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Research Article

Sweet potato crop response to phosphate fertilization[1]

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ABSTRACT

Sweet potato yields in Brazil are well below the crop's potential due to inadequate soil fertility and fertilization management. This study aimed to evaluate the effect of phosphate fertilizer on sweet potato yield and nutrition under field conditions. Five rates of P_2O_5 (0, 100, 200, 400 and 600 kg ha^{-1}) were evaluated in areas of Humic Cambisol, in two cropping seasons. The maximum technical efficiency (38.5 t ha^{-1}) occurred with a rate of 380 kg ha^{-1} of P_2O_5, and the economic optimum rate with 121 kg ha^{-1} of P_2O_5, corresponding to the marketable yield of 33.3 t ha^{-1}. The sweet potato's response to the phosphate fertilizer application in Humic Cambisol decreases or ceases if the available P level is higher than 13 mg dm^{-3}, corresponding to the marketable yield of 37.7 t ha^{-1}. The increase in the P_2O_5 rates in the soil resulted in a negative correlation between P and Fe, P and B, P and Cu, and P and Zn in the shoot, and a negative correlation between P and K in the shoot, storage root and whole plant.

KEYWORDS: *Ipomoea batatas* (L.) Lam., phosphate fertilizer, mineral nutrition.

RESUMO

Resposta da cultura da
batata-doce à fertilização fosfatada

O rendimento da batata-doce no Brasil está bem abaixo do potencial da cultura devido à fertilidade inadequada do solo e manejo inadequado da fertilização. Objetivou-se avaliar o efeito da adubação fosfatada no rendimento e nutrição de batata-doce em condições de campo. Cinco doses de P_2O_5 (0, 100, 200, 400 e 600 kg ha^{-1}) foram avaliadas em áreas de Cambissolo Húmico, em dois anos agrícolas. A máxima eficiência técnica (38,5 t ha^{-1}) foi obtida com a dose de 380 kg ha^{-1} de P_2O_5, e a dose econômica ótima com 121 kg ha^{-1} de P_2O_5, correspondendo ao rendimento comercial de 33,3 t ha^{-1}. A resposta da batata-doce à aplicação de fertilizante fosfatado em Cambissolo Húmico diminui ou cessa se o nível de P disponível for superior a 13 mg dm^{-3}, correspondendo ao rendimento comercial de 37,7 t ha^{-1}. O aumento nas doses de P_2O_5 no solo resultou em correlação negativa entre P e Fe, P e B, P e Cu, e P e Zn na parte aérea, e correlação negativa entre P e K na parte aérea, raiz tuberosa e planta inteira.

PALAVRAS-CHAVE: *Ipomoea batatas* (L.) Lam., fertilizante fosfatado, nutrição mineral.

INTRODUCTION

The high nutritional quality of sweet potato [*Ipomoea batatas* (L.) Lam], due to carbohydrates, vitamins, dietary fiber and essential minerals, contributes to the great popularity of this vegetable among consumers (Liu et al. 2024). Furthermore, the increasing evidence of the health-protective effects of its bioactive constituents has attracted interest from the food industry, consumers and scientists (Laveriano-Santos et al. 2022). Therefore, sweet potato plays an important role in the human diet, being considered the second most produced and consumed staple food in developed and developing countries after potato, when considering roots and storage roots (Neela & Fanta 2019).

Despite the importance of sweet potato for human consumption, in current agricultural systems, the cultivation of this crop is generally carried out in soils with low fertility, especially in soils deficient in phosphorus (Li et al. 2020). That reflects this crop's low yield. Although the average yield of sweet potato worldwide was more than 86 million tons in 2022, the average yield was only 11.9 t ha^{-1} (FAO 2023). According to the same FAO dataset, the average production in Brazil was more than 847 thousand tons in 2022, while the average yield was 14.5 t ha^{-1}. In Brazil, the low agricultural yield of sweet potato is

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due to several factors, such as using obsolete genetic materials, cultivation in low-fertility soils and lack of adequate soil management and fertility, use of production technologies and especially information on organic and mineral fertilizers suitable for the crop (Andrade Júnior et al. 2022).

Most Brazilian regions are deficient in phosphorus (P), which has been the most critical element in fertilization in recent decades (Raij 2011). Furthermore, the efficiency of P applied to the soil through fertilizers is low and varies between 10 and 30 % (Kareem et al. 2020). However, sweet potato efficiently uptakes P, especially from low-fertility soils, as the storage roots are associated with soil mycorrhizal fungi. This association increases the P absorption capacity (Rós et al. 2015). Phosphorus stimulates root development, especially pencil and fibrous roots (Kareem et al. 2019). In soils with low P levels, phosphate fertilization increases the yield, starch and total sugar contents of sweet potato storage roots. In soils with adequate P availability, sweet potato generally has no response to phosphate fertilization (Fernandes et al. 2022).

Thus, increasing sweet potato yield with the efficient use of phosphate fertilizers is essential. Therefore, this study aimed to evaluate the effect of increasing P_2O_5 rates on sweet potato yield and nutrition in experiments under field conditions.

MATERIAL AND METHODS

The study was conducted at the Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina, in Ituporanga, Santa Catarina state, Brazil (27º25'S, 49º30'W and altitude of 475 m), in the 2021/2022 and 2022/2023 cropping seasons. According to the Köppen classification, the region's climate is Cfa (Alvares et al. 2013), with hot summer and without dry season.

The experiment evaluated five P_2O_5 rates (0, 100, 200, 400 and 600 kg ha^{-1}) and was installed in areas of Humic Cambisol (Santos et al. 2013) or Humic Dystrudept (USDA 2022). Figure 1 shows the maximum and minimum temperatures and rainfall during the two crops. Both areas had low P levels (CQFS-RS/SC 2016; Table 1).

Seedlings of the SCS372 Marina cultivar with six buds were planted in ridges made with a tractor in the two cropping seasons. Each experiment used a randomized block design with four replications, and each experimental area was divided into 20 plots, where five P_2O_5 rates (0, 100, 200, 400 and 600 kg ha^{-1}) were applied in each block. The plots comprised 48 plants (Brito et al. 2006) spaced 1.10 m between rows and 0.30 m between plants. In each cropping season, 40 kg ha^{-1} of N and 125 kg ha^{-1} of K_2O were added to the soil (CQFS-RS/SC 2016). The lower the soil fertility, more significant is

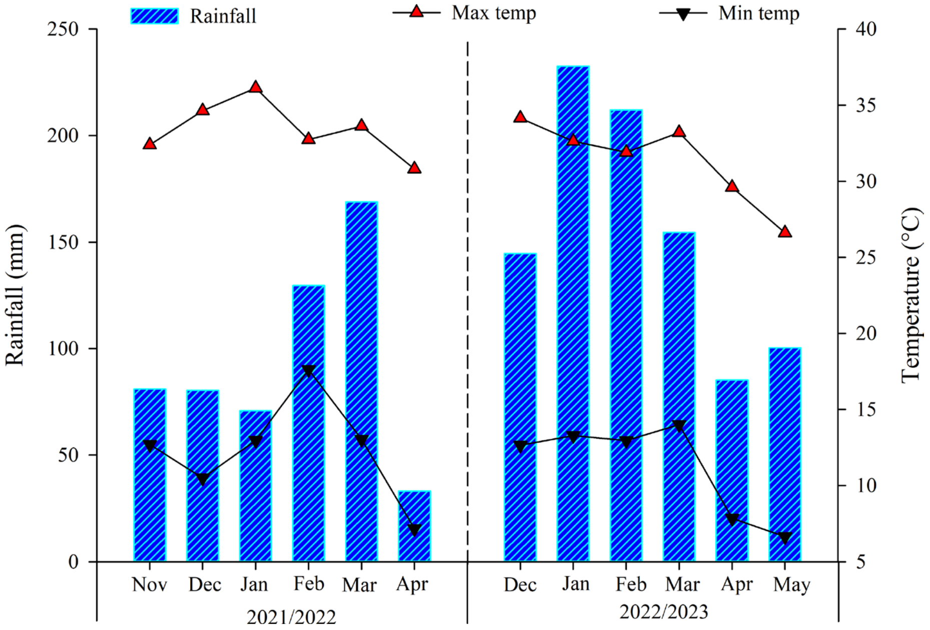

Figure 1. Climate data during the two cropping seasons.

Table 1. Soil analysis before planting the sweet potato seedlings in the 0-0.20 m depth layer.

Soil characteristics	Cropping season	
	2021/2022	2022/2023
Clay (%)	25.40	16.40
Sand (%)	32.80	47.90
Silt (%)	41.80	35.70
pH	6.00	5.40
Available P (mg dm^{-3})*	3.40	5.30
Available K (mg dm^{-3})*	170.30	133.00
Organic matter (g kg^{-1})	40.00	38.00
Potential CEC ($cmol_c$ dm^{-3})	19.97	14.57
Base saturation (%)	79.96	51.26
H + Al ($cmol_c$ dm^{-3})	4.00	7.10
Al^{3+} ($cmol_c$ dm^{-3})	0.00	0.10
Ca^{2+} ($cmol_c$ dm^{-3})	9.60	4.70
Mg^{2+} ($cmol_c$ dm^{-3})	5.90	2.40
S-SO_4^{2-} (mg dm^{-3})	49.00	55.80
B (mg dm^{-3})	0.40	0.20
Cu^{2+} (mg dm^{-3})	0.40	1.00
Fe^{2+} (mg dm^{-3})	129.00	170.00
Mn^{2+} (mg dm^{-3})	1.10	3.50
Zn^{2+} (mg dm^{-3})	1.50	0.90

* Mehlich-1 soil test. CEC: cation exchange capacity.

the contribution of fertilizers to plant nutrition (Malavolta 2006). For this reason, the experiments were carried out with P_2O_5 rates in different areas with low P_2O_5 content.

The P_2O_5 source was simple superphosphate, the N source was ammonium nitrate and the K_2O source was potassium chloride (KCl). Regarding fertilization, only P_2O_5 was applied throughout the planting. The P_2O_5 rates were applied to the total area of each plot after the soil was plowed and harrowed and before making the ridges with the tractor. Nitrogen was split 50 % at planting and 50 % at 30 days after planting (DAP). Potassium oxide (K_2O) was supplied 50 % at planting, and the remaining 50 % were divided into equal parts at 30 and 60 DAP (Brito et al. 2006).

Each year, the experiment was irrigated during the first month of cultivation to ensure seedling survival. Up to 45 DAP, manual weeding was conducted when necessary. No herbicides, insecticides or fungicides were applied in the experiments. The eight plants on the central lines without the border were considered useful areas for evaluating the total and marketable yield in each plot. After harvesting, the total and marketable yield of storage root fresh matter were evaluated at 145 DAP. Soil subsamples were also collected at six points (0-0.20 m) within the useful area to comprise the samples per plot to evaluate soil fertility and determine the soil's phosphorus level (CQFS-RS/SC 2016).

According to regional producers' criteria, marketable storage roots weighed at least 120 g. In each plot, at harvest, the shoot of four plants and two storage roots were collected, washed with deionized water, and dried in an oven with forced air circulation at 65 ºC, until constant weight, to determine the dry matter. Then, the dried tissue samples were taken to the laboratory to determine the N, P, K, Ca, Mg, S, B, Cu, Fe, Zn and Mn contents after dry digestion (Embrapa 2009). After determining the nutrient contents, the nutrients uptake by the shoot, storage root and whole plant (shoot + storage root) were calculated.

The average collected data were subjected to assumption and regression analyses in the R environment (R Core Team 2023). The adjusted second-degree equations were significant ($p < 0.05$).

This study determined the economic optimum rate of P_2O_5 for the marketable yield of sweet potato storage root according to Natale et al. (1996). The equivalence ratio of 4.42 was obtained by the ratio between the values of \$ 2.21 kg^{-1} of P_2O_5 (Conab 2023) and \$ 0.50 kg^{-1} of sweet potato (Ceasa/SC 2024). To calculate the economic rate of P_2O_5, the equivalence ratio was equated with the first derivative of the regression model adjusted for the average marketable yield of sweet potato (two cropping seasons) as a function of the P_2O_5 rates.

RESULTS AND DISCUSSION

The linear increase for P availability depended on the increased rates of P_2O_5 applied to the soil. Figure 2 shows the relationship between the increasing rates of P_2O_5 applied to the soil and the average level of P available in the 0-0.20 m soil layer (two cropping seasons). This linear behavior of P availability in the soil as a function of the application of increasing P_2O_5 rates corroborates the results found in the literature (Oliveira et al. 2005b, Cruz et al. 2016, Cordeiro et al. 2023).

Figure 3 shows the total and marketable yields of sweet potato storage root fresh matter in two cropping seasons as a function of the evaluated P_2O_5 rates. A quadratic increase in yield was observed with the increasing rates of P_2O_5 added. The maximum total yields were 42 t ha^{-1} in 2021/2022 and 47 t ha^{-1} in 2022/2023. Furthermore, the maximum marketable yields were 36 t ha^{-1} in 2021/2022 and 41 t ha^{-1} in 2022/2023. The lower total and marketable yield (Figure 3) in the 2021/2022 crop is probably due to the lower rainfall (Figure 1). Water scarcity in the soil decreases root activity, reducing nutrient uptake (Raij 2011), which may result in lower plant yields. In 2021/2022, the rainfall was 546 mm, while, in 2022/2023, it was 929 mm (Figure 1).

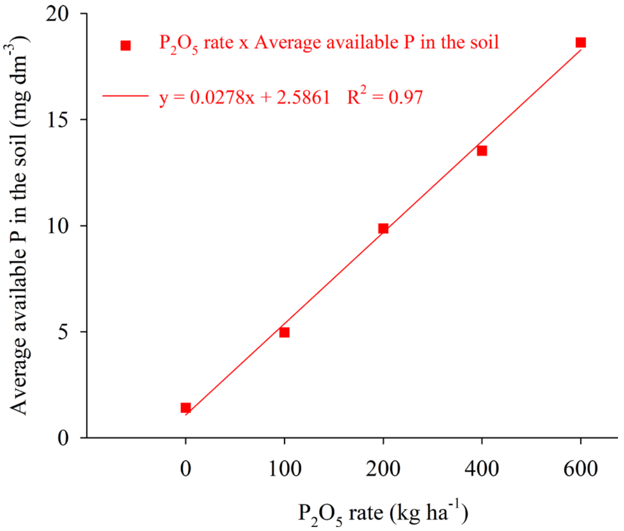

Figure 2. Relationship between P_2O_5 rates and average available P in the soil at the 0-0.20 m depth layer, after harvesting in the two cropping seasons.

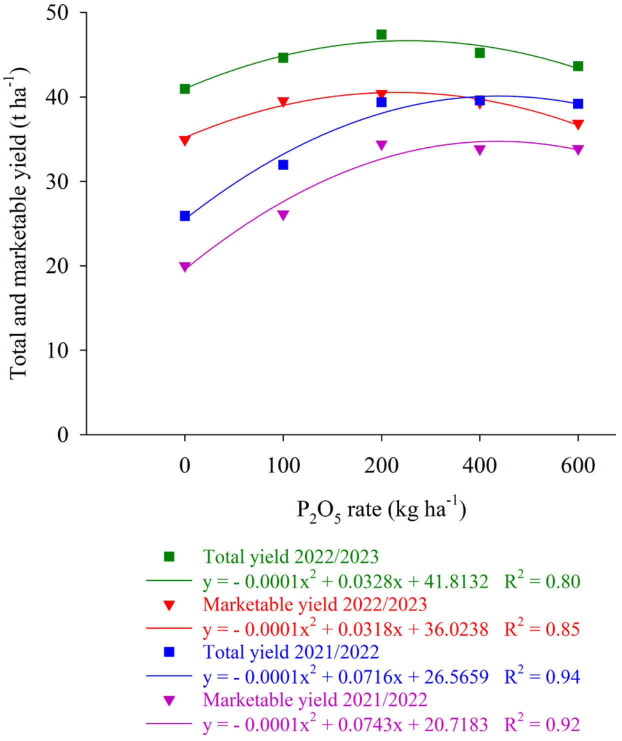

Figure 3. Total and marketable yield of sweet potato storage root fresh matter as a function of P_2O_5 rates, for the two cropping seasons.

Figure 4 shows the relationship between P_2O_5 rates and average marketable yield (Figure 4A), and between average available P in the soil and average marketable yield (Figure 4B).

The maximum average marketable yield or maximum technical efficiency was 38.5 t ha^{-1} (Figure 4A), with a rate of 380 kg ha^{-1} of P_2O_5. According to Figure 2, 380 kg ha^{-1} of P_2O_5 is equivalent to 13.15 mg dm^{-3} of P in the soil. As verified here, this yield is well above the national average of 14.5 t ha^{-1} and higher than the average for the Santa Catarina state, which is 19.2 t ha^{-1} (IBGE 2022). In Entisols, the maximum technical efficiency was 18.9 t ha^{-1}, with a rate of 210 kg ha^{-1} of P_2O_5 (Oliveira et al. 2005b). In Ultisols, the maximum technical efficiency was 16.7 t ha^{-1}, with a rate of 191 kg ha^{-1} of P_2O_5 (Cruz et al. 2016). In sandy loam soil from Ethiopia, the maximum technical efficiency was 30.22 t ha^{-1}, with a rate of 30 kg ha^{-1} of P_2O_5 (Dawit & Habte 2023).

The economic optimum rate in Figure 4A was obtained with a rate of 121 kg ha^{-1} of P_2O_5, corresponding to 34 % of the rate responsible for maximum technical efficiency and to the marketable yield of 33.32 t ha^{-1}. Both the rates of 121 kg ha^{-1} of P_2O_5 (economic optimum rate) and 380 kg ha^{-1} of P_2O_5 (maximum technical efficiency) are above the 100 kg ha^{-1} of P_2O_5 recommended for soils with low P level for sweet potato cultivation (CQFS-RS/SC 2016). Oliveira et al. (2005b) found a rate of 173 kg ha^{-1} of P_2O_5 for economic optimum rate, which is higher than that of the present study. On the other hand, Cruz et al. (2016) found a value lower than ours. Moreover, they found an economic optimum rate of 104 kg ha^{-1} of P_2O_5. These differences in economic optimum rate values found in the literature are probably due to the type of soil, climate conditions, cultivar used and value of the storage root in different consumer markets.

According to the equation in Figure 4B, the maximum technical efficiency yield of the sweet potato storage root (37.7 t ha^{-1}) was reached when the available P level in the soil was 13 mg dm^{-3}. Thus,

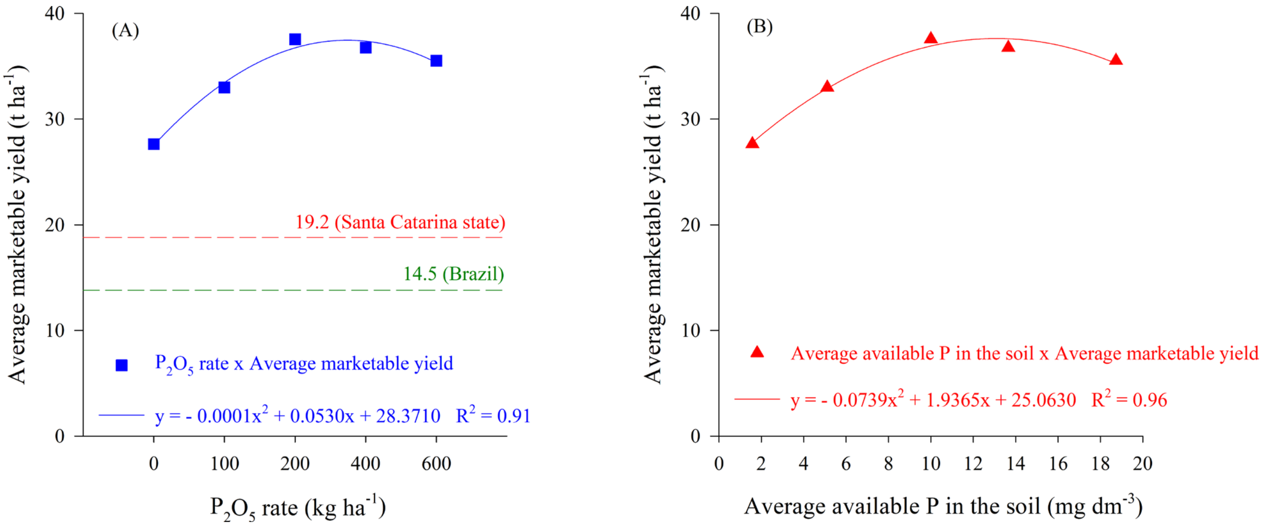

Figure 4. Relationship between P_2O_5 rates (0, 100, 200, 400 and 600 kg ha^{-1}) and average marketable yield of sweet potato for the two cropping seasons (A), and between average available P in the soil and average marketable yield for the two cropping seasons (B). The reference lines comprise the average yield data (IBGE 2022).

for Humic Cambisols, the response of sweet potato yield to phosphate fertilization tends to decrease or be absent if the available P level in the soil is higher than 13 mg dm^{-3}.

According to the equation in Figure 2, 13 mg dm^{-3} of P available in the soil corresponds to the application of 375 kg ha^{-1} of P_2O_5, being very close to 13.15 mg dm^{-3}, which corresponds to the maximum technical efficiency obtained with the rate of 380 kg ha^{-1} of P_2O_5 (Figure 4A). This value of 13 mg dm^{-3} of available P is above the critical level, which is 9 mg dm^{-3} (CQFS-RS/SC 2016). However, if we consider the rate of 121 kg ha^{-1} of P_2O_5 that represents the economic optimum rate (Figure 4A), the P available in the soil corresponds to 5.95 mg dm^{-3} in Figure 2, below the aforementioned critical value. In other words, to achieve the economic optimum rate, the rate of P_2O_5 (121 kg ha^{-1}) and the critical content of P in the soil (5.95 mg dm^{-3}) are lower than the recommended rates and critical levels (CQFS-RS/SC 2016) and lower than those to reach the maximum technical efficiency.

In an Entisol, the economic optimum rate (18.7 t ha^{-1}) was reached when the available P level in the soil was 19 mg dm^{-3} (Oliveira et al. 2005b). In a sandy loam soil, 6.80 mg dm^{-3} of available P was recommended for sweet potato production (Kareem et al. 2020). In Oxysols of sandy texture, when the P level is higher than 20 mg dm^{-3} (resin method), there is no response to phosphate fertilization. However, when the P level is less than 3.7 mg dm^{-3} (resin method), it is recommended that 68 kg ha^{-1} of P_2O_5 be applied to obtain a maximum yield in sweet potato (Cordeiro et al. 2023). According to these authors, increasing the rate of P_2O_5 in soils with a high P availability decreases the starch concentration in the storage root. The opposite occurs in soils with low P availability.

The dry matter accumulation of the shoot, storage root and whole plant (shoot + storage root) were a function of the applied P_2O_5 rates (Figure 5). The maximum dry matter (t ha^{-1}) obtained by the whole plant, storage root and shoot, and the respective rates of P_2O_5 were 15.74 (355 kg ha^{-1}), 12.2 (353 kg ha^{-1}) and 3.54 (365 kg ha^{-1}). The dry matter accumulation showed a quadratic behavior. When evaluating the dry matter accumulation up to 60 DAP for the shoot and storage root, Cruz et al. (2016) also observed a quadratic behavior. The dry matter accumulation in the storage root and the whole plant at the harvest also showed a quadratic behavior with increasing nitrogen rates (Fernandes et al. 2020).

Figure 6 shows the relationships between the P_2O_5 rates and the average levels (both cropping seasons) of macronutrient uptake by the whole plant, storage root and shoot, after the sweet potato harvest. The N uptake (Figure 6A) by the shoot showed a quadratic response depending on the increase in the applied P_2O_5 rates. Therefore, the maximum amount of N uptake by the shoot was 59 kg ha^{-1}.

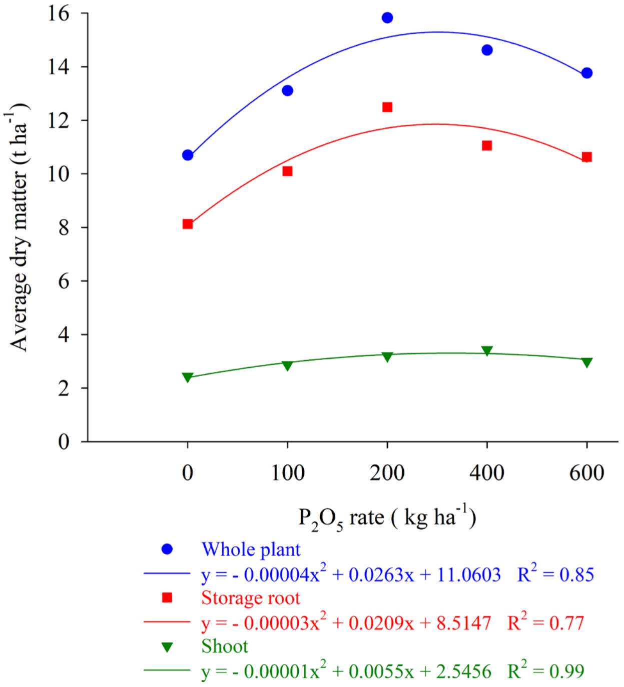

Figure 5. Whole plant, storage root and shoot dry matter accumulation at harvest. Data comprise the means of the two cropping seasons.

Regarding P uptake, there was a quadratic response for the shoot, storage root and whole plant depending on the P_2O_5 rates that were applied. The maximum amounts of P uptake were 11.09 kg ha^{-1} (shoot), 27.62 kg ha^{-1} (storage root) and 38.51 kg ha^{-1} (whole plant). These values are higher and with higher uptake by the storage root than by the shoot, concerning the values of 7.5 kg ha^{-1} (shoot) and 5.3 kg ha^{-1} (storage root) found by Cruz et al. (2016). Echer et al. (2009) also reported a higher P uptake by the shoot (23 kg ha^{-1}), when compared to the storage root (16 kg ha^{-1}). The P values uptake by the whole plant and the storage root in this study are above 10-20 kg ha^{-1} and 8-16 kg ha^{-1}, respectively (Feltran et al. 2022). These differences may have occurred due to the cultivar, soil type, P_2O_5 rates and the phosphate fertilizer source used. Phosphorus influences the formation and accumulation of starch in the storage root, and the maximum starch content was obtained with a rate of 293 kg ha^{-1} of P_2O_5 in an Entisol (Oliveira et al. 2005a).

The application of P influences the production of total carotenoids, and the production of these elements is maximized in the sweet potato storage root with a rate of 174.09 kg ha^{-1} of P_2O_5 (Nascimento et al. 2019). Furthermore, P improves the physical-chemical quality of minimally processed orange sweet potato by protecting against oxidative damage caused by the accumulation of bioactive compounds (Santos-Silva et al. 2023).

The potassium uptake was linearly reduced in the storage root and in the whole plant depending on the P_2O_5 rates applied (Figure 6C). There was a reduction in K uptake of 26.9 g ha^{-1} in the storage root and 36.4 g ha^{-1} in the whole plant for each kg of P_2O_5 applied to the soil. One hypothesis for this reduction is that the source of P used was simple superphosphate, which contains sulfate. Sulfate has a lower adsorption preference in the soil than phosphate. It may have bound to potassium and descended through the soil profile (Furtini Neto et al. 2007), reducing the K uptake by sweet potato as the rates of simple superphosphate applied to the soil increased. The uptakes of Ca (Figure 6D), Mg (Figure 6E) and S (Figure 6F) were not significantly influenced depending on the P_2O_5 rates applied.

Figure 7 shows the relationship between the P_2O_5 rates and the average levels (both cropping seasons) of micronutrient uptake by the whole plant, storage root and shoot, after the sweet potato harvest. The uptake of B (Figure 7A), Cu (Figure 7B) and Zn (Figure 7E) were not significantly influenced depending on the P_2O_5 rates applied. The iron uptake by the storage root (Figure 7C) showed a quadratic response as a function of the P_2O_5 rates. Therefore, the maximum Fe uptake was 630.98 g ha^{-1}. The manganese uptake was linear for the whole plant and the shoot as a function of increasing P_2O_5 rates (Figure 7D). For each kg of P_2O_5 applied to the soil, the Mn uptake increased by 28.5 mg ha^{-1} (whole plant) and 21.6 mg ha^{-1} (shoot). The maximum Mn uptake in the storage root was 37.52 g ha^{-1} (Figure 7D).

Figure 8 shows the Pearson's correlation among nutrient uptake by the shoot (Figure 8A), storage root (Figure 8B) and whole plant (Figure 8C). Generally, the shoot had more negative correlations between nutrients (Figure 8A), while the storage root had more positive correlations (Figure 8B). Figure 6 shows the negative correlations between P and K (Figures 8B and 8C). However, the shoot also negatively correlated with these two nutrients (Figure 8A). The negative correlation between Ca and K in the shoot, storage root and whole plant is a competitive inhibition between these nutrients (Faquin 2005). This negative correlation

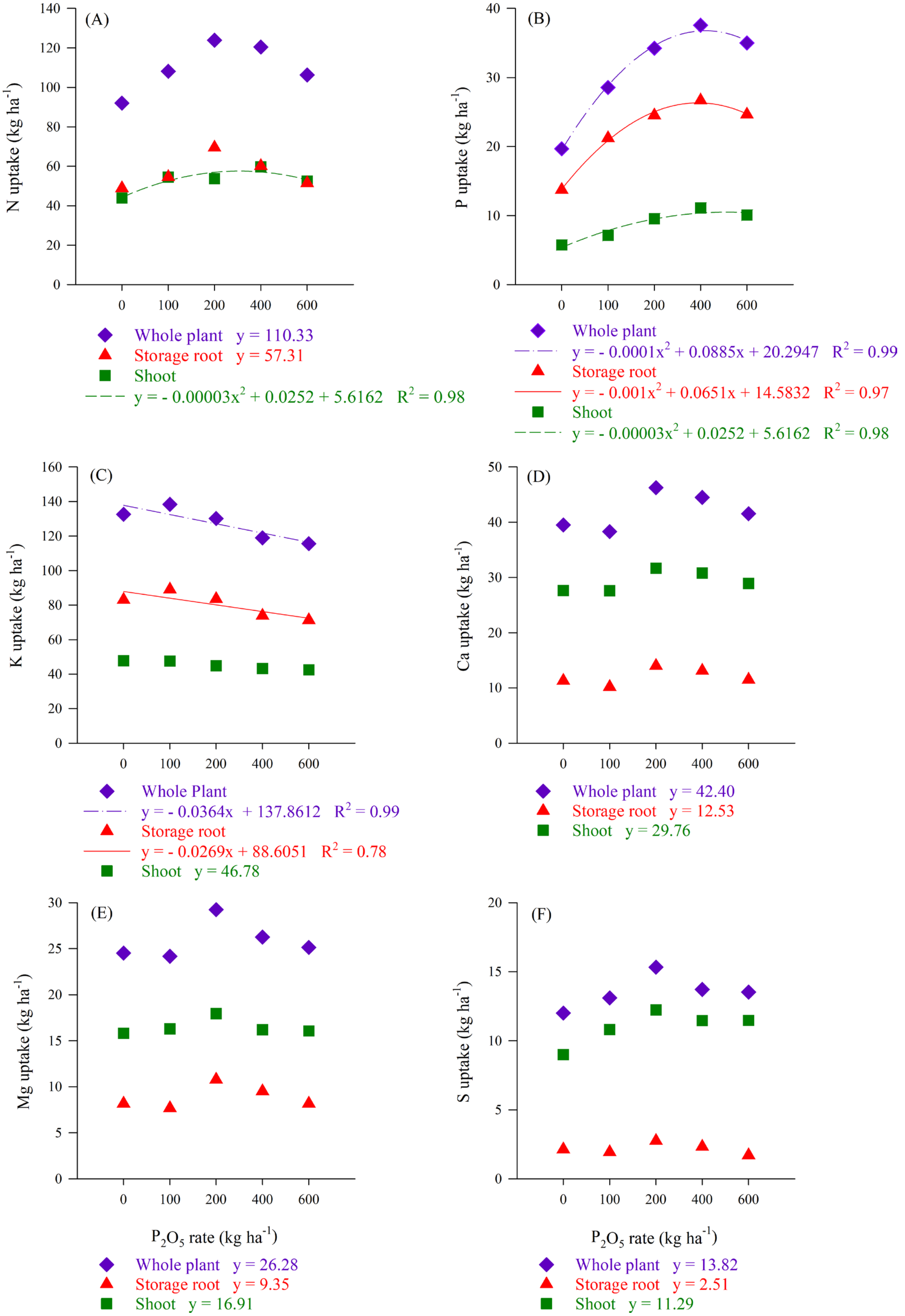

Figure 6. Relationship between P_2O_5 rates (0, 100, 200, 400 and 600 kg ha^{-1}) and average uptake nutrients (two cropping seasons) by whole plant, storage root and shoot.

may have occurred with the increase in the simple superphosphate rates applied to the soil, as this fertilizer contains Ca. Figure 7D shows the positive correlations between P and Mn (Figures 8A and 8C). The negative correlations between P and Fe, P and Cu, and P and Zn (Figure 8A) are likely due to noncompetitive inhibition and a positive correlation between P and Ca, and P and Mg (Figures 8A, 8B and 8C). They may be due to the synergism between these nutrients (Malavolta 2006).

In addition to the interaction between nutrients, other factors influence the uptake of nutrients by

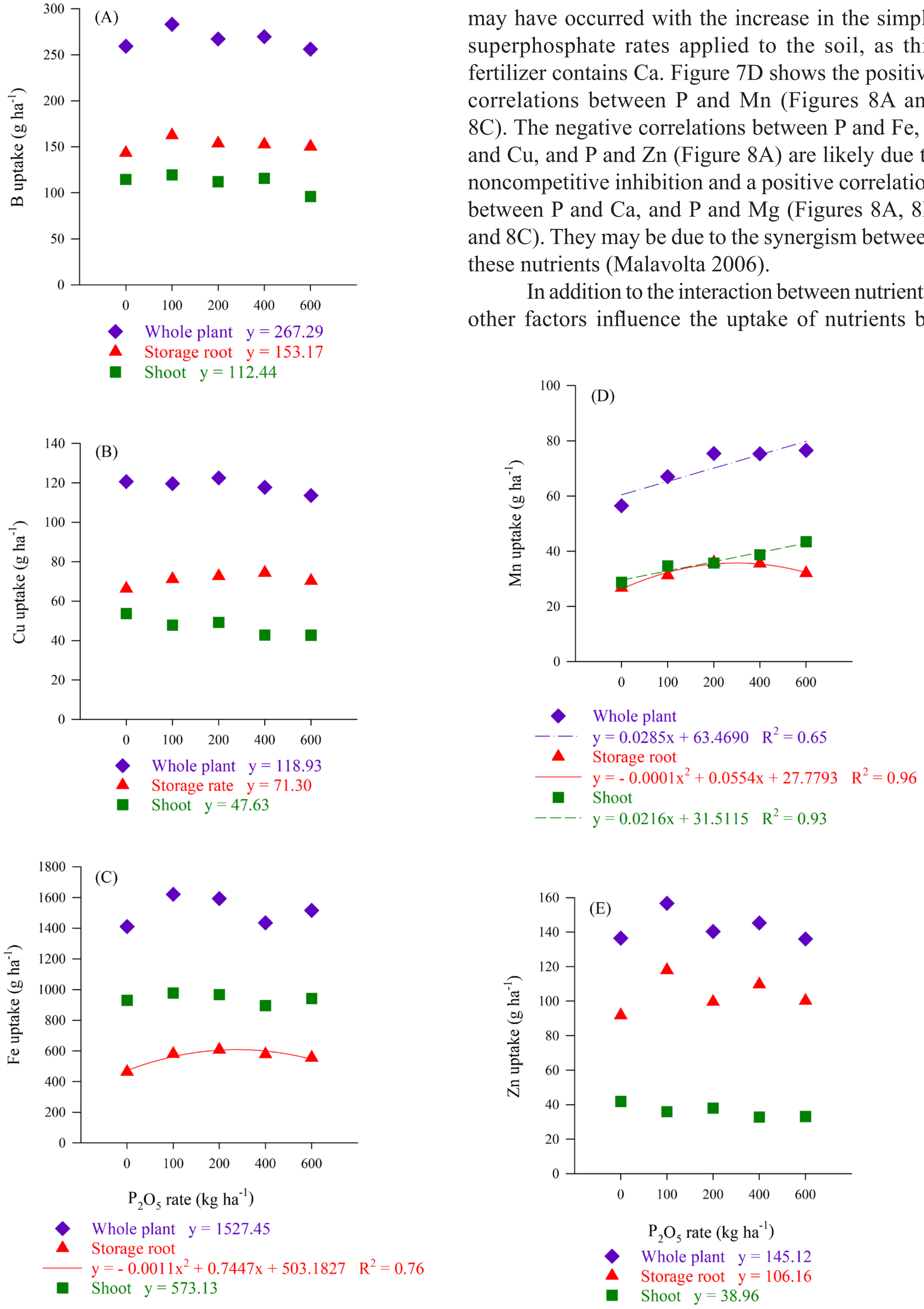

Figure 7. Relationship between P_2O_5 rates (0, 100, 200, 400 and 600 kg ha^{-1}) and average uptake nutrients (two cropping seasons) by whole plant, storage root and shoot.

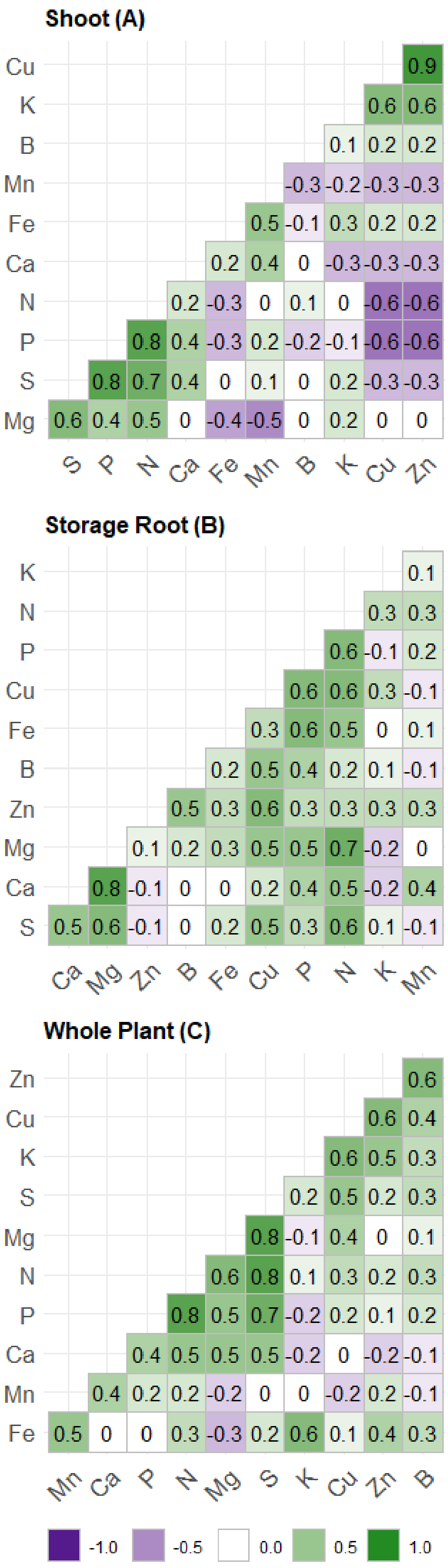

Figure 8. Pearson's correlation between average uptake nutrients (two cropping seasons) for shoot (A), storage root (B) and whole plant (C).

the root (Prado 2020): nutrient availability, soil pH, soil aeration, environmental temperature, soil humidity, uptake speed of each element, occurrence of arbuscular mycorrhizal fungi, plant's genetic potential, internal ionic state, metabolic intensity, transpiration and growth intensity, and root morphology. Sweet potato is efficient in nutrient uptake due to its branched root system (Oliveira et al. 2005b, Mota et al. 2016). However, nutrient supply directly affects sweet potato root differentiation, especially in the early stages of development (Li et al. 2020).

CONCLUSIONS

1. The maximum technical efficiency (38.5 t ha^{-1}), regarding the average marketable yield of two harvests of sweet potato, was obtained at 380 kg ha^{-1} of P_2O_5;
2. The economic optimum rate, regarding the average marketable yield of two harvests (33.3 t ha^{-1}), was obtained at 121 kg ha^{-1} of P_2O_5;
3. The sweet potato's response to phosphate fertilization in Humic Cambisols tends to decrease or be absent if the available P level is higher than 13 mg dm^{-3}, corresponding to the marketable yield of 37.7 t ha^{-1};
4. The increase in the P_2O_5 rates in the soil resulted in a negative correlation between P and Fe, P and B, P and Cu, and P and Zn in the shoot, and a negative correlation between P and K in the shoot, storage root and whole plant.

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