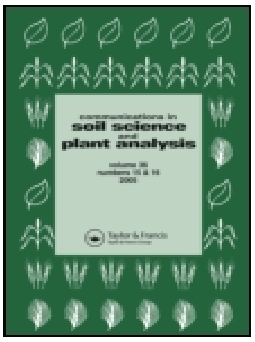

Communications in Soil Science and Plant Analysis

ISSN: 0010-3624 (Print) 1532-2416 (Online) Journal homepage: https://www.tandfonline.com/loi/lcss20

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COMMUNICATIONS IN SOIL SCIENCE AND PLANT ANALYSIS
2016, VOL. 47, NO. 5, 657–669
http://dx.doi.org/10.1080/00103624.2016.1141923

# Phosphorus Sources and Rates Associated with Nitrogen Fertilization in Mombasa Grass Yield

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**ABSTRACT**
Nitrogen (N) and phosphorus (P) deficiency is one of the important causes of degradation of cultivated pasture under tropical conditions. The aim of this study was to evaluate phosphate rates and sources, and N rates on the concentration and uptake of N and P, and shoot dry mass (SDM) yield of *Megathyrsus maximum* grass cv Mombasa in an Ultisol. The trial was carried out in a greenhouse in pots with 4.0 $dm^{-3}$ of soil. The experiment was arranged in a completely randomized design with four replicates. The 3 × 3 × 3 factorial treatments consisted of phosphorus sources [reactive rock phosphate from Morocco (RPM), reactive rock phosphate from Algeria (RPA) and triple superphosphate (TSP)], three phosphorus rates (0, 150, and 300 mg $kg^{-1}$), and three N rates (0, 250, and 500 mg $kg^{-1}$). The SDM and tillering of Mombasa grass were significantly influenced with the TSP, RPM, and RPA application associated with N fertilization. The RPM, RPA, and TSP met the nutritional demands of Mombasa grass. The three P sources showed the same effect on the total N uptake by Mombasa grass. The P use efficiency (PUE) when fertilizer-P sources were added alone by Mombasa grass was <12% of the added P, and PUE decreased as follows: TSP > RPA > RPM. When P and N-fertilizer were added together, the fertilizer-N use efficiency (NUE) was 62%. The reactive phosphate (RPM and RPA) is an efficient P sources for Mombasa grass, but requiring higher rate of application compared to TSP source.

**ARTICLE HISTORY**
Received 23 April 2015
Accepted 9 November 2015

**KEYWORDS**
Fertilizers; *Megathyrsus maximum*; phosphate; plant nutrition; reactive rock phosphate

## Introduction

For forage, to express all their yield potential, they need the best management practices of animals and plants designed for specific climatic and soil. Among the latter, the use of fertilizers is essential, which provide nutrients necessary for plant development. Most of the time, the supply of nutrients in the soil is inadequate for production of high technological standards (Vuolo 2006). Among the macronutrients, N and P have a fundamental role in plant nutrition (Mengel and Kirkby 2001; Marschner 2012).

Nitrogen is directly related to forage quality (Teixeira et al. 2011; Heinrichs et al. 2013), since a part in the synthesis of organic compounds that form the plant structure, such as amino sugars, amines, amides, vitamins, pigments, amino acids, proteins, nucleic acids, and molecule chlorophyll (Mengel and Kirkby 2001). N in plants is responsible for the emergence and development of tillers, leaf, and stem size and formation of proteins (Epstein and Bloom 2005).

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On the other hand, phosphorus (P) has important functions in the initial phase of the development of forage plants. Cantarutti et al. (2002) indicated that in the initial growth stage, P is important as there is intense meristematic activity, due to the development of the root system, tillering, stem development, and cell division and for its role in the structure of nucleic acids. According to Hodgson (1990), tillering is considered to be the basic unit of development of forage plants, because the grasses use it as a means of growth and development leading to increased productivity and persistence of pastures.

Nutrient interactions occur when the supply of a nutrient affects the uptake, distribution, functions, or other nutrients (Robson and Pitman 1983). In agricultural yield, nutrient interactions assume added significance, affecting crop productivity and the return on investment in fertilizers. With the yield intensification, the extent, and severity of nutrient deficiencies, the practical significance of interactions increases (Aulakh and Malhi 2005).

The use of reactive natural rock phosphates (NRPs) in forage crops may be beneficial as they are characterized by a slow release of P, thereby reducing the loss of nutrients (McDowell and Monaghan 2003). When NRP is associated with nitrogen (N), a great potential of forage yield may occur. According to Vilela et al. (2002), the P and N deficiency is the most frequent cause of loss in pasture productivity and increased environmental degradation. It has often been shown that in soil with high deficiency of P, only the application of N has little impact on crop yields, as its application plus P can drastically increase the response to the fertilizer applied (Moreira and Malavolta 2001; Singh 2001; Dwivedi et al. 2003; Moreira et al. 2010).

*Megathyrsus maximum*, varieties of "Tanzania-grass", and "Mombasa-grass" are among the innovative pastures responsible for the technological leap that increased productivity per area, as well as the nutritional value of pasture in the Brazilian production system (Vuolo 2006). However, fertilization is necessary to express all their productive potential, due to its greatest nutritional requirement cultivars. Although N is the nutrient required in largest amounts by plants, there is need to pay attention to its interaction with other elements, so that the production is not limited, especially that of P, due to its limited availability in Brazilian Ultisols (Vilela et al. 2002).

The objective of this work was to evaluate the effect of rates and sources of P and N on the Mombasa grass (*Megathyrsus maximum*) tiller and biomass yield [shoot dry mass (SDM) yield], and N and P concentration and uptake in the plant.

## Materials and methods

### *Forage plant and soil*

The experiment was conducted under greenhouse conditions at São Paulo State University, Campus of Dracena (21°29′ LS and 51° 2′ LW; 396 m altitude), São Paulo State, Brazil, using the forage grass *Megathyrsus maximum* cv. Mombasa. The soil was a dystrophic Ultisol, with Cerrado vegetation, with the following chemical properties: pH (calcium chloride ($CaCl_2$) 0.1 mol $L^{-1}$) = 4.1; soil organic matter (SOM) = 15 g $kg^{-1}$; available P (resin-extracted) = 1.0 mg $kg^{-1}$; sulfate ($S\text{-}SO_4{}^{2})^{-}$ = 3.0 mg $kg^{-1}$; exchangeable potassium ($K^+$) = 0.5 $mmol_c$ $kg^{-1}$; exchangeable calcium ($Ca^{2+}$) = 1.0 $mmol_c$ $kg^{-1}$; exchangeable magnesium ($Mg^{2+}$) = 1.0 $mmol_c$ $kg^{-1}$; exchangeable aluminum ($Al^{3+}$) = 5.0 $mmol_c$ $kg^{-1}$; potential acidity hydrogen + aluminum ($H^+$ + $Al^{3+}$) = 20.0 $mmol_c$ $kg^{-1}$; cation exchange capacity (CEC) = 22.5 $mmol_c$ $kg^{-1}$; base saturation—[(ΣK, Ca, Mg)/(ΣK, Ca, Mg,H + Al)] × 100 (V) = 11.0%; available boron (B) = 0.13 mg $kg^{-1}$; available cooper (Cu) = 1.0 mg $kg^{-1}$; available iron (Fe) = 27.0 mg $kg^{-1}$; available manganese (Mn) = 13.0 mg $kg^{-1}$; and available zinc (Zn) = 0.6 mg $kg^{-1}$. Phosphorus, $K^+$, $Ca^{2+}$, $Mg^{2+}$, and $Al^{3+}$ were extracted by the resin extracting solution, B was extracted by hot water, and Cu, Fe, Mn, and Zn by diethylene tetramine penta acetic acid-triethanolamine (DTPA-TEA), pH 7.3 (van Raij et al. 2001). For the experiment, soil was sampled from a 0–20 cm depth for a composite sample; the soil was crumbled, air-dried, and sieved (4.0 mm).

### Experimental design and treatments

The experiment was arranged in a completely randomized block design with four replicates. The $3 \times 3 \times 3$ factorial treatments consisted of P sources (reactive rock phosphate from Morocco (RPM—31% of phosphorus pentoxide ($P_2O_5$)), reactive rock phosphate from Algeria (RPA—29% of $P_2O_5$), and triple superphosphate (TSP—42% of $P_2O_5$), added at three P rates (0, 150, and 300 mg $kg^{-1}$), and three N rates (0, 250, and 500 mg $kg^{-1}$) in the form of ammonium nitrate—32% N (i.e., a total of 27 treatment combinations). The quantities of P sources were calculated based on the total concentration in the fertilizer material. Fertilizers RPM and RPA were applied as a branny (95% past mesh 3.36 mm) and TSP as granulated (95% past mesh 4.0 mm) and mixed with 4 $dm^3$ of soil per pot (soil density was 1.3 g $cm^{-3}$). The nitrogen fertilizer was applied as a solution in two applications, one third at sowing and two thirds at the beginning of tillering.

### Experimental conditions and plant growth

The base saturation (V) of soil was increased to 70% (van Raij et al. 1996) by adding calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$), p.a. reagents at 3:1. The soil plus carbonate salts were then incubated for 30 days in the pots for reaction, maintaining moisture at 80% field capacity. At the end of the incubation period, the soil was air-dried for seven days. The soil of each pot (4.0 $dm^{-3}$) was filled in plastic trays where the treatments and fertilizers were applied: 150 mg $kg^{-1}$ of K [potassium sulfate ($K_2SO_4$)], 0.5 mg $kg^{-1}$ of B (boric acid ($H_3BO_3$)], 0.05 mg $kg^{-1}$ of Co [cobalt chloride ($CoCl_2$)], 1.0 mg $kg^{-1}$ of Cu [copper sulfate ($CuSO_4$)], 0.05 mg $kg^{-1}$ of Mo [molybdic acid ($H_2MoO_4$)], 0.05 mg $kg^{-1}$ of Ni [nickel sulfate ($NiSO_4$)], 10 mg $kg^{-1}$ of Mn [manganese sulfate ($MnSO_4 \times 5H_2O$)], and 3.0 mg $kg^{-1}$ of Zn [zinc sulfate ($ZnSO_4 \times 7H_2O$)]. Four $dm^3$ of the treated soil was transferred to the treatment labeled pots and after four days, Mombasa grass was sown and the seeds were evenly covered with a thin soil layer. After two weeks, the plants were thinned to five plants per pot. Soil moisture was maintained close to 80% field capacity by daily irrigation with deionized water. The amount of water to be added was determined by weighing five pots.

The plants were cut 5.0 cm above the soil surface. The first cut was 60 days after sowing, and each of the second and the third cuts were done after 45 days of growth. The plant material was dried at 65 ± 2 °C to constant weight (72 h) to determine the SDM. The number of tillers was counted at cutting. The dried plant material was ground in a Willey mill and the total content of N and P determined as described by Malavolta, Vitti, and Oliveira (1997).

### Statistical analysis

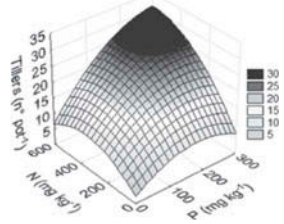
The results of SDM yield and P and N concentration were evaluated by analysis of variance (ANOVA), *F*-test, and models of regression and interactions by 5% of probability (Pimentel-Gomes and Garcia 2002).

## Results and discussion

### Tillers and shoot dry mass yield

In the first cut, the number of tillers per pot was similar between the P sources. The maximum number of 33 tillers per pot was attained with 374 mg $kg^{-1}$ of P and 637 mg $kg^{-1}$ of N (Figure 1a). Bonfim-Silva et al. (2012) in a study with Marandu grass noted that the utilization of reactive rock phosphates requires higher rates of 250 mg $dm^{-3}$ to obtain the maximum yield of tillers. In the

(a)

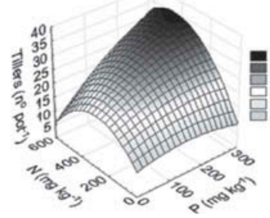



Tillers (n° $pot^{-1}$) = 2.3704 + 0.0858xP + 0.0465xN – 0.0002x$P^2$ + 0.0001xP x N –6.5778 x $10^{-5}$x$N^2$, $R^2$ = 0.85*

Maximum: P = 373.9; N = 637.7;

Tillers: 33 n° $pot^{-1}$

(b)

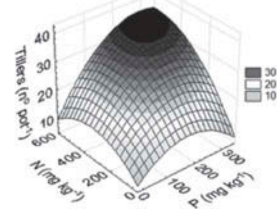



Tillers (n° $pot^{-1}$) = 9.1481 + 0.0322xP + 0.0713xN – 0.0001x$P^2$ + 0.0001xPxN – 0.0001x$N^2$, $R^2$ = 0.74*

Maximum: P = 452.3; N = 582.7;

Tillers: 37 n° $pot^{-1}$

(c)

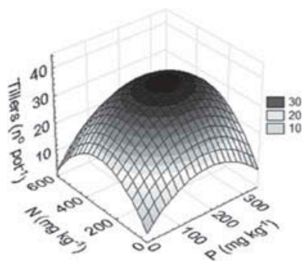



Tillers (n° $pot^{-1}$) = 6.3333 + 0.1048xP + 0.056xN – 0.0003x$P^2$ + 0.0001xPxN – 8.5333x$10^{-5}$x$N^2$, $R^2$ = 0.75*

Maximum: P= 254.2; N = 477.1;

Tillers: 33 n° $pot^{-1}$

(d)

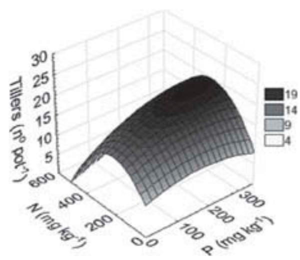



Tillers (n° $pot^{-1}$) = 3.3611 + 0.1435xP + 0.1023xN – 0.0004x$P^2$ + 5.1111x$10^{-5}$ xPxN – 0.0002x$N^2$, $R^2$ = 0.68*

Maximum: P = 197.3; N = 280.9;

Tillers: 32 n° $pot^{-1}$

(e)

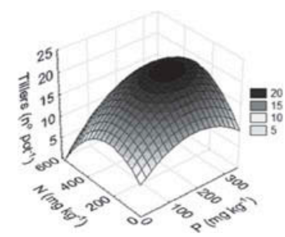



Tillers (n° $pot^{-1}$) = 8.1296 + 0.0296xP + 0.0633xN – 8.642x$10^{-5}$x$P^2$ + 6.6667x$10^{-5}$xPxN – 0.0002x$N^2$, $R^2$ = 0.69*

Maximum: P= 248.3; N = 199.6;

Tillers: 18 n° $pot^{-1}$

(f)

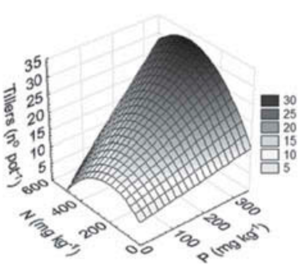



Tillers (n° $pot^{-1}$) = 7.3426 + 0.0646xP + 0.0399xN – 0.0002x$P^2$ + 5.5556xPxN – 9.1556x$10^{-5}$x$N^2$, $R^2$ = $0.25^{ns}$

Maximum: P= 200.2; N = 278.6;

Tillers: 19 n° $pot^{-1}$

(g)




Tillers (n° $pot^{-1}$) = 6.7143 + 0.0165xP + 0.0483xN + 1.0582x$10^{-6}$x$P^2$ + 0.0001xPxN – 0.0001x$N^2$, R2 = 0.74*

**Figure 1.** Effects of N rates and P sources and rates on the number of tillers of *Megathyrsus maximum* cv. Mombasa. First cut: (a) the average of three sources of P; second cut: (b) reactive P from Morocco; (c) reactive P from Algeria; (d) triple superphosphate (TSP); third cut: (e) reactive P from Morocco; (f) reactive P from Algeria; (g) TSP. * Significant at $P \leq 0.05$; ns not significant at $P \leq 0.05$

second and third cuts, the number of tillers varied according to the P sources and N and P rates applied. Note that the rates of RPM and N necessary for the maximum shoot yield are higher than the rates of TSP with N (Figure 1b–g). These results can be attributed to the solubility sources of P, since only about 30% of the reactive phosphate sources is soluble in 2.0% of citric acid, and P was released slowly during several cuts.

In the second cut, the use of RPM produced 37 tillers per pot (Figure 1b), which was higher than the number produced by RPA and TSP (Figure 1c and d). These results may be associated with differences in the solubility of rock phosphates. The slower P release from fertilizers may promote the uptake of nutrients, such as P and tillering along the forage growth cycle (Moreira and Malavolta 2001; Oliveira Júnior, Prochnow, and Klepker 2011).

The ANOVA for the SDM yield revealed a significant effect ($P \leq 0.01$) for the interaction of rates between P sources and N rates during the three cuts (Figure 2a–i). Even at low concentrations of N, and high P rates, the SDM yield remained low. Braga et al. (2004), studying N fertilization in Mombasa grass in the field, observed that the largest tillering occurred with a rate of 406 kg ha$^{-1}$ of N. In turn, Ferreira et al. (2008) also observed a significant effect of $P_2O_5$ on the number of tillers in the study of Mombasa grass. The results obtained from our experiment confirm the importance of N and P fertilization for tillering to increase the forage yield using Mombasa grass. The higher tillers number was obtained with the estimated rate of 296 g/kg N, almost double the rate reported by Lavres Júnior et al. (2011).

It is important to note that, with the increasing N rate, the number of tillers increased up to a maximum, as many tillers are short-lived due to competition, associated with the increase in the leaf area index, causing ultimately a premature stoppage of tillering (Nabinger and Medeiros 1995). The shoot dry mass yield was maximized only when N and P rates were associated. (Figure 2a–i). Similar results to those of Brambilla et al. (2012) who found a significant contribution of N fertilization on forage yield, which in turn was reflected in the higher weight gain of the animals, were obtained.

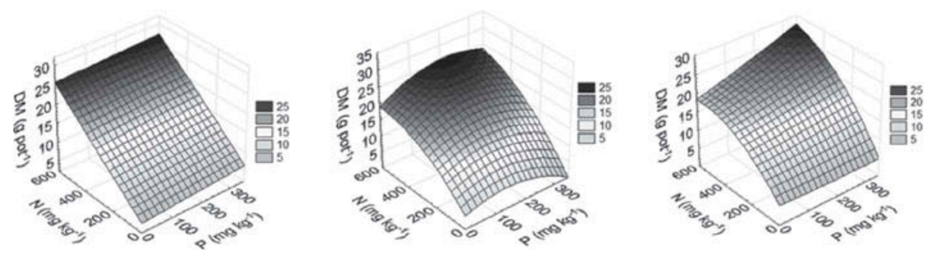
In general, our study indicates that RPA produced the highest amount of SDM (Figure 2b, e, and h), being a trend very close to the yield achieved under TSP, proving that RPA is an efficient alternative P-fertilizer which can be added in association with N to Mombasa grass. From the first to the third grass growth cycle, the maximum SDM yield and tillers were reduced to nearly 50% and 60%, respectively. This reduction can be associated with the large extraction of nutrients by forage, as well as the restriction on root growth due to the pot volume.

The same trend was observed for the SDM yield and the number of tillers during the three cuts, especially under the RPA treatment, that at 310 mg kg$^{-1}$ P and 585 mg kg$^{-1}$ of N produced 98 tillers (Figure 3a–c). The latter represented 15% and 24% higher tiller numbers than the TSP and RPM, respectively. The P rate for the maximum of SDM yield was lower with TSP (179 mg kg$^{-1}$) than with RPA (182 mg kg$^{-1}$) and RPM (332 mg kg$^{-1}$) (Figure 3d–f). The rock phosphate sources are less water-soluble than TSP, thus they need to be added at higher rates to meet the nutritional demand of crops (Moreira and Malavolta 2001; Silva et al. 2013). Noteworthily, RPM produced greater amounts of SDM than the other two P sources and within the range of the values found by Eichler et al. (2008). The latter may be associated with differences in rates of P release during the growth cycles of Mombasa grass. These results warrant further research on the P release rates from the two natural rock phosphates once they are added to a cropped soil.

### *Concentration of nitrogen and phosphorus in shoot*

There was a significant interaction ($P \leq 0.01$) between the rate and sources of P and N levels on the N concentration in the SDM of Mombasa grass (Figure 4a–i). In all cuts, we found that in the absence of fertilizer-N, the plants showed low concentration of N (<15 g kg$^{-1}$). In the first cut, the three P sources had similar effects on shoot N concentration (27 g kg$^{-1}$) (Figure 4a–c). The amount of fertilizer-N needed to achieve this N shoot concentration varied from 475 mg kg$^{-1}$ of N in the presence of RPA (Figure 4b) to 692 mg kg$^{-1}$ of N when TSP was added (Figure 4c). The positive

(a) (b) (c)

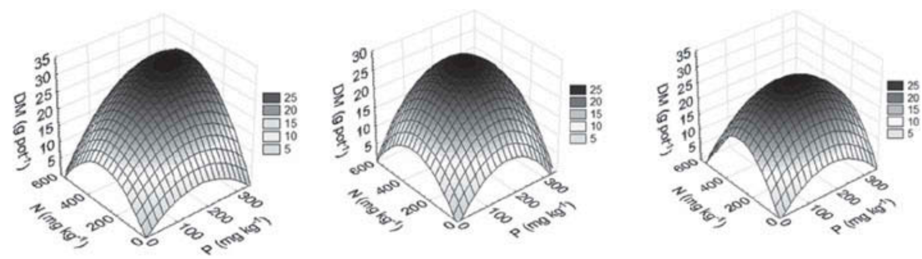



(a) Dry mass (g) = 4.6061 + 0.0005xP + 0.0349xN, $R^2 = 0.84$*

(b) Dry mass (g) = 4.1777 + 0.0363xP + 0.0498xN - $0.0001xP^2$ + $4.2187x10^{-5}$xPxN - 4.2352 $x10^{-5}xN^2$, $R^2 = 0.90$*
Maximum: P: 341.4; N = 757.9;
Dry mass: 29 g $pot^{-1}$

(c) Dry mass (g) = 5.4705 - 0.0045xP + 0.0478xN + $7.4691x10^{-6}xP^2$ + $4.8189x10^{-5}$ xPxN - $4.4004x10^{-5}xN^2$, $R^2 = 0.94$*
Critical point not found.

(d) (e) (f)

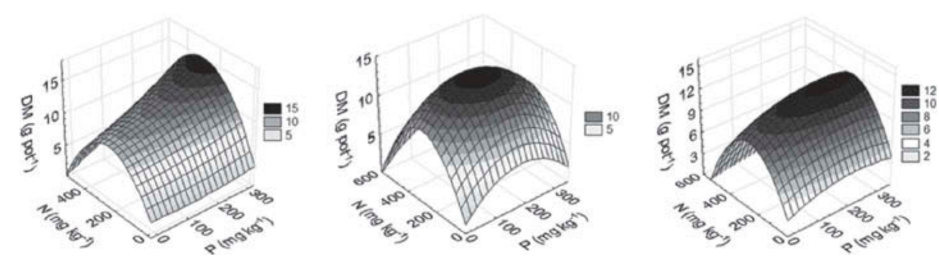



(d) Dry mass (g) = -0.1119 + 0.0962xP +0.0865xN - $0.0003xP^2$ + 0.0001xPxN - $0.0002xN^2$, $R^2 = 0.82$*
Maximum: P: 204.9; N = 267.5;
Dry mass: 21 g $pot^{-1}$

(e) Dry mass (g) = -1.4859 + 0.1362xP + 0.0793xN - $0.0004xP^2$ + $6.5778x10^{-5}$xPxN - $0.0001xN^2$, $R^2 = 0.78$*
Maximum: P: 208.5; N = 465.1;
Dry mass: 31 g $pot^{-1}$

(f) Dry mass (g) = -0.9501 + 0.1188xP + 0.1222xN - $0.0003xP^2$ + $9.5778x10^{-1}$xPxN - $0.0002xN^2$, $R^2 = 0.78$*
Maximum: P: 202.9; N = 310.4;
Dry mass: 30 g $pot^{-1}$

(g) (h) (i)



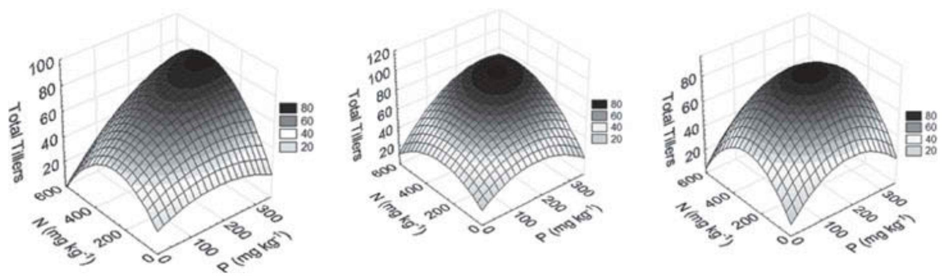

(g) Dry mass (g) = 3.5333 - 0.0019xP + 0.0537xN + $1.5877x10^{-5}xP^2$ + 4.838x10-5xPxN - $0.0001xN^2$, $R^2 = 0.82$*
Critical point not found.

(h) Dry mass (g) = 1.1561 + 0.0485xP + 0.0571xN - $0.0001xP^2$ - 3.5222 $x10^6$xPxN - $9.9298x10^{-5}$xN, $R^2 = 0.64$*
Maximum: P: 237.5; N = 283.3
Dry mass: 15 g $pot^{-1}$

(i) Dry mass (g) = 2.229 + 0.0195xP + 0.056xN - $4.2434x10^{-5}xP^2$ + $1.1632x10^{-5}$xP xN - $0.0001xN^2$, $R^2 = 0.83$*
Maximum: P = 270.3; N = 295.7;
Dry mass: 13 g $pot^{-1}$

**Figure 2.** Effects of N rates and P sources and rates on shoot dry mass (DM) of *Megathyrsus maximum* cv. Mombasa. First cut: (a) reactive P from Morocco; (b) reactive Ps from Algeria; (c) TSP. Second cut: (d) reactive P from Morocco; (e) reactive P from Algeria; (f) TSP; third cut: (g) reactive P from Morocco; (h) reactive P from Algeria; (i) TSP. * Significant at $P \leq 0.05$.

(a) (b) (c)

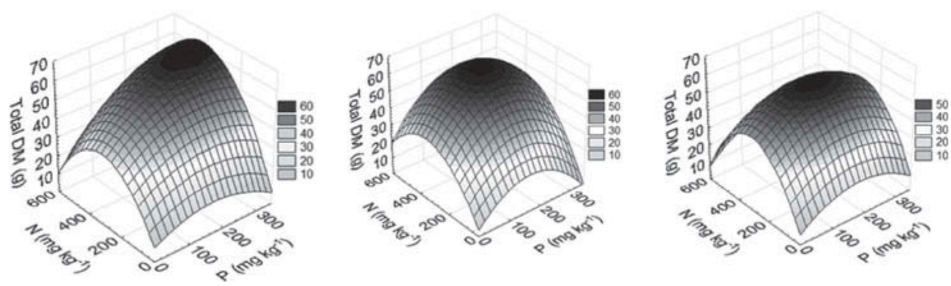



(a) Total tillers (n° $pot^{-1}$) = 18.287 + 0.1409xP + 0.1919xN – 0.0004x$P^2$ + 0.0003xPxN – 0.0004$N^2$, $R^2$ = 0.79*
Maximum: P = 309.6; N = 356.0;
Tillers = 74 n° $pot^{-1}$

(b) Total tillers (n° $pot^{-1}$) = 16.3796 + 0.2587xP + 0.1412xN – 0.0007x$P^2$ + 0.0003xPxN – 0.0002$N^2$, $R^2$ = 0.73*
Maximum: P = 310.30; N = 585.7;
Tillers = 98 n° $pot^{-1}$

(c) Total tillers (n° $pot^{-1}$) = 9.7037 + 0.2329xP + 0.2328xN – 0.0008x$P^2$ + 0.0001xPxN – 0.0004x$N^2$, $R^2$ = 0.77*
Maximum: P = 222.7; N = 318.9;
Tillers = 82 n° $pot^{-1}$

(d) (e) (f)




(d) Dry mass (g) = 7.72 + 0.1113xP + 0.1979xN – 0.0003x$P^2$ + 0.0002xPxN – 0.0003x$N^2$, $R^2$ = 0.88*
Maximum: P = 332.4; N = 440.63;
Dry mass = 70 g $pot^{-1}$

(e) Dry mass (g) = 3.8478 + 0.221xP + 0.1863xN – 0.0007x$P^2$ + 0.0001xPxN – 0.0003x$N^2$, $R^2$ = 0.88*
Maximum: P = 182.2; N: 340.8;
Dry mass = 56 g $pot^{-1}$

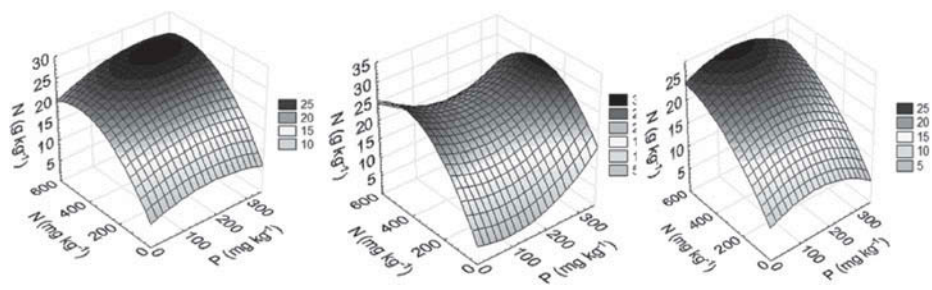
(f) Dry mass (g) = 5.8734 + 0.1513xP + 0.2366xN – 0.0004x$P^2$ + 2.7347x$10^{-5}$xPxN – 0.0004$N^2$, $R^2$ = 0.90*
Maximum: P = 179.2; N = 289.6;
Dry mass = 54 g $pot^{-1}$

**Figure 3.** Effects of N rates and P sources and rates on total numbers tillers and total shoot dry mass (DM) (g $pot^{-1}$) in three growth cycles of *Megathyrsus maximum* cv. Mombasa. (a) reactive P from Morocco; (b) reactive P from Algeria; (c) TSP; (d) reactive P from Morocco; (e) re active P from Algeria; (f) TSP. * Significant at $P \leq 0.05$.

response from Mombasa grass at the N and P concentration in SDM due to fertilization showed the potential of high quality in forage yield.

Addition of RPA revealed the existence of a saddle response of shoot N concentration in the first cut, thus it was not possible to determine the maximum N concentration in the shoot (Figure 4b). The latter result may be associated with a dilution effect due to the increase of the dry mass (Marschner 2012). In the second cut, there was no found the critical point in shoot N concentration because of the N and P fertilization (Figure 4d–f). In the third cut, N shoot concentration was only increased by RPM. Volpe et al. (2008) reported a N concentration of 20 g $kg^{-1}$ in diagnostic leaves of *Megathyrsus maximum* cv. Massai.

(a) (b) (c)




(a) $N\ (g\ kg^{-1}) = 5.7903 + 0.0321xP + 0.0699xN - 8.6074x10^{-5}xP^2 + 2.1933x10^{-5}xPxN - 7.832x10^{-5}xN^2$, $R^2 = 0.98^*$

Maximum: P: 247.7; N = 481.0; N = 27 g kg$^{-1}$

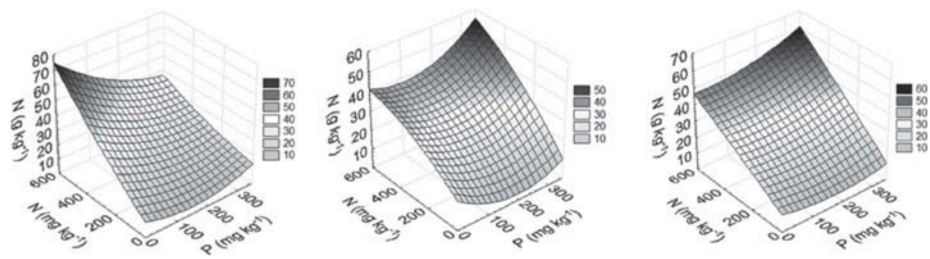
(b) $N\ (g\ kg^{-1}) = 4.9419 - 0.0347xP + 0.1046xN + 0.0002xP^2 - 6.0089x10^{-5}xPxN - 0.0001xN^2$, $R^2 = 0.81^*$

Minimum: P: 158.2; N = 475.5; N = 27 g kg$^{-1}$

(c) $N\ (g\ kg^{-1}) = 7.1992 + 0.0377xP + 0.0487xN - 0.0001xP^2 + 3.8x10^{-6}xPxN - 3.5707x10^{-5}xN^2$, $R^2 = 0.98^*$

Maximum: P = 201.6; N = 692.6; N = 28 g kg$^{-1}$

(d) (e) (f)




(d) $N\ (g\ kg^{-1}) = 10.4647 - 0.0729xP + 0.0905xN + 0.0002xP^2 - 0.0002xPxN + 2.776x10^{-5}xN^2$, $R^2 = 0.88^*$

Critical point not found.

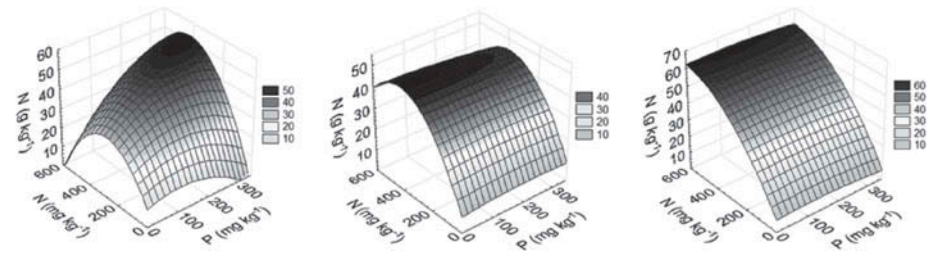
(e) $N\ (g\ kg^{-1}) = 15.0911 - 0.1186xP + 0.0706xN + 0.0003xP^2 + 9.2622x10^{-5}xPxN - 4.5547x10^{-5}xN^2$, $R^2 = 0.74^*$

Critical point not found.

(f) $N\ (g\ kg^{-1}) = 10.5704 - 0.0442xP + 0.0634xN + 0.0001xP^2 + 7.0933x10^{-5}xPxN - 5.6089x10^{-6}xN^2$, $R^2 = 0.91^*$

Critical point not found.

(g) (h) (i)




(g) $N\ (g\ kg^{-1}) = 9.3304 + 0.0618xP + 0.1679xN - 0.0003xP^2 + 0.0003xPxN - 0.0003xN^2$, $R^2 = 0.71^*$

Maximum: P = 323.9; N = 441.8; N = 56 g kg$^{-1}$

(h) $N\ (g\ kg^{-1}) = 7.757 + 0.0129xP + 0.1978xN - 3.1025x10^{-5}xP^2 - 2.8622x10^{-5}xPxN - 0.0002xN^2$, $R^2 = 0.96^*$

Critical point not found.

(i) $N\ (g\ kg^{-1}) = 7.4233 + 0.0093xP + 0.173xN - 4.5556x10^{-5}xP^2 + 4.2667x10^{-6}xPxN - 0.0001N^2$, $R^2 = 0.98^*$

Critical point not found.

**Figure 4.** Effects of N rates and P sources and rates on N concentration on shoot of *Megathyrsus maximum* cv. Mombasa. First cut: (a) reactive P from Morocco; (b) reactive P from Algeria; (c) TSP. Second cut: (d) reactive P from Morocco; (e) reactive P from Algeria; (f) TSP. Third cut: (g) reactive P from Morocco; (h) reactive P from Algeria; (i) TSP. * Significant at $P \leq 0.05$.

Studying the responses of Mombasa grass to N fertilizers, Manarin and Monteiro (2002) found that the N concentration in emerging leaves responded linearly to N applied (0–462 mg $L^{-1}$), and the variation in N concentration was 7.5–23.7 g $kg^{-1}$. In our study, the concentration of N in the SDM was related to the N rate, reaching the maximum concentration level of 56 g $kg^{-1}$ of fertilizer-N added (Figure 4g).

There was a significant interaction ($P \leq 0.01$) between the rate and phosphate sources and N levels on the P concentration in the SDM of Mombasa grass during the first and second cuts (Figure 5a–f). In the third cutting, the effect was according to the N rates (Figure 5g) and P, in the average of the three sources (Figure 5h). There was no difference between P sources, indicating that during Mombasa grass growth, the rock phosphates are important fertilizer sources to increase the forage yield and element concentration with varying effects due to the culture, climate, and soil conditions (Moreira et al. 2010; Oliveira Júnior, Prochnow, and Klepker 2011; Bonfim-Silva et al. 2012).

For the three phosphate sources (TSP, RPA, and RPM), Mombasa grass showed a positive response to the P concentration in the SDM (Figure 5a–h), starting from the P deficiency in grass tissues without fertilization to adequate levels with the application of P and N fertilizers (Reuter and Robinson 1997). These results are important for production, because high P content in the forage is an important source of energy in animal feeding, thus reducing the amount of P supplied in the animal feed supplements, and increasing the resistance of the animals to environmental stress (Bernier et al. 2014).

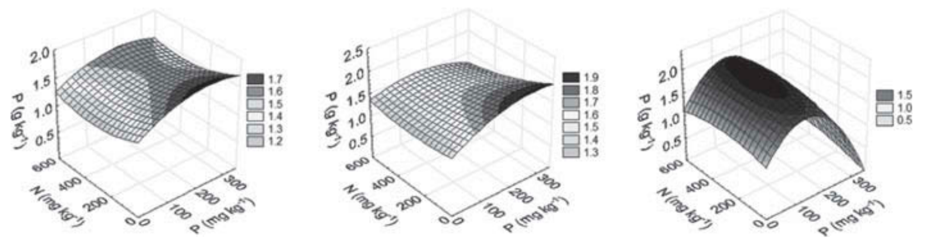
In the first cut, the minimum P concentration in the SDM (1.52 g $kg^{-1}$) was achieved with RPM at a rate of 251 mg $kg^{-1}$ of P and 375 mg $kg^{-1}$ of N (Figure 5a). This value was similar to the maximum concentration value with the TSP, which was 1.94 g $kg^{-1}$ P, however the required fertilizer rate was lower (130 mg $kg^{-1}$ P) due to the higher solubility of TSP (Figure 5c). In the second cut, we observed a smaller P rate to reach the point of maximum P concentration in the SDM with RPM compared to the TSP, a result that may be related to differences in their P rates release and/or the residual effect of the RPM source after the first cut (Figure 5d and f).

Relative to TSP, the reactive phosphate sources RPM and RPA reduced P concentration in the first cut (Figure 5a–c). In successive cuts, however, RPM and RPA presented the same or even exceeded the grass response to TSP. The latter may be due to lower fertilizer-P fixation by clay colloids, the development of a larger root system, an increase in the PUE by grass, or better temporal synchrony between fertilizer-P release and P uptake by the crop (Moreira and Malavolta 2001; Oliveira Júnior, Prochnow, and Klepker 2008; Bonfim-Silva et al. 2012). In the third cut, the highest P concentration in the SDM was observed with the lowest N rate (Figure 5g). Our results are similar to those reported by Batista (2002), who found that the highest P concentration in Marandu grass leaves was in low quantity of N. This result may be related to the effect of P concentration, due to the lower SDM yield (Marschner 2012). Independent of the fertilizer-P source, the concentration of P in the SDM showed a linear relation to P rates, showing the increased P uptake and PUE of natural reactive phosphate in pastures.

## *Uptake of nitrogen and phosphorus in Mombasa grass*

The total amount of N uptake by the Mombasa grass during the three growth cycles was similar for the three P sources. There was also a significant interaction between the average P and N rates applied on the total N uptake by Mombasa grass (Figure 6a), which resulted in an estimated fertilizer-N NUE of 62% by the grass crop. On the other hand, the total amount of P uptake was influenced by P sources: the maximum P uptake achieved with TSP was 83.9 mg/pot > RPM (77.7 mg/pot) > RPA (63.5 mg/pot), for the rates of P 168.8, 349.8, and 229.7 mg $kg^{-1}$, respectively (Figure 6b–d). The estimated efficiency of the accumulated P uptake by Mombasa grass, in the three cuts, was 12% for TSP, 6.9% for RPA, and 5.6% for RPM. The results of P uptake in the tree growth

(a) (b) (c)

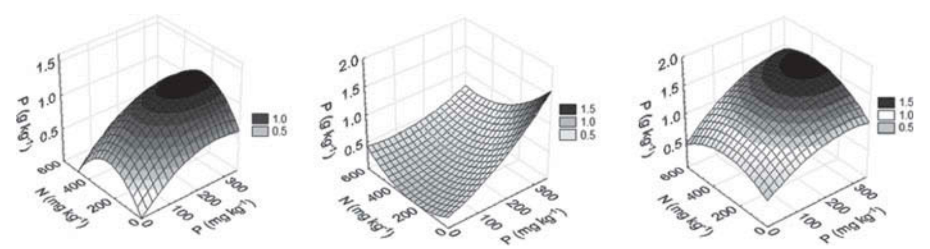



(a) $P\ (g\ kg^{-1}) = 1.37437 + 0.00313xP - 0.0013xN - 5.9866x10^{-6}xP^2 - 2.485x10^{-7} xPxN + 1.8156x10^{-6}xN^2$, $R^2 = 0.95$*
Minimum: P = 251.1; N = 375.3;
P = 1.52 g kg$^{-1}$

(b) $P\ (g\ kg^{-1}) = 1.31704 + 0.00431xP - 0.00057xN - 7.447\ x10^{-6}xP^2 - 3.2791x10^{-6}xPxN + 1.0281\ x10^{-6}xN^2$, $R^2 = 0.83$*
Critical point not found.

(c) $P\ (g\ kg^{-1}) = 1.12416 + 0.00992xP + 0.00095xN - 0.00004xP^2 + 1.555x10^{-6}xPxN - 1.6359x10^{-6} xN^2$, $R^2 = 0.84$*
Maximum: P = 130.8; N = 352.5;
P = 1.94 g kg$^{-1}$

(d) (e) (f)




(d) $P\ (g\ kg^{-1}) = 0.01137 + 0.00474xP + 0.00404xN - 8.8039x10^{-6}xP^2 + 7.7987x10^{-7} xPxN - 8.4217x10^{-6}xN^2$, $R^2 = 0.79$*
Maximum: P = 280.4; N = 252.8;
P = 1.19 g kg$^{-1}$

(e) $P\ (g\ kg^{-1}) = 0.20854 + 0.00216xP - 0.00172xN + 5.1253\ x10^{-6}xP^2 - 5.0083\ x10^{-6} xPxN + 3.4813x10^{-6}xN^2$, $R^2 = 0.81$*
Critical point not found.

(f) $P\ (g\ kg^{-1}) = 0.48439 + 0.00409xP + 0.00199xN - 7.4912x10^{-6}xP^2 + 2.239 x10^{-6}\ xPxN - 3.4445x10^{-6}xN^2$, $R^2 = 0.46$*
Maximum: P = 332.3; N = 396.8;
P = 1.56 g kg$^{-1}$

(g) (h)

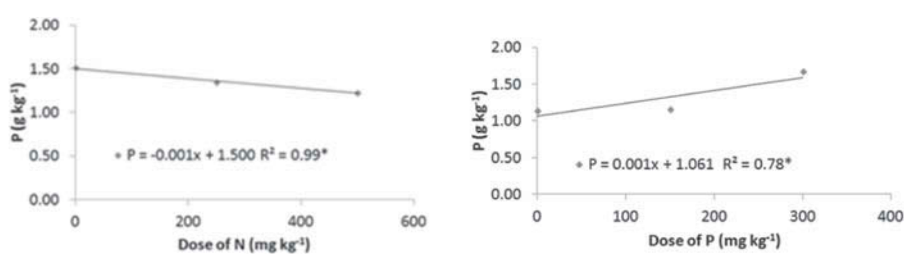
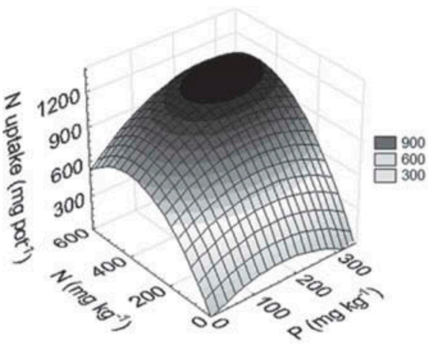



**Figure 5.** Effects of N rates and P sources and rates on P concentration on shoot of *Megathyrsus maximum* cv. Mombasa. First cut: (a) reactive P from Morocco; (b) reactive P from Algeria; (c) TSP. Second cut: (d) reactive P from Morocco; (e) reactive P from Algeria; (f) TSP. Third cut: (g) Average data for three P sources of P concentration and N rates; (h) Average data for three P sources of P concentration and P rates. * Significant at $P \leq 0.05$.

(a)

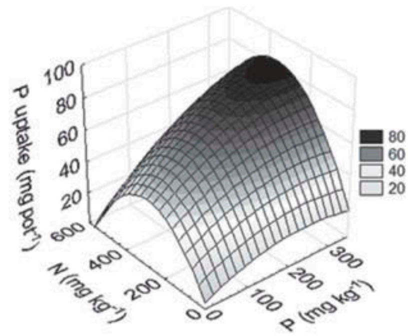



$N\ (mg\ pot^{-1}) = -12.6776 + 2.2746xP + 3.7872xN - 0.007xP^2 + 0.0027xPxN - 0.0048N^2$, $R^2 = 0.94*$

Maximum: P = 252.2; N = 465.4;

N uptake = 1,155.5 mg pot$^{-1}$

(b)



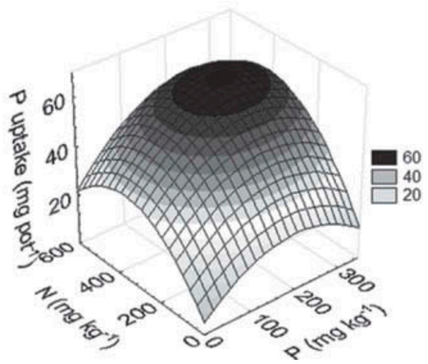

$P\ (mg\ pot^{-1}) = 3.9256 + 0.1397xP + 0.281xN - 0.0003xP^2 + 0.0002xPxN - 0.0005xN^2$,

$R^2 = 0.82*$

Maximum: P = 349.8; N = 350.9;

P uptake: 77.7 mg pot$^{-1}$

(c)

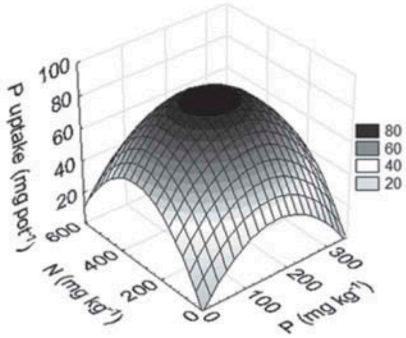



$P\ (mg\ pot^{-1}) = 5.1778 + 0.1874xP + 0.1612xN - 0.0005xP^2 + 9.2718x10^{-5}xPxN - 0.0002xN^2$, $R^2 = 0.80*$

Maximum: P = 229.7; N = 456.2;

P uptake = 63.5 mg pot$^{-1}$

(d)




$P\ (mg\ pot^{-1}) = -1.2971 + 0.4066xP + 0.3194xN - 0.0012xP^2 - 4.7515x10^{-6}xPxN - 0.0005N^2$, $R^2 = 0.87*$

Maximum: P = 168.8; N = 318.6;

P uptake = 83.9 mg pot$^{-1}$

**Figure 6.** Effects of N rates and P sources and rates on total amounts of N and P uptake in three growth cycles of *Megathyrsus maximum* cv. Mombasa. (a) The average of the three sources of P; (b) reactive P from Morocco; (c) reactive P from Algeria; (d) TSP. * Significant at $P \le 0.05$.

cycles of Mombasa grass is consistent with previous publications and demonstrates the potential use of two natural rock phosphates to meet its P nutritional demand.

## Conclusions

Pasture is the main food source for Brazilian livestock. The utilization of forage species with high potential for production associated with balanced fertilization is essential to the technological advancement in the production system. The SDM yield and tillering of Mombasa (*Megathyrsus maximum*) grass were favored with the application of triple superphosphate (TSP), reactive rock phosphate from Morocco (RPM), and reactive rock phosphate from Algeria (RPA) associated with N fertilization. The RPM, RPA, and the TSP met the nutritional demands of Mombasa grass. The reactive phosphates (RPM and RPA) require a higher rate of application compared to the TSP source. Upon the total uptake of nitrogen by Mombasa grass, the three P sources showed the same behavior. The uptake efficiency of P, in decreasing order was TSP > RPA > RPM.

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