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PHOSPHORUS FERTILIZATION AND SOIL TEXTURE AFFECT POTATO YIELD¹

JÉSSYCA DELLINHARES LOPES MARTINS^{2*}, ROGÉRIO PERES SORATTO³, ADALTON MAZETTI FERNANDES⁴, PEDRO HENRIQUE MARTINS DIAS²

ABSTRACT - Potato (*Solanum tuberosum* L.) is a nutritionally demanding crop, and phosphorus (P) is a nutrient that exerts a large effect on tuber yield. However, as the availability of P is influenced by soil texture, there are doubts about how P supplementation affects the growth and yield of potato plants in different soil textures. Thus, here we aimed to evaluate the effect of P fertilization and soil texture on the nutrition, growth, tuber yield, and P use efficiency (PUE) of potato plants. The experiment was conducted under greenhouse conditions in a randomized block design with a 4×2 factorial scheme and five replications. The treatments were represented by four P rates (10, 50, 100, and 200 mg dm⁻³ P) and two soil textures (clayey and sandy). The concentrations of P, Ca, and Mg in the leaves were higher in sandy soil, and P rates increased the concentrations of N, P, and Ca in the leaves of potato plants. Phosphorus fertilization increased plant growth, the amount of P accumulated in the shoot, and tuber yield in both soils; this trend was stronger in the potato cultivated in the clayey soil than in the sandy soil. The applied-PUE was not affected by soil texture. In the potato cultivated in the sandy soil, the taken up-PUE was reduced due to the decrease in dry matter production and an increase in P concentration in the organs of the plant with higher P fertilizer rates.

Keywords: *Solanum tuberosum*. Sandy soil. Clayey soil. Dry matter. Phosphorus accumulation.

ADUBAÇÃO FOSFATADA E TEXTURA DO SOLO INFLUENCIAM NA PRODUTIVIDADE DA BATATA

RESUMO - A batata (*Solanum tuberosum* L.) é uma cultura nutricionalmente exigente e o fósforo (P) é um dos nutrientes que exerce grande efeito sobre a produtividade de tubérculos. Porém, como a disponibilidade de P é influenciada pela textura do solo, existem dúvidas de como o fornecimento de P afeta o crescimento e a produtividade das plantas de batata em solos de texturas diferentes. Assim, objetivou-se com esta pesquisa avaliar o efeito da adubação fosfatada e da textura do solo na nutrição, crescimento, produtividade e eficiência de uso (EU) do P das plantas de batata. O experimento foi conduzido em casa de vegetação no delineamento de blocos casualizados em esquema fatorial 4×2, com cinco repetições. Os tratamentos foram representados por quatro doses de P (10, 50, 100 e 200 mg dm⁻³ P) e duas texturas de solo (argiloso e arenoso). Os teores foliares de P, Ca e Mg foram maiores no solo arenoso e as doses de P aumentaram os teores de N, P e Ca nas folhas. A adubação fosfatada aumentou o crescimento das plantas, a quantidade de P acumulada na parte aérea e a produtividade de tubérculos em ambos os solos, porém, de forma mais expressiva e até maiores doses na batata cultivada no solo argiloso. A EU do P aplicado não foi afetada pela textura do solo. Na batata cultivada no solo arenoso, a EU do P absorvido foi reduzida em função da diminuição na produção de MS e aumento nos teores de P nos órgãos da planta com fornecimento de altas doses de P.

Palavras-chave: *Solanum tuberosum*. Solo arenoso. Solo argiloso. Matéria seca. Acúmulo de fósforo.

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INTRODUCTION

Potato (*Solanum tuberosum* L.) is a crop that has high production efficiency in a relatively short cycle, thus presenting high nutrient demand (FERNANDES; SORATTO; PILON, 2015). This demand varies, in addition to other factors, depending on the nutrient dynamics in the soil and the nutrient uptake capacity in the soil by the crop. For potato crops, phosphorus (P) is not the most taken up nutrient (FERNANDES; SORATTO; SILVA, 2011), but phosphate fertilizers have been used at high rates because the plant is considered inefficient in P uptake, especially in soils deficient in this nutrient (DECHASSA et al., 2003). However, P is essential for potato development, being intensely translocated to the tubers during the tuber bulking, where the amounts of P directed to the tubers are similar to those taken up (FERNANDES; SORATTO; SILVA, 2011). Thus, P deficiency can significantly reduce the yield and size of tubers formed (FERNANDES; SORATTO, 2016; HOPKINS et al., 2010). Therefore, the management of phosphorus fertilization must be performed to maintain sufficient P availability in the soil to meet the nutritional needs of the crop.

The adequate P availability in the soil also depends on factors related to soil texture. Most Brazilian soils are deficient in P, due to their source material and the strong interaction of P with soil (RAIJ, 1991). Under these conditions the availability of P applied to the soil is generally limited, because these soils are rich in iron and aluminum oxides and because P applied to the soil undergoes precipitation, adsorption, and diffusion reactions, which limit the P availability for plants (ALMEIDA; TORRENT; BARRON, 2003). Soil texture directly influences P availability in soil (MACHADO; SOUZA, 2012). Sandy textured soils are more fragile and loose, which facilitates the growth of the tubers, while the clayey soils are less fragile and present high capacity of P adsorption, which has a positive correlation with the clay content (FALCÃO; SILVA, 2004). Thus, in clayey soils, P adsorption is higher, whereas, in sandy soils, the available P concentrations remain higher after the application of the P fertilization (MACHADO et al., 2011).

Thus, considering that little is known about the differences in the response of potato to P fertilization in clayey and sandy soils, to meet the P demand of the plant without exceeding its nutritional needs, it is necessary to optimize the P fertilization in this crop. The objective of this research was to evaluate the effect of P fertilization and soil texture on the nutrition, growth, tuber yield, and P use efficiency of the potato crop.

MATERIAL AND METHODS

The experiment was conducted in a greenhouse from February to July 2015, at the São Paulo State University in Botucatu, São Paulo, Brazil, in a randomized block design with a 4×2 factorial scheme and five replications. The treatments consisted of four P rates (10, 50, 100, and 200 mg dm⁻³) applied to two soils of different texture (clayey and sandy). Each pot containing 35 L of soil with a single plant represented one experimental unit. During the experiment, the maximum and minimum temperatures and the photoperiod in the greenhouse were maintained at 27°C, 14°C, and 12 h, respectively.

Both soils of the experiment were classified as Oxisol (SANTOS et al., 2006). Before the installation of the experiment, a sample of each soil was collected separately and analyzed for the chemical and granulometric characteristics (RAIJ et al., 2001) (Table 1).

Because the clayey soil showed high acidity and low base saturation, we applied dolomitic limestone (PRNT = 96%) to increase its base saturation to 60% (LORENZI et al., 1997), and, then, the moist soil (80% water retention capacity) was incubated for 30 days.

In both soils, planting fertilization was carried out with 30 mg dm⁻³ N, 150 mg dm⁻³ K, and prescribed P rates for each treatment. We used the fertilizers ammonium sulfate (20% N), potassium chloride (60% K₂O), and triple superphosphate (46% P₂O₅) as sources of N, P, and K, respectively. Micronutrient fertilization was carried out with 5 mg dm⁻³ Zn, 1 mg dm⁻³ B, 0.4 mg dm⁻³ Cu, 1.7 mg dm⁻³ Fe, 1.1 mg dm⁻³ Mn, and 0.06 mg dm⁻³ Mo. As a source of micronutrient fertilizer, we used fritted trace elements. The potatoes were planted during March 2015, putting in each pot a seed tuber, type III, cv. Agata, to a depth of 12 cm and covered with soil.

During the course of the experiment, we performed all cultural practices recommended for potato crop, including irrigation. At 8 days after emergence (DAE), the stems were cut leaving only two stems, of medium height, per plant. N sidedressing fertilization was performed by applying 80 mg dm⁻³ N (urea) in a split application, with the first application at 10 DAE, followed by the hilling operation. The hilling was performed by adding a 3 L portion of soil from each treatment with P, around the base of the plant. The second N sidedressing application was performed at 40 DAE.

At 30 DAE, the third expanded leaf from the plant apex (diagnostic leaf) was collected in each experimental unit (LORENZI et al., 1997) and the sampled material was oven dried, ground, and used for the determination of N, P, K, Ca, Mg, S, and Zn (MALAVOLTA; VITTI; OLIVEIRA, 1997).

Table 1. Chemical and granulometric characteristics of the soils used in the experiment.

Characteristics	Soil	
	Clayey	Sandy
pH (CaCl ₂)	4.1	5.4
OM (g dm ⁻³)	21	7
P (resin) (mg dm ⁻³)	3	8
S (mg dm ⁻³)	38	3
Al (mmol _c dm ⁻³)	10	0
H+Al (mmol _c dm ⁻³)	73	14
K (mmol _c dm ⁻³)	0.5	0.8
Ca (mmol _c dm ⁻³)	6	13
Mg (mmol _c dm ⁻³)	3	6
SB (mmol _c dm ⁻³)	9	20
CEC (mmol _c dm ⁻³)	82	33
BS (%)	11	59
B (mg dm ⁻³)	0.07	0.09
Fe (mg dm ⁻³)	17	13
Cu (mg dm ⁻³)	11.1	0.5
Mn (mg dm ⁻³)	2.4	13.9
Zn (mg dm ⁻³)	0.4	0.8
Sand (g kg ⁻¹)	174	874
Silt (g kg ⁻¹)	226	22
Clay (g kg ⁻¹)	600	102

The final potato harvest occurred at 70 DAE. At this time, the plants were collected, and the number of leaves was evaluated by counting, and the leaf area was estimated using a leaf area meter (Li-Cor, model LI-3100C). Then, the plants were separated into the shoot (leaf, stem, and stolon), roots, and tuber parts. Fresh tubers were weighed to determine total tuber yield per plant. Using the tuber yield data, the applied P use efficiency was calculated (applied-PUE) according to Fernandes and Soratto (2016) and the taken up P use efficiency (taken up-PUE) was calculated according to Fageria, Baligar and Jones (1997):

Applied-PUE (g mg⁻¹) = [tuber yield in the treatment – tuber yield in the control (g plant⁻¹)] / amount of P applied (mg dm⁻³)

Taken up-PUE (g mg⁻¹) = whole plant dry matter accumulation (g) / whole plant P accumulation (mg)

The samples of shoot, roots, and tubers were left to dry in air circulation at 65°C for 72 h and weighed for determination of dry matter accumulation (DM). Whole plant DM was calculated by the sum of the values obtained in the shoot, roots, and tubers. These same samples were milled in a Wiley type mill with a 1-mm sieve and submitted to P concentration analysis (MALAVOLTA; VITTI; OLIVEIRA, 1997). Phosphorus accumulations were obtained by multiplying the P concentration by DM accumulated in each plant organ.

The data were submitted to analysis of variance. The values for soil texture were compared by the LSD test ($p \leq 0.05$), while the effects of P rates were evaluated by regression analysis.

RESULTS AND DISCUSSION

The leaf concentration of K and Zn were not influenced by the factors studied and were, on average, 59.8 g kg⁻¹ and 25.4 mg kg⁻¹, respectively (Table 2). These results demonstrate that the potato plants were not deficient in these nutrients since the concentration obtained were within the range described as suitable for the crop (40 to 65 g kg⁻¹ K and 20 to 60 mg kg⁻¹ Zn) (LORENZI et al., 1997).

The P rates influenced, separately, only the N concentration in leaves, providing increased concentration until the estimated rate of 121 mg dm⁻³ P (Table 2). This increase in leaf N concentration occurred because the P fertilization increases the N concentration in the potato leaves (MAIER et al., 2002) and the amounts of N taken up by the plants (MUNDA et al., 2015; SORATTO; FERNANDES, 2016), due to the fact of P interacts with N uptake (FAGERIA, 2001). At the lower P rates, the N concentration in leaves was deficient, but at the higher P rates, they were within the range considered adequate by Lorenzi et al. (1997) (40-50 g kg⁻¹ N), indicating that P fertilization also improved the N nutrition of the potato plants (Table 2).

Table 2. Nutrient concentration in diagnostic leaf of the potato crop in response to soil texture and P rates.

Analyzed variables	Soil texture		P rate (mg dm ⁻³)				Effect	ST×P
	Clayey	Sandy	10	50	100	200		
N (g kg ⁻¹)	40.5 a	42.0 a	38.5	42.4	43.1	41.0	Q ⁽¹⁾	ns
P (g kg ⁻¹)	2.2 b	2.7 a	1.8	2.4	2.5	3.1	L ⁽²⁾	*
K (g kg ⁻¹)	58.6 a	61.0 a	59.4	60.7	61.1	57.9	ns	ns
Ca (g kg ⁻¹)	7.2 b	9.5 a	7.1	8.0	9.3	9.1	Q ⁽³⁾	*
Mg (g kg ⁻¹)	4.3 b	7.7 a	4.1	4.6	4.6	4.8	ns	ns
S (g kg ⁻¹)	0.95 a	0.93 a	0.99	0.91	0.84	1.02	ns	**
Zn (mg kg ⁻¹)	25.5 a	25.2 a	24.1	25.2	26.1	26.0	ns	ns

Values followed by same letter within a row for the soil texture are not significantly different by LSD test at 5% probability. Q: quadratic equation. L: linear equation. ST×P: soil texture × P rate interaction.

⁽¹⁾ $y = 37.91 + 0.097**x - 0.0004**x^2$ $R^2 = 0.94$; ⁽²⁾ $y = 1.89 + 0.0061**x$ $R^2 = 0.93$; ⁽³⁾ $y = 6.64 + 0.0378**x - 0.0001**x^2$ $R^2 = 0.98$. ns is not significant. * and ** are significant at 5 and 1% probability by t test, respectively.

The leaf Mg concentration was influenced only by soil texture, and the highest Mg concentrations occurred in the leaves of plants grown in sandy soil (Table 2), which is probably due to the higher Mg concentration in this soil (Table 1). However, in both soils, the Mg concentration in the plant's leaves was within or above of the range considered as suitable for the crop (3-5 g kg⁻¹ Mg) (LORENZI et al., 1997).

The concentrations of P, Ca, and S in the potato leaves were influenced by soil texture × P rate interaction (ST×P) (Table 2). Phosphorus fertilization linearly increased the leaf P concentration in the sandy soil, but in the clayey soil, the increases in leaf P concentration occurred only up to the estimated rate of 151 mg dm⁻³ P (Figure 1a). Luz et al. (2013) observed a reduction in leaf P concentration in the potato cultivated in clayey soil, with an increase in P supply, although the P availability in the soil increased. In the lower and higher P rates, the P concentration in the leaves of the potatoes cultivated in the sandy soil was higher than in the potatoes cultivated in the clayey soil, possibly due to relatively higher increase in P availability in the sandy soil compared to the clayey soil. Machado et al. (2011) observed that in sandy soil, the application of P rates linearly increased the P availability in the soil when compared to clayey soils. Thus, because P is more available in the sandy soil, where P adsorption by soil colloids is lower, the potato plants probably taken up more P from this soil, resulting in higher leaf P concentration than those of clayey soils (Figure 1a). However, only at rates above 100 mg dm⁻³ P in the sandy soil, the leaf P concentration was within the range described as suitable for potato, which is 2.5 to 5.0 g kg⁻¹

(LORENZI et al., 1997).

In the clayey soil, the Ca concentration linearly increased with P application, whereas in the sandy soil they increased up to the estimated rate of 142 mg dm⁻³ P (Figure 1b). At lower P rates, the leaf Ca concentration did not differ among soils of different textures, whereas in the other P rates, Ca concentration in the leaves of plants cultivated in the sandy soil was higher than in the leaves of the plants cultivated in the clayey soil. However, only at the highest P rates in the sandy soil, the Ca concentration reached the range considered adequate (10-20 g kg⁻¹) for the crop by Lorenzi et al. (1997), although there were no symptoms of plant deficiency or a sign of deficiency of this nutrient in tuber yield, as observed by Pulz et al. (2008).

The leaf S concentration was not influenced by P fertilization in the clayey soil, with a mean value of 0.95 g kg⁻¹; however, in the sandy soil, this value decreased to 133 mg dm⁻³ P and increased at higher P rates (Figure 1c). A study carried out in nutrient solution showed that higher P rates could decrease the S concentrations in the shoot of the potato (FERNANDES; SORATTO, 2012), which agrees, in part, with the results obtained in the sandy soil, where the initial P availability in the soil was already greater. At the lower P rate, the leaf S concentration in the sandy soil was higher than in the clayey soil. However, at the rate of 100 mg dm⁻³ P, the opposite occurred. At the other tested P rates, the leaf S concentration did not differ between the two soil types. Regardless of soil texture and phosphorus fertilization, the S concentration was below the range considered adequate for the crop (2.5-5.0 g kg⁻¹) (LORENZI et al., 1997); however, no symptoms of S deficiency were observed in plants.

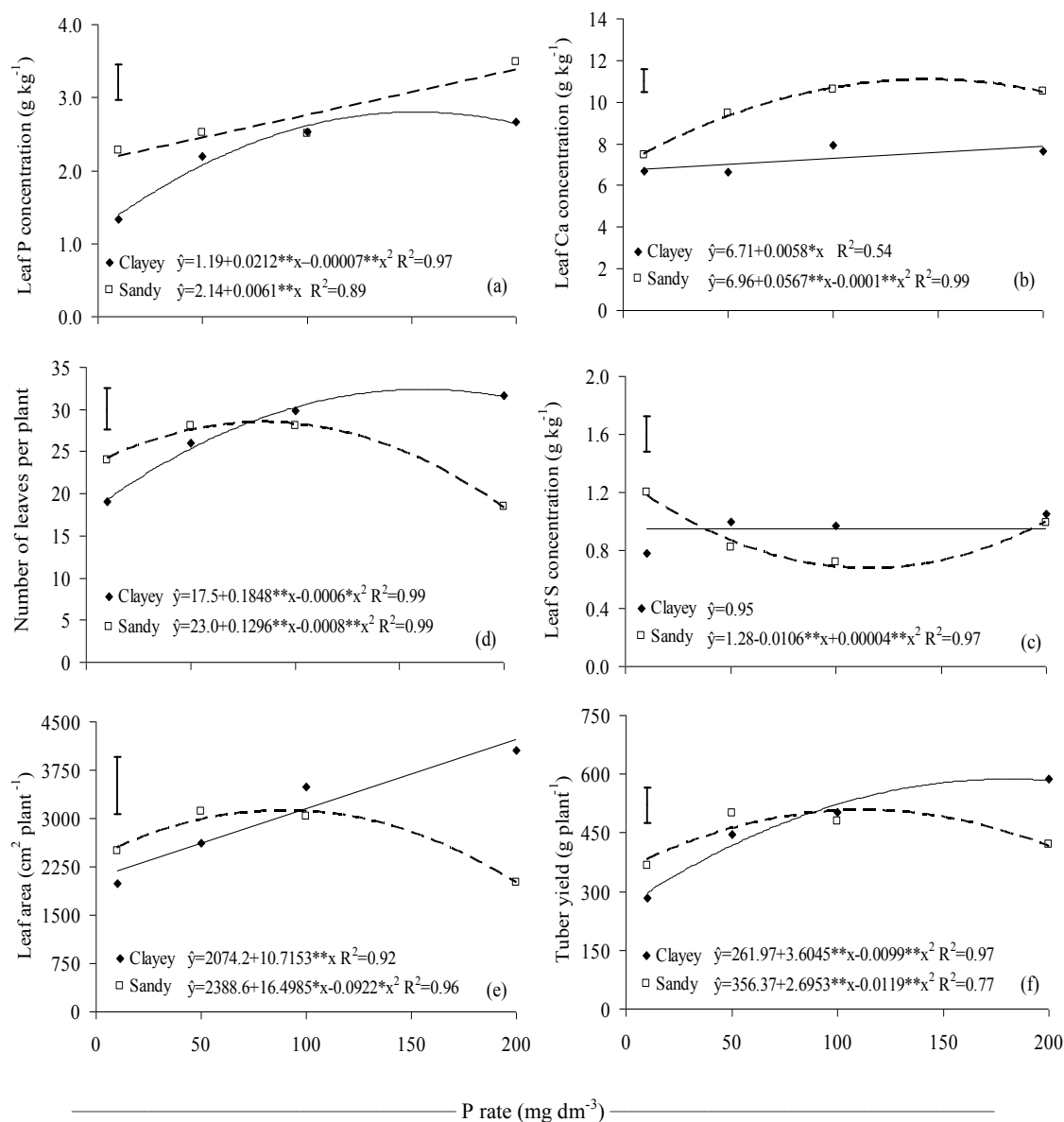


Figure 1. Concentrations of P (a), Ca (b), and S (c) in diagnostic leaf, the number of leaves per plant (d), leaf area (e), and tuber yield (f) of the potato crop in response to soil texture and P rates. * $p \leq 0.05$ and ** $p \leq 0.01$. Vertical bars represent the least significant difference by LSD test ($p \leq 0.05$).

The number of leaves per plant and leaf area of the potato were influenced by the ST×P interaction (Table 3). Phosphorus fertilization increased the number of leaves per plant until 81 and 154 mg dm⁻³ P in sandy and clayey soils, respectively (Figure 1d). At the rate of 10 mg dm⁻³ P, the plants of the clayey soil presented fewer leaves. Because in clayey soil the increase in the number of leaves occurred until higher P rates, the plants presented more leaves per plant than in the sandy soil in the rates above 100 mg dm⁻³ P. Phosphorus fertilization linearly increased the leaf area of the potato plants in the clayey soil, but in the sandy soil the leaf area increased only up to the 89 mg dm⁻³ P, because the number of leaves emitted per plant decreased in rates higher than 81 mg dm⁻³ P (Figures 1d and 1e). Likewise, P application has been shown to linearly increase the leaf area of the coffee tree in

clayey soil and in a quadratic form in the sandy soil (JESUS SOUZA et al., 2014). At rates lower than 100 mg dm⁻³ P, the leaf area of the potato plants did not differ between the two studied soils, demonstrating that, in the clayey soil, greater leaf development only occurs when the P supply is high (Figure 1e). The increase in potato leaf area, regardless of soil texture, was expected because phosphorus fertilization may increase stem length, leaf number, and leaf area of potato (FLEISHER et al., 2013; SUN; CUI; LIU, 2015) and, consequently, the plant biomass production and tuber yield (FERNANDES; SORATTO, 2016).

Tuber yield was influenced by the ST×P interaction, but applied-PUE was affected only by P rates (Table 3). In both soils, the tuber yield increased in a quadratic manner up to the rates of 113 and 182 mg dm⁻³ P in the sandy and clayey soil,

respectively (Figure 1f). However, only at rates above 100 mg dm⁻³ P, the tuber yield of the plants cultivated in the clayey soil was higher than the plants grown in the sandy soil. The higher yield of the plants grown in the clayey soil and fertilized with higher P rates resulted from the increase in the number of leaves per plant and leaf area, which contributed to an increase in the amount of solar radiation intercepted, as well as the production of photoassimilates translocated to the tubers. Potato plants grown under conditions of high P supply are more productive because of the greater development of lateral stems, leaf area (FLEISHER et al., 2013), and DM production (FERNANDES; SORATTO, 2016). A study carried out with different potato cultivars also found that those plants with the highest

number of leaves per plant during most of the development cycle were those with higher tuber yield (FERNANDES et al., 2010). The applied-PUE was reduced up to the estimated rate of 167 mg dm⁻³ P, due to the increase in the P availability in soil and the stabilization of tuber yield in the higher P rates (Table 3).

In the roots, the amounts of DM accumulated were influenced by the isolated factors (Table 3). In the sandy soil, the root DM was higher than in the clayey soil, but, independently of the soil texture, the root DM increased up to the estimated rate of 113 mg dm⁻³ P, which agrees with Crusciol et al. (2005), who observed an increase in the root DM of rice cultivars with the same P rates used in the present study.

Table 3. Number of leaves per plant, leaf area, tuber yield, applied and taken up P use efficiency (PUE), dry matter (DM), P concentration and accumulation in the shoot, root, tuber and whole plant of the potato crop in response to soil texture and P rates.

Analyzed variables	Soil texture		P rate (mg dm ⁻³)				Effect	ST×P
	Clayey	Sandy	10	50	100	200		
Number of leaves per plant	27 a	25 b	21	27	29	25	Q ⁽¹⁾	**
Leaf area (cm ² pl ⁻¹)	3039 a	2661 a	2239	2864	3264	3031	Q ⁽²⁾	**
Tuber yield (g pl ⁻¹)	455 a	441 a	325	473	492	503	Q ⁽³⁾	**
Applied-PUE (g mg ⁻¹)	2.31 a	1.90 a	-	3.45	1.83	1.02	Q ⁽⁴⁾	ns
Shoot DM (g pl ⁻¹)	18 a	16 b	13	18	18	17	Q ⁽⁵⁾	**
Root DM (g pl ⁻¹)	1.9 b	2.6 a	2.0	2.4	2.6	2.0	Q ⁽⁶⁾	ns
Tuber DM (g pl ⁻¹)	80 a	75 a	53	82	87	88	Q ⁽⁷⁾	**
Whole plant DM (g pl ⁻¹)	93 a	100 a	69	102	108	107	Q ⁽⁸⁾	**
Shoot P concentration (g kg ⁻¹)	1.3 a	1.4 a	1.3	1.4	1.4	1.5	L ⁽⁹⁾	**
Root P concentration (g kg ⁻¹)	1.7 b	2.2 a	2.0	2.0	1.9	1.9	ns	ns
Tuber P concentration (g kg ⁻¹)	2.0 b	2.6 a	2.1	2.1	2.4	2.6	L ⁽¹⁰⁾	**
Shoot P accumulation (mg pl ⁻¹)	24 a	22 a	17	25	25	25	Q ⁽¹¹⁾	**
Root P accumulation (mg pl ⁻¹)	3.2 b	5.8 a	4.0	5.0	5.2	3.9	ns	ns
Tuber P accumulation (mg pl ⁻¹)	159 b	195 a	112	178	203	217	Q ⁽¹²⁾	ns
Whole plant P accumulation (mg pl ⁻¹)	186 b	224 a	133	207	234	246	Q ⁽¹³⁾	ns
Taken up-PUE (g mg ⁻¹)	0.53 a	0.42 b	0.52	0.50	0.46	0.43	L ⁽¹⁴⁾	*

Values followed by same letter within a row for the soil texture are not significantly different by LSD test to 5% probability. Q: quadratic equation. L: linear equation. ST×P: soil texture × P rate interaction.

⁽¹⁾y = 20.24 + 0.1572**x - 0.0006**x² R² = 0.98; ⁽²⁾y = 2058.9 + 19.45**x - 0.0730*x² R² = 0.99; ⁽³⁾y = 309.17 + 3.1499**x - 0.0109**x² R² = 0.90; ⁽⁴⁾y = 5.88 - 0.0566x* + 0.0001x** R² = 1.00; ⁽⁵⁾y = 12.88 + 0.1071**x - 0.0004**x² R² = 0.88; ⁽⁶⁾y = 1.90 + 0.0135*x - 0.00006**x² R² = 0.99; ⁽⁷⁾y = 49.61 + 0.6379**x - 0.0022**x² R² = 0.92; ⁽⁸⁾y = 64.40 + 0.7585**x - 0.0027**x² R² = 0.92; ⁽⁹⁾y = 1.29 + 0.0010**x R² = 0.95; ⁽¹⁰⁾y = 2.04 + 0.0026x** R² = 0.98; ⁽¹¹⁾y = 16.54 + 0.1608**x - 0.0006**x² R² = 0.87; ⁽¹²⁾y = 100.26 + 1.60**x - 0.0051**x² R² = 0.97; ⁽¹³⁾y = 120.58 + 1.7970**x - 0.0058**x² R² = 0.97; ⁽¹⁴⁾y = 0.52 - 0.0004x* R² = 0.96. ns is not significant. * and ** are significant at 5 and 1% probability by the t test, respectively.

The ST×P interaction affected the amounts of DM accumulated in the shoot, tubers, and whole plant (Table 3). At the lower P rates, the amounts of DM accumulated in the shoot, tubers, and whole plant of the treatments of the sandy soil were higher than in the clayey soil, but in the rates higher than 100 mg dm⁻³ P, the reverse occurred (Figures 2a, 2b, and 2c). This is because, in the sandy soil, the phosphate fertilization increased the DM of these plant parts and of the whole plant up to those rates between 96 and 115 mg dm⁻³ P, while in the clayey soil the response to P was higher and occurred until the rates between 172 and 197 mg dm⁻³ P (Figures 2a, 2b, and 2c).

In the sandy soil, P fertilization increased the plant DM by 38%, but in the clayey soil, the increase in plant DM in response to P was 108%. This finding indicates that the response to P was higher in the clayey soil than in sandy soil. Fernandes, Soratto and Pilon (2015) found that potato plants of cv. Agata cultivated with high P availability in soil accumulated about 27% more DM than those grown in the condition of low P availability. It has been demonstrated that high P supply can decrease the DM accumulation in the crop, especially in the sandy soil, demonstrating that excessive P rates can reduce the growth of potato by causing nutritional imbalance, as verified by Barben et al. (2010).

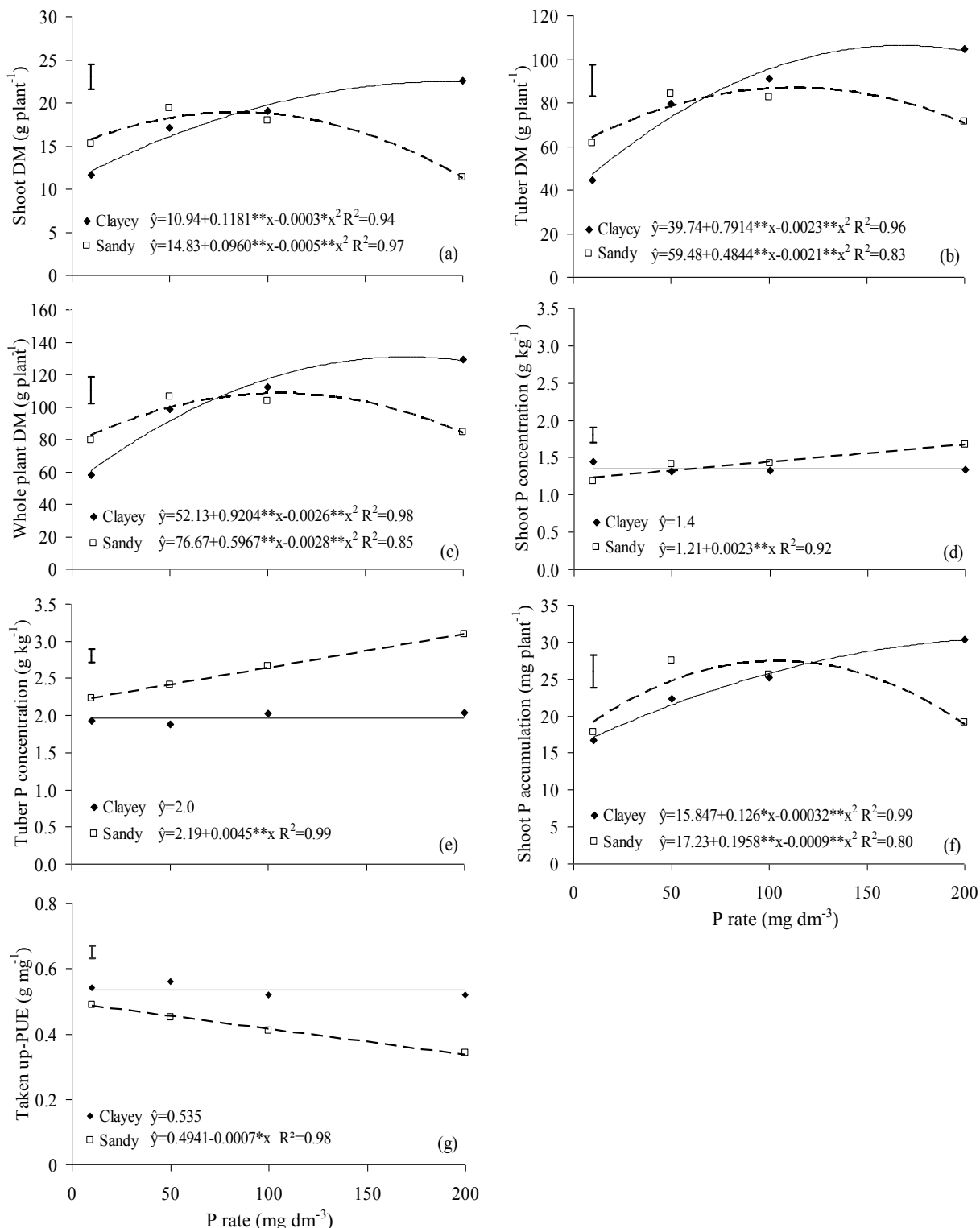


Figure 2. Amounts of dry matter (DM) accumulated in shoot (a), tubers (b), and whole plant (c), P concentration in shoot (d), and tubers (e), shoot P accumulation (f), and taken up-PUE (g) of the potato crop in response to soil texture and P rates. * $p \leq 0.05$ and ** $p \leq 0.01$. Vertical bars represent the least significant difference by LSD test ($p \leq 0.05$).

The P concentration in the roots was influenced only by the soil texture, whose higher root P concentrations occurred in the sandy soil, where the initial P availability was higher (Table 3). In the shoot and tubers, the P concentration was influenced by ST×P interaction (Table 3). In the clayey soil, the

P concentration in the shoot and tubers were not affected by the phosphorus fertilization and were, on average, 1.4 and 2.0 g kg⁻¹, respectively (Figure 2d and 2e). However, in the sandy soil, the P concentrations in these potato plant organs linearly increased with P fertilization. Thus, at the lower P

rates, the concentration of this element in the shoot and tubers of the plants of the two soils did not differ. However, at the higher P rates, the P concentration was higher in the sandy soil than the clayey soil. This occurred because P fertilization produced a linear increase in the P concentration in the shoot and tubers of the potato plants cultivated in the sandy soil, whereas this remained unchanged for the plants cultivated in the clayey soil (i.e., the expressive increase in the plant DM of the clayey soil with application of increasing P rates caused the dilution of their concentrations in the plant) (Figures 2c, 2d, and 2e). In soils with a lower amount of clay (i.e., more sandy soil with higher concentrations of available P in the soil solution) (BEDIN et al., 2003; MACHADO et al., 2011) there is increased the nutrient influx, which leads to an increase in the concentrations of the element in the plant parts, such as leaves (BEDIN et al., 2003); a trend we observed in the present study.

There was an ST×P interaction for the amount of P accumulated in the shoot (Table 3). The amount of P accumulated in the shoot of the plants grown in the sandy soil was increased up to 109 mg dm⁻³ P and decreased at higher nutrient rates, due to the reduction in shoot DM in the higher P rates (Figure 2a and 2f). In the clayey soil, the P accumulation in the shoot of the plants increased in a quadratic form with the P fertilization (i.e., even if the fertilization did not alter the P concentration in shoot, it increased the amount of DM accumulated in this plant organ), which contributed to a greater accumulation of P in the shoot of plants from clayey soil than in the sandy soil, especially under the higher P application rates (Figures 2a, 2d, 2e, and 2f).

The P accumulation in the roots was affected only by the soil texture, with a higher P accumulation in roots of the plants cultivated in the sandy soil, in which the DM and root P concentration were higher (Table 3). In tubers and the whole plant, the amounts of P accumulated were affected by the isolated factors (Table 3). Regardless of the P fertilization, in the sandy soil, the P accumulation in tubers and the whole plant were higher than in the clayey soil. This trend is caused by the higher P concentration in the tubers of plants of the sandy soil; potato tubers are a strong sink of P in the plant and accumulate about 78-89% of all P taken up by plants during the cycle (FERNANDES; SORATTO; SILVA, 2011). Because the P adsorption capacity presents a positive correlation with the clay content (FALCÃO; SILVA, 2004), it is expected that, in the sandy soil, the P available concentration will remain higher than in the clayey soil, and thus the potato can take up and accumulate more P. A study with soybean in multiple soil types has also shown that the plants cultivated in less buffered soil (Quartzarenic Neosol, i.e., with less P adsorption capacity) accumulate larger P amounts in the grain than plants grown in clayey soils (BEDIN et al.,

2003); which agrees with the results of the present study.

Phosphorus fertilization increased amounts of P accumulated in tubers and whole plants up to the estimated rates of 157 and 155 mg dm⁻³ P, respectively (Table 3). These results demonstrate that phosphorus fertilization increases the growth, tuber yield, and P uptake of potato plants, but that the application of high P rates can decrease the uptake of this nutrient by reducing the DM production of the plants, with this effect being more drastic in sandy soils.

The taken up-PUE was affected by the ST×P interaction (Table 2). In clayey soil, the taken up-PUE was not influenced by P fertilization and was, on average, 0.53 g mg⁻¹ (Figure 2g). At the highest P rates in sandy soil, the taken up-PUE was lower than in the clayey soil, because the P fertilization linearly decreased the taken up-PUE in the higher P rates, in which the soil P availability was higher. The lower taken up-PUE under the higher P rates in the sandy soil occurred because, at the higher P rates, the potato had its DM production reduced but had the P concentration in the shoot and in the tubers increased in a linear manner (i.e., there was a decrease in the efficiency of conversion of P taken up into biomass production) (Figure 2). Fernandes and Soratto (2012) also found lower taken up-PUE by potato in conditions of greater P availability.

CONCLUSIONS

The concentrations of P, Ca, and Mg in the leaves were higher in sandy soil than clayey soil, and P rates increased the concentrations of N, P, and Ca in the leaves of potato plants. Phosphorus fertilization increased the plant growth, the amount of P accumulated in the shoot and tuber yield in both soils, but in a more expressive way and up to higher P rates in the potato cultivated in the clayey soil. The applied-PUE was not affected by soil texture. In the potato cultivated in the sandy soil, the taken up-PUE was reduced due to the decrease in DM production and increase in P concentration in the plant organs with a supply of higher P rates.

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