants decreased successively after each growth stage, which was confirmed by the decreasing soil pH values in this experiment. The reduction of the pH values increases P adsorption to the solid phases of the soil since in acidic soil conditions, the phosphate reacts rapidly with the octahedral of Al by replacing the OH groups located on the surface of the oxyhydroxides of Fe and Al, forming a complex internal sphere. Also, in acidic soils, low-solubility compounds are formed by P precipitation with ionic forms of Al and Fe (Chien et al., 2011). Therefore, increasing adsorption of P to the soil intensified the soil-plant competition



* Data transformed by $x^{0.5}$

Figure 2. Effects of the sources and doses of P on Ca content (A) and K content (B) in the soil during three growth periods.

for P, reducing its absorption by the roots and the P content in the shoots of Marandu grass.

The Ca contents in the shoots were increased as a function of the doses of P applied to the soil (Figure 3B). The DP was higher in supplying Ca to the plants during all growth stages, which is consistent with the most significant increases of this nutrient in the soil with DP application compared to TS application. There were no significant effects of the sources and doses of P on the Mg levels in the shoots of the plants (Table 1). This result can infer that the small increase in Mg content in the soil (at the second sampling) was not enough to raise the level of this nutrient in the shoots of Marandu grass, which supports the hypothesis that DP has a minimal quantity of Mg.

No significant changes were observed in the K, S, and Cu contents in the shoots of the plants because of liming and the sources and doses of P, as well as the interactions of S × L, L × D, and S × D. The K, S, and Cu contents ranged from 27 to 33 g kg^{-1}, 1.8 to 2.9 g kg^{-1}, and 8 to 13 mg kg^{-1}, respectively. These nutrient contents are within or above the range considered adequate for *B. brizantha* (Werner et al., 1996). The Mn and Zn contents in the shoots of the plants decreased with liming. Moreover, the sources of P did not show differences in the contents of these nutrients in the shoots of the Marandu grass (Table 1). The contents of Mn and Zn in the shoots of the plants ranged from 90 to 132 mg kg^{-1} and 60 to 139 mg kg^{-1}, respectively. Regardless of the liming, the Mn and Zn contents in the shoots of Marandu grass were above the range considered adequate (Werner et al., 1996). No deficiency or toxicity symptoms of micronutrients were observed throughout this experiment.

Tillering and dry matter production of Marandu grass

The number of tillers produced during each growth stage (tillering dynamics) increased with doses of P regardless of the

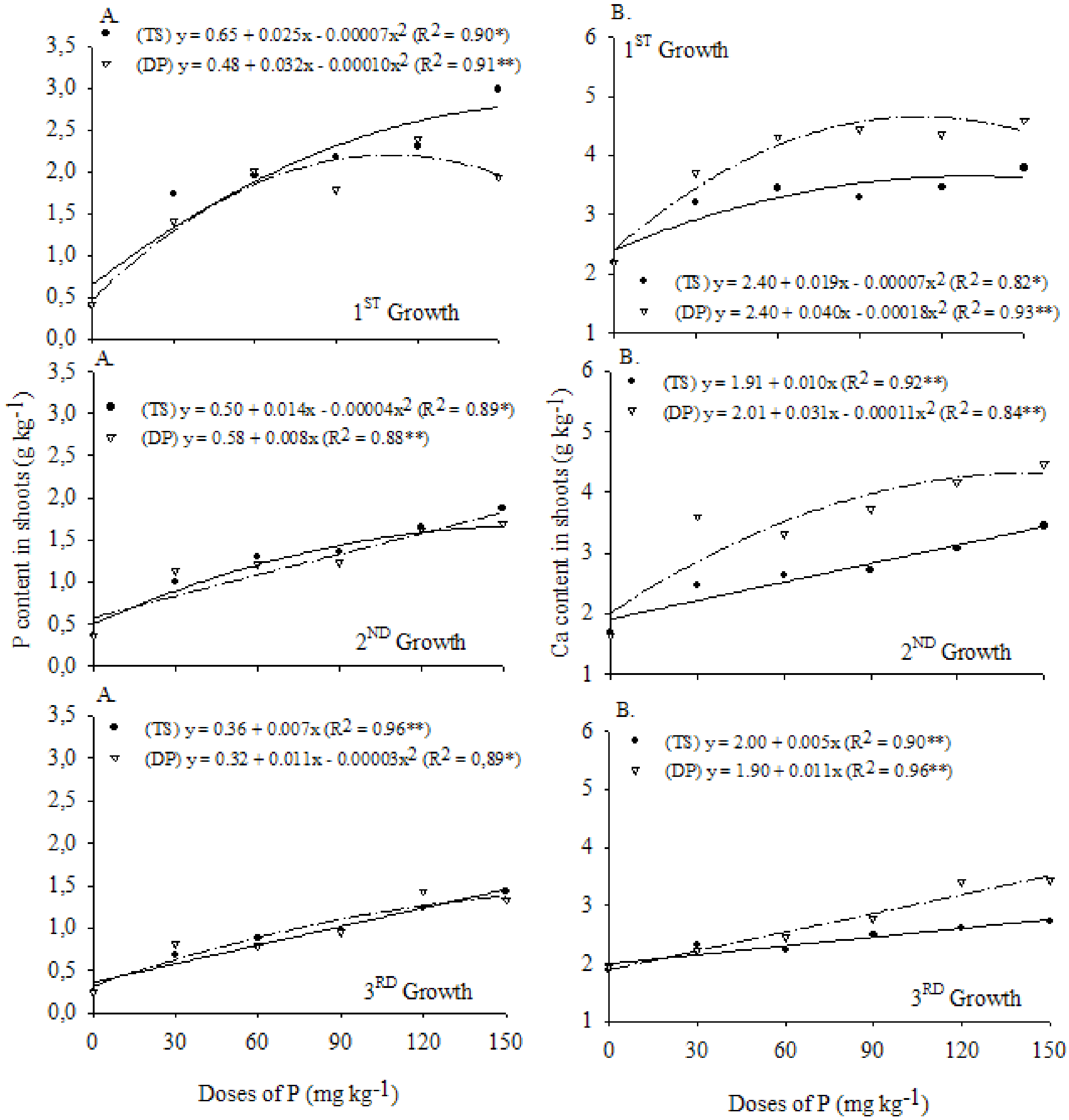


Figure 3. Effects of the sources and doses of P on P content (A) and Ca content (B) in the shoots of Marandu grass at three growth stages.

fertilizer used (Figure 4A). The production of tillers was lower with DP application than with TS application only during the first growth period. During the second and third growth periods, there were no significant differences between the fertilizers in the production of tillers. Thus, the highest levels of P in shoots of the plants provided by TS compared to the DP, during the first growth period, resulted in higher numbers of tillers. The first growth stage was vital for the production of tillers and plant growth because after the first growth stage the fertilizers did not vary in supplying P to plants and in initiating the production of tillers. Also, it is noteworthy that the number of tillers produced was reduced from the first to the second and third growth stages, which highlights the importance of phosphate fertilization during the implantation of pastures (Lima et al., 2007b).

According to Cecato et al. (2008), the productive capacity of pastures is closely related to the supply of P to plants because this nutrient is essential to produce tillers. As a constituent of nucleic acid (DNA and RNA of enzymes and coenzymes), P is vital in the processes of photosynthesis, respiration, energy transfer, and the division and development of meristematic tissues of plant cells. In this study, it was observed that treatments without phosphate fertilizer application had less number of tillers (Figure 4A), confirming the contribution of P to tillering. A behavior similar to the number of tillers (S × D interaction) was observed for dry matter production of the shoots of the plants (Figure 4B). During the first growth stage, the application of DP resulted in lower production of dry mass than application TS. After the first growth stage, the fertilizers did not differ in initiating dry matter production of the shoots of the plants. Lima et al. (2007b) also observed lower dry matter production for natural phosphates than the TS up to 75 days after sowing. The same authors explained that the residual effect of less soluble phosphates might increase over time because of the low soil acidity required for P solubilization. Ramos et al. (2009) verified the higher dry matter production

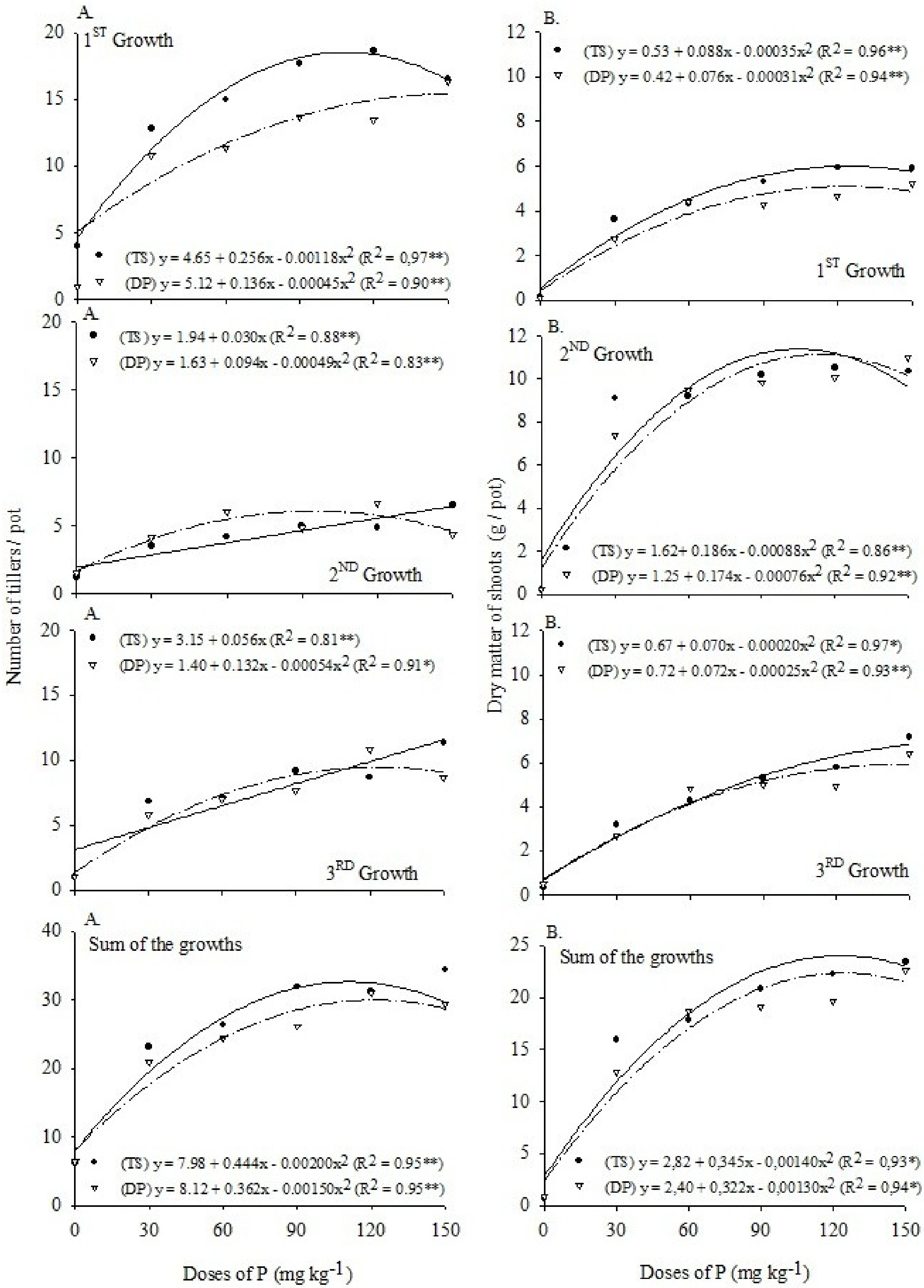


Figure 4. Effects of the sources and doses of P on the number of tillers (A) and dry matter of Marandu grass (B) at three growth stages and the entire growth period.

and P accumulation with TS application than with application of the Arad reactive phosphate (less soluble). However, over the entire growth period, it was observed that DP resulted in lower dry matter production than TS, reaffirming the contribution of the first growth stage to lower production of Marandu grass as affected by DP. According to Mesquita et al. (2010), the number of tillers is strongly associated with dry matter yield of forage species.

Table 3. Significant interaction of P source and liming (S × L) for dry matter production of the shoots and the number of tillers of Marandu grass at three growth stages and over the entire plant growth period.

P source	1ST growth stage		2ND growth stage		3RD growth stage		Sum	
	A/L	P/L	A/L	P/L	A/L	P/L	A/L	P/L
	Dry matter of shoots (g/pot)							
TS	5.25aA	3.17 aB	7.91 aB	8.63 aA	3.58 bB	5.09 aA	16.75 aA	16.89 aA
DP	5.30aA	1.85 bB	8.18 aA	7.80 bA	4.37 aA	3.74 bA	17.84 aA	13.39 bB
	Tillers produced by growth (tillers/pot)							
TS	16 aA	12 aA	3 bB	5 aA	8 aA	7 aA	27 aA	24 aB
DP	13 aA	10 aA	6 aA	3 bB	7 aA	6 aA	27aA	20 bB

Average values followed by the same letter, lower case in the column and capital letter in the row, indicate that they do not differ by Tukey test ($p < 0.05$).

However, when studying the behavior of the sources of P as a function of liming (S × L) in the context of changes in tillering, it was found that, over the entire growth period, the fertilizer sources did not differ significantly in the number of tillers in the absence of lime (Table 3). Following the soil corrective measure, the effect of DP on tiller production was lower than that of TS. Also, there was no significant interaction between fertilizer source and liming (S × L) in the number of tillers during the first and third growth periods. These results were similar to the trend of P content in the soil. The lowest nutrient levels in soil were observed when the DP was applied in the presence of lime. When lime was not applied to soil, the fertilizers did not differ in affecting P content in the soil (Table 3). No significant interaction between P source and liming was observed for P content in the shoots of the plants, making the relationships of S × D and L × D difficult to explain, in the contexts of P content in the soil and shoots of the plants, and in the number of tillers of the Marandu grass (Table 1)

For dry matter production of the shoots plants, the behavior of the sources of P as a function of liming (S × L interaction) was like that observed for the number of tillers (Table 3). When limestone was not applied, the sources of P did not differ in initiating dry matter production of the shoots of the plants, except during the third growth period, during which the effect of DP on inducing dry matter production of plant shoots was higher than that of TS. This fact may be related to the effects of DP on increasing the pH and reducing the potential acidity of soil, and thus, supplying Ca to the plants, since the P content in the shoots of the plants at this growth stage did not differ significantly between the fertilizer types. However, when the soil acidity was corrected, DP was significantly lower than TS in initiating dry matter production of the forage at all growth stages, taking the sum of the growth at a lower dry matter production in the shoots of the plant.

Conclusions

Decanted phosphate can be used for fertilization during pastures implantation because of its residual effect and ability to supply P mainly after the first growth period.

This by-product decreases the soil acidity, increases the Ca content in soil and plant tissues, and improves the production of Marandu grass.

The supply of P by DP is favored by low soil acidity. Furthermore, the application of DP did not change the contents of Zn, Mn, and Cu in the shoots of Marandu grass.

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