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Nutrient Uptake and Removal by Potato Cultivars as Affected by Phosphate Fertilization of Soils with Different Levels of Phosphorus Availability

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ABSTRACT: Studies in the past decades have focused on how tuber yield of potato grown on different types of soil is affected by phosphate fertilizer rates. However, little is known about the effects of phosphorus availability in the soil and of phosphate fertilization on nutrient uptake and removal by the main potato cultivars currently grown in Brazil. Thus, in this study we investigated the influence of P fertilization rates on dry matter (DM) yield and nutrient uptake and removal in five potato cultivars grown on soils with different levels of P availability. Experiments were conducted on soil with low (14 mg dm^{-3}), medium (36 mg dm^{-3}), and high (70 mg dm^{-3}) P availability, in randomized complete blocks with a 5 × 5 factorial arrangement with four replications. The treatments consisted of five potato cultivars (Agata, Asterix, Atlantic, Markies, and Mondial) and five P rates (0, 125, 250, 500, and 1,000 kg ha^{-1} P_2O_5) applied in the planting furrow. In soils with low, medium, and high P availability, P fertilization increased plant growth and tuber DM yield up to rates of 500, 250, and 125 kg ha^{-1} P_2O_5, respectively. At a specific initial P availability, all potato cultivars responded to the same P rate for plant growth, tuber yield, and nutrient uptake and removal. At the highest P fertilization rates, leaf analysis showed that the nutritional status of potato plants was not significantly changed and no nutritional deficiency was induced, regardless of the soil P availability levels. However, in the soils with higher P availability, P fertilization decreased plant Mn and Zn and tuber Mn concentrations in a linear manner. The increases in the uptake of N, K, Ca, Mg, S, B, Cu, and Fe and the removal of most nutrients in response to P fertilization were related more to the increase in plant biomass and tuber DM yield than to changes in concentrations of these nutrients in the plant. Application of P at high rates in soil with high P availability caused luxury P uptake, which reduced Mn uptake by 10 % and prevented higher Zn uptake, by reducing plant Zn concentrations, despite the increase in plant biomass.

Keywords: *Solanum tuberosum*, mineral nutrition, phosphorus rate, nutrient accumulation, nutrient partitioning.

INTRODUCTION

The tuber yield of potato (*Solanum tuberosum* L.) has increased considerably over the past decades (Faostat, 2015) due to improvements in management practices (Fernandes and Soratto, 2012a) and use of more productive cultivars (ABBA, 2010). Balanced mineral nutrition is essential for high tuber yield and quality (Houghland, 1960; Mesquita et al., 2007; Rosen and Bierman, 2008; Fernandes and Soratto, 2012a). High yield potential, short crop cycle, and high nutrient requirements of potato (Jenkins and Mahmood, 2003; Fernandes et al., 2011) demand nutrients in readily available form in the soil solution. Therefore, nutrient requirements must be met to maximize the yield performance of potato.

The largest increases in potato tuber yield have come from P applications, especially in P-deficient soils (Fontes et al., 1997; Alvarez-Sánchez et al., 1999; Rosen and Bierman, 2008; Soratto et al., 2015; Fernandes and Soratto, 2016), although K, N, and Ca are taken up in greater amounts by potato plants (Fernandes et al., 2011). Since costs are high in establishing the potato crop, many farmers prefer to ensure high yields through possible over application of fertilizers than to adhere to the recommended levels for fertilization. P_2O_5 is applied at amounts up to 500 kg ha^{-1} above the recommended threshold (Sangoi and Kruse, 1994), even in soils with high P availability.

A balanced P supply can increase the dry matter yield (DM) and P uptake by potato plants (Alvarez-Sánchez et al., 1999; Jenkins and Mahmood, 2003; Fernandes and Soratto, 2012b; Soratto et al., 2015; Soratto and Fernandes, 2016) and, additionally, can affect the uptake and concentration of other nutrients in different parts of plants that are grown in the nutrient solution (Barben et al., 2010a,b; Fernandes and Soratto, 2012b) or soil (Jenkins and Mahmood, 2003; Fernandes et al., 2015; Munda et al., 2015; Soratto and Fernandes et al., 2016). In P-deficient soil, phosphate fertilization increased the uptake and removal of most nutrients as well as growth and tuber yield in the Agata and Mondial potato cultivars (Soratto and Fernandes, 2016).

The potato cultivars currently planted in Brazil differ considerably with regard to the amounts of nutrients taken up and removed by tubers (Fernandes et al., 2011; Soratto et al., 2011); therefore, we would expect that phosphate fertilization would affect the nutritional demands of each cultivar differently. Previous studies in Brazil have investigated the amount of nutrients taken up and removed by potato tubers (Gargantini et al., 1963; Macedo et al., 1977; Paula et al., 1986), and more recent articles have focused on the main potato cultivars currently grown (Fernandes et al., 2011; Soratto et al., 2011). However, preliminary research in a greenhouse indicated that DM production, fresh tuber yield, and nutrient uptake response to P application varied widely among potato cultivars (Fernandes et al., 2015; Soratto et al., 2015). In addition, studies have indicated that P supply may alter the allocation of some nutrients to the tubers and that this effect is cultivar specific (Fernandes et al., 2015; Soratto et al., 2016). Therefore, this study was based on the hypothesis that P, applied in the planting furrow, will have a different effect on nutrient uptake and partitioning for the tubers of potato cultivars grown in soils with different P availabilities.

The phosphate fertilization recommendations currently available for potato (Lorenzi et al., 1997) were established at a time of lower tuber yield levels; current cultivars are more productive (ABBA, 2010). The potato crop is now cultivated in soils with medium/high P availability and treated with high rates of phosphate fertilizer (Soratto et al., 2016); the management of phosphate fertilization for this crop should be reappraised. The effects of soil P availability and phosphate fertilization on nutrient uptake and removal by tubers need to be examined in a more detailed manner under field conditions for the main potato cultivars planted in Brazil.

With the hypothesis that phosphate fertilization differently affects the nutritional demand of each potato cultivar grown in soils with different levels of P availability, the objective of this study was to evaluate the influence of P fertilization rates on DM yield and nutrient uptake and removal for five potato cultivars grown in soils with different levels of P availability.

MATERIALS AND METHODS

Study site, soil, and climate

Three experiments were carried out on potato-producing farms in the following municipalities of the state of São Paulo, Brazil: Avaré (48° 47' W, 23° 02' S,744 m amsl), Itaí (49° 01' W, 23° 28' S, 649 m amsl), and Cerqueira César (49° 12' W, 23° 07' S, 737 m amsl). In the area of Avaré, soil P availability was low (P_{resin} ≤25 mg dm^{-3}), medium in Itaí (P_{resin} = 26-60 mg dm^{-3}), and high in Cerqueira César (P_{resin} >60 mg dm^{-3}), based on the criteria established by Raij et al. (1997).

Prior to the experiments, the soil with low P availability had been planted to *Urochloa decumbens* pasture, with medium P availability to soybean, and with high P availability to rice. The low P availability area had been treated with 2,500 kg ha^{-1} of dolomitic limestone. The soils of the three sites had a clay texture and were classified as *Latossolo Vermelho* (Embrapa, 2006) or Oxisol (Soil Survey Staff, 2006). In each area, prior to the experiment, soil samples were taken from the 0.00-0.20 m layer to determine chemical (Raij et al., 2001) and textural (Claessen, 1997) properties (Table 1). Data on rainfall, irrigation, and maximum and minimum temperatures recorded during the experiments are shown in figure 1.

Experimental design and treatments

The experiments were conducted in a randomized complete block design with a 5 × 5 factorial arrangement and four replications. The treatments consisted of five cultivars (Agata, Asterix, Atlantic, Markies, and Mondial) and five P rates (0, 125, 250, 500, and 1,000 kg ha^{-1} P_2O_5) applied in the planting furrow. Each plot consisted of five 5-m-long plant rows in an area of 20 m^2. For the evaluations, only the plants of the three central rows were used and sections of 0.5 m at both ends of the plots rows were disregarded.

Table 1. Chemical and textural properties of the soils in the experimental areas before potato planting

Soil property[1]	Site - Soil P availability		
	Avaré - Low	Itaí - Medium	Cerqueira César - High
pH($CaCl_2$)	5.7	4.8	4.8
OM (g dm^{-3})	47.6	26.7	27.8
P_{resin} (mg dm^{-3})	14	36	70
K^+ ($mmol_c$ dm^{-3})	2.3	2.3	3.3
Ca^{2+} ($mmol_c$ dm^{-3})	60	32	31
Mg^{2+} ($mmol_c$ dm^{-3})	19	11	9
H+Al ($mmol_c$ dm^{-3})	27	46	51
CEC ($mmol_c$ dm^{-3})	108	90	94
BS (%)	75	49	46
B (mg dm^{-3})	0.33	0.64	0.77
Cu (mg dm^{-3})	8.3	1.2	6.2
Fe (mg dm^{-3})	60.7	44.0	32.7
Mn (mg dm^{-3})	24.6	8.2	9.3
Zn (mg dm^{-3})	1.04	1.55	2.88
Sand (g kg^{-1})	311	292	153
Silt (g kg^{-1})	289	184	245
Clay (g kg^{-1})	400	524	602

[1] Soil chemical and textural analysis as described by Raij et al. (2001) and Claessen (1997). OM: organic matter; CEC: cation exchange capacity; BS: base saturation.

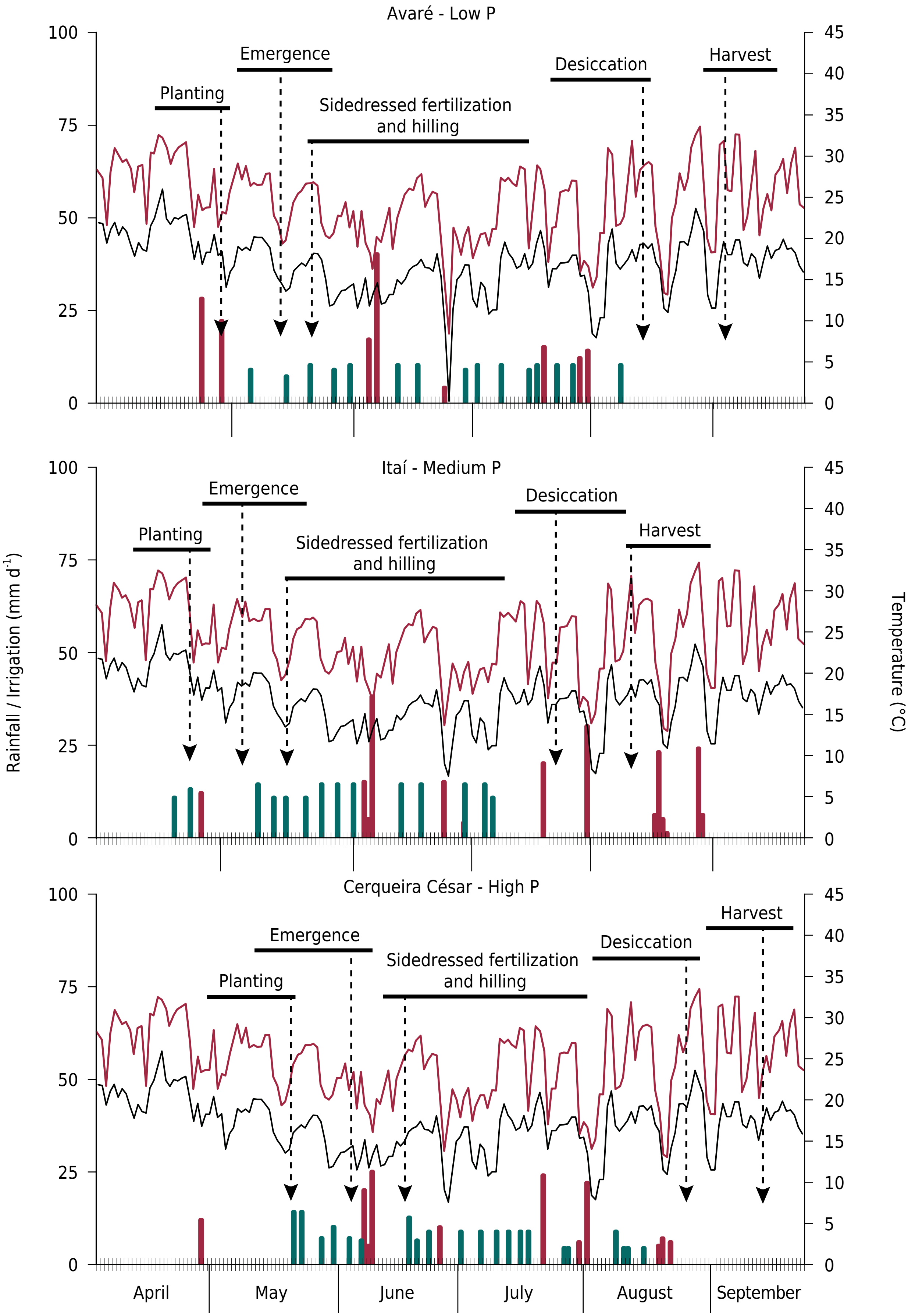

Figure 1. Daily rainfall ( ), irrigation ( ), and maximum ( ) and minimum ( ) temperatures in the three experimental areas with low, medium, and high soil P availability, from April to September 2011.

Crop management

The following tillage operations were performed according to the management system of the producer: two heavy disk harrow operations, one chisel plow operation, and one light harrow operation on the day before planting. Potatoes were planted in the areas with low, medium, and high soil P availability on April 28, 2011, April 20, 2011, and May 20, 2011, respectively. A potato furrower-planter opened furrows spaced at 0.80 m and the fertilizers were applied manually in the open furrows. In the plots of all three areas, fertilization at planting consisted of 62 kg ha^{-1} N (ammonium sulfate, 20 % N and 22 % S) and 124 kg ha^{-1} K_2O (potassium chloride, 60 % K_2O and 45 % Cl). Phosphorus was also applied in the planting furrow according to the treatments, using triple superphosphate (45 % P_2O_5 and 8 % Ca) as the source. Fertilizer was manually incorporated into the soil of the open furrows with hoes, and then type III seed tubers (mean weight 35 g) were manually distributed at a spacing of 0.30 m. The pesticides thiamethoxam (155 g ha^{-1} a.i.), chlorpyrifos (557 g ha^{-1} a.i.), pencicuron (280 g ha^{-1} a.i.), methyram (77 g ha^{-1} a.i.), fluazinam (1,155 g ha^{-1} a.i.), and streptomycin (17 g ha^{-1} a.i.) were applied on the seed tubers, and the furrows were manually closed with a hoe.

The plants emerged on May 14, 2011 (16 days after planting - DAP), May 05, 2011 (15 DAP), and June 05, 2011 (16 DAP) in the areas with low, medium, and high soil P availability, respectively. Fertilizer was sidedressed at the rate of 43 kg ha^{-1} N (urea, 45 % N) at 22 DAP in the area with low P availability, of 64 kg ha^{-1} N (urea) at 24 DAP in the area with medium P availability, and of 41 kg ha^{-1} N (mixture containing 21 % N, 8 % Ca, and 4.6 % Mg) at 28 DAP in the area with high P availability. In all areas, thiamethoxam (150 g ha^{-1} a.i.) and fluazinam (1,035 g ha^{-1} a.i.) were applied simultaneously with hilling, immediately after sidedressing.

In all areas, the crop was managed according to recommended regional practices, including sprinkler irrigation. Pests and diseases were controlled with crop-specific insecticides and fungicides.

Plant sampling and analysis

In the three experiments, leaf samples (third expanded leaf from the apex) were taken from each plot at about 48 DAP to evaluate the nutritional status of the plants (Lorenzi et al., 1997). The leaf samples were washed in tap water and deionized water and then dried in an oven with forced-air circulation at 65 °C for 72 h. On the day before desiccation of the plant shoots, four plants per plot were collected to determine DM accumulation and nutrient uptake because, in this phase, the potato plants have peak DM and nutrient accumulation (Fernandes et al., 2010; Fernandes et al., 2011; Soratto et al., 2011). The plants were washed and separated into roots, stolons, shoots (leaves and stem), and tubers. Stolons and shoots were evaluated together. The samples were then dried in an oven with forced-air circulation at 65 °C for 96 h. The dry samples were weighed and the weights added together to obtain DM accumulation.

The shoots of the potato plants were desiccated with the herbicide diquat (331 g ha^{-1} a.i) on August 18, 2011 (112 DAP), July 23, 2011 (94 DAP), and August 25, 2011 (97 DAP) in the areas with low, medium, and high soil P availability, respectively. The tubers were harvested approximately 19 days after shoot desiccation. The tubers of 10 plants (two 1.5-m-long rows) were harvested from the area that was evaluated in each plot, washed, and weighed to obtain the total tuber yield. The samples were sliced, dried in an oven with forced-air circulation at 65 °C for 96 h, and weighed to determine tuber DM accumulation.

The plant tissue samples were ground in a Willey mill and sieved (1 mm mesh), and the nutrient concentrations (N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn) were determined as proposed by Malavolta et al. (1997). The whole plant nutrient concentrations were calculated from the weighted average of nutrient concentrations in the different plant parts: whole plant weighted concentration = [(concentration in root × root DM) + (concentration in shoot × shoot DM) + (concentration in tuber × tuber DM)]/(root DM + shoot DM + tuber DM). The amounts of nutrients taken up by potato plants were calculated by multiplying the nutrient concentration in the whole plant by the DM accumulation of the whole plant. The amounts of nutrients removed by tubers were calculated by multiplying the tuber nutrient concentration by the tuber DM yield.

Statistical analyses

Analysis of variance was performed on the results of each experiment separately. The means of the cultivars were compared by the Tukey test ($p \leq 0.05$), and the effects of the P rates in the planting furrow were evaluated by regression analysis.

RESULTS

Nutrient concentration as shown by leaf diagnosis

The leaf P concentrations in the treatment without P application in the planting furrow were deficient (i.e. <2.5 g kg^{-1} P) only in the soil with low initial P availability (data not shown). For the three levels of initial soil P availability, phosphate fertilization increased the P concentration in leaves used for diagnosis up to the highest P rate studied, but most intensely under low soil P availability (data not shown). The leaf N, K, Ca, and Mg concentrations increased slightly after P application in the planting furrow only in soil with low initial P availability. The leaf S, B, Cu, and Fe concentrations were practically unaffected by the initial soil P availability and by phosphate fertilization rates in the planting furrow, whereas the leaf Mn and Zn concentrations of plants in the low P availability soil decreased with increasing phosphate fertilization rates (data not shown). The mean values of nutrient concentrations under all the different treatments exhibited the following ranges: 46-57 g kg^{-1} for N, 1.6-5.3 g kg^{-1} for P, 52-81 g kg^{-1} for K, 12-18 g kg^{-1} for Ca, 5-7 g kg^{-1} for Mg, 2.2-3.3 g kg^{-1} for S, 20-29 mg kg^{-1} for B, 10-251 mg kg^{-1} for Cu, 326-465 mg kg^{-1} for Fe, 58-111 mg kg^{-1} for Mn, and 39-190 mg kg^{-1} for Zn.

Dry matter accumulation and plant nutrient concentration

In all three soils, the amount of DM accumulated in the whole plant was influenced by the cultivar and P rate factors (Table 2). In general, DM accumulation was highest in cv. Mondial and lower in cv. Agata, Atlantic, and Markies. Regardless of the cultivar, phosphate fertilization increased whole plant DM up to 500, 250, and 125 kg ha^{-1} P_2O_5 in soils with low, medium, and high initial P availability, respectively (Figure 2a).

In the three soils, the concentrations of most nutrients in the whole plant were only affected by the cultivar (Table 2). Lower nutrient concentrations were found in plants of cv. Mondial, especially in soils with low and high P availability, and higher nutrient concentrations were found in plants of cv. Agata, especially in soils with medium and high P availability.

Phosphate fertilization significantly affected the P, Mn, and Zn concentrations in the plants grown on all three soils, the Mg concentration in plants on soils with low and medium P availability, and the S, Cu, and Fe concentrations in plants on P-deficient soil (Table 2). At all levels of initial soil P availability, phosphate fertilization increased the P concentration in potato plants up to application rates estimated from 833 to 909 kg ha^{-1} P_2O_5 (Figure 2b). In soils with low and medium P availability, the phosphate rates applied caused a slight reduction in the plant Mg concentration (Figure 2c). In the soil with low P availability, plant S concentrations decreased with phosphate fertilizer application up to the rate of 250 kg ha^{-1} P_2O_5, while plant Cu concentrations increased with phosphate application up to an estimated rate of 678 kg P_2O_5 ha^{-1} and decreased at the highest P rates (Figures 2d and 2e). The plant Fe concentrations decreased up to

Table 2. Whole plant dry matter accumulation (WPDM) and nutrient (N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn) concentrations in the whole plant of five potato cultivars as affected by rates of P applied in the planting furrow in soils with low, medium, and high P availability

Treatment	WPDM	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
	kg ha^{-1}	g kg^{-1}						mg kg^{-1}				
Cultivar	Low P availability (14 mg dm^{-3})											
Agata	3,188 b	20.7 ab	2.5 a	34.6 a	4.3 ab	2.1 ab	1.3 a	13.3 a	36.1 a	751.2 a	24.9 b	28.2 a
Asterix	3,333 b	19.1 bc	2.3 b	30.3 b	4.2 ab	2.1 ab	1.3 a	13.8 a	29.6 b	562.4 b	24.7 b	25.8 ab
Atlantic	2,914 b	19.5 b	2.3 b	30.1 b	3.9 b	2.2 a	1.3 a	12.4 a	31.8 ab	600.7 b	30.6 a	24.2 b
Markies	3,157 b	21.6 a	2.6 a	33.3 a	4.5 a	2.3 a	1.2 b	12.6 a	32.3 ab	527.5 b	22.5 b	28.5 a
Mondial	4,586 a	17.5 c	2.0 c	30.4 b	3.9 b	2.0 b	1.1 c	12.1 a	29.4 b	555.5 b	24.6 b	24.0 b
	F probability											
Cultivar (C)	<0.001	<0.001	<0.001	<0.001	0.026	0.002	<0.001	ns	0.005	<0.001	<0.001	<0.001
Furrow-applied P rate (P)	<0.001	ns	<0.001	ns	ns	<0.001	<0.001	ns	<0.001	<0.001	<0.001	<0.001
C × P	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Cultivar	Medium P availability (36 mg dm^{-3})											
Agata	4,118 d	21.4 a	2.4 a	37.8 a	5.5 a	2.6 a	1.6 a	21.7 a	23.6 a	393.0 ab	30.9 a	33.8 a
Asterix	6,388 b	18.3 b	2.0 b	31.8 b	4.0 b	2.2 b	1.2 c	20.2 ab	20.3 b	341.9 b	30.9 a	31.8 a
Atlantic	5,602 c	19.2 b	2.0 b	29.3 b	3.8 b	2.2 b	1.3 bc	18.4 bc	21.0 ab	399.4 a	26.3 ab	31.1 a
Markies	6,062 bc	20.3 ab	2.1 b	29.9 b	4.2 b	2.3 b	1.4 b	18.2 bc	18.9 b	367.3 ab	30.9 a	34.7 a
Mondial	8,175 a	18.3 b	2.1 b	30.5 b	3.7 b	2.2 b	1.3 bc	17.6 c	20.5 b	373.2 ab	25.8 b	31.6 a
	F probability											
Cultivar (C)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.034	0.002	ns
Furrow-applied P rate (P)	<0.001	ns	<0.001	ns	ns	0.045	ns	ns	ns	ns	<0.001	<0.001
C × P	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Cultivar	High P availability (70 mg dm^{-3})											
Agata	6,260 b	18.4 a	2.3 a	36.7 a	4.1 a	2.0 ab	1.2 a	15.9 a	12.6 a	417.4 ab	27.8 a	19.5 a
Asterix	7,515 a	16.8 ab	2.0 ab	33.9 a	3.6 ab	1.9 ab	1.1 a	16.2 a	9.8 bc	363.1 b	30.5 a	19.9 a
Atlantic	6,194 b	16.1 ab	2.0 ab	35.2 a	3.6 ab	2.1 a	1.2 a	13.3 b	10.9 ab	477.3 a	30.1 a	21.1 a
Markies	6,666 b	17.6 ab	2.0 ab	34.4 a	4.1 a	2.1 a	1.1 a	14.0 ab	8.7 c	402.2 b	30.3 a	21.3 a
Mondial	7,484 a	15.8 b	1.8 b	33.5 a	2.9 b	1.8 b	1.1 a	14.1 ab	9.3 bc	366.8 b	24.3 a	20.3 a
	F probability											
Cultivar (C)	<0.001	0.040	0.014	ns	<0.001	0.045	ns	0.003	<0.001	<0.001	0.031	0.473
Furrow-applied P rate (P)	<0.001	ns	<0.001	ns	ns	ns	ns	ns	ns	ns	0.040	0.002
C × P	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Means followed by the same letter in a column are not significantly different at p≤0.05 according to Tukey's test. ns: not significant at p≤0.05.

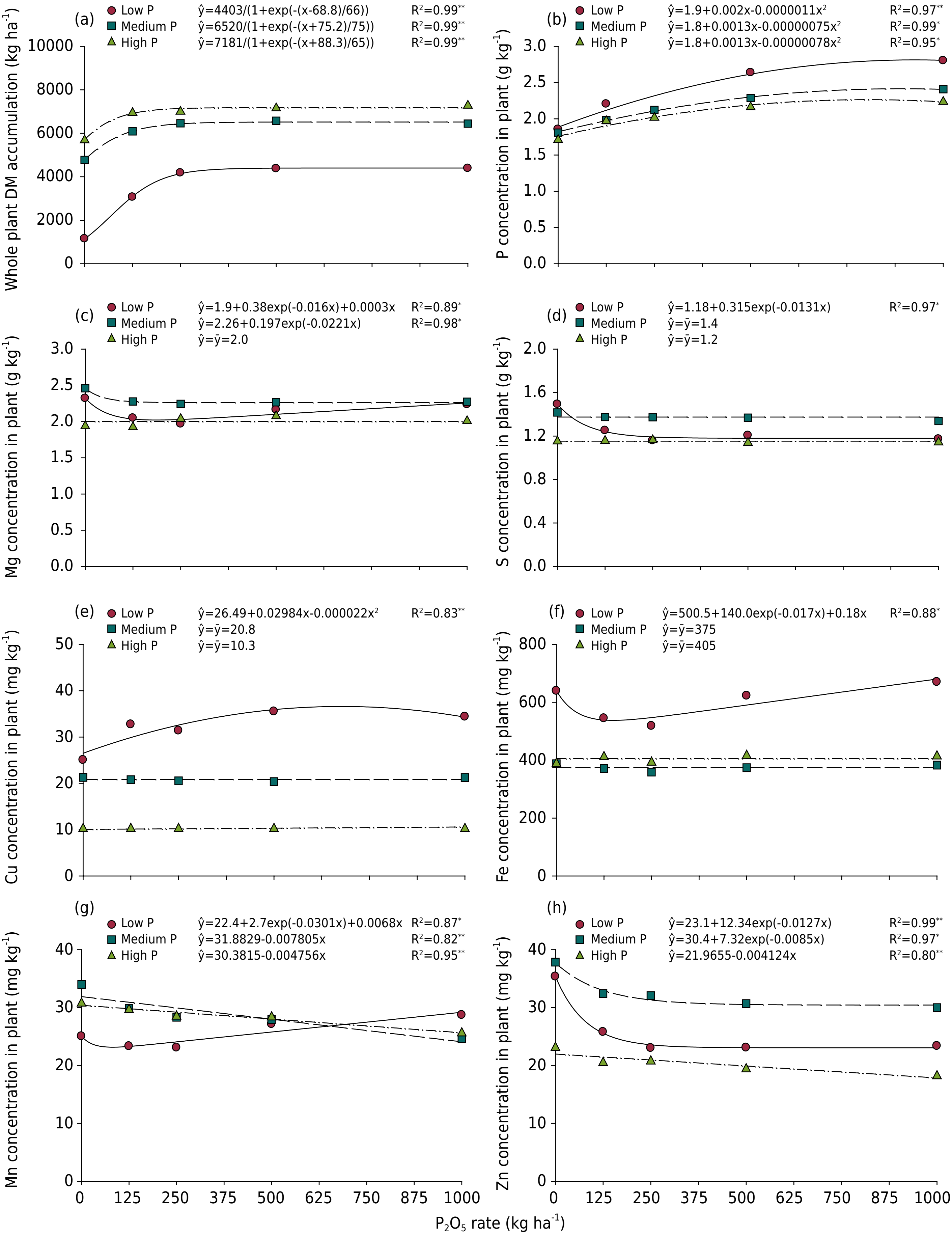

Figure 2. Whole plant dry matter (DM) accumulation (a), and concentrations of P (b), Mg (c), S (d), Cu (e), Fe (f), Mn (g), and Zn (h) in whole potato plants as affected by rates of P applied in the planting furrow in soils with low, medium, and high P availability. Mean of five cultivars. * and **: significant at 5 and 1 % by the F test.

the 125 kg ha^{-1} P_2O_5 rate, but increased with the application of higher P rates (Figure 2f). Manganese concentration in the plants grown on the most P-fertile soils decreased linearly with phosphate fertilization; however, in the low P soil, the Mn concentrations increased after applying the highest P rates (Figure 2g). In the soils with low and medium P availability, the plant Zn concentrations decreased significantly with applications up to 250 kg ha^{-1} P_2O_5, but in the soil with high P availability, the reduction in plant Zn concentrations was linear and weaker (Figure 2h).

Nutrient uptake

In the soil with high P availability, the uptake of Mg, S, and Fe was influenced only by the P rate factor, and Zn uptake was affected only by the cultivar factor (Table 3). However, in all three soils, the amounts of other nutrients taken up by potato plants were influenced by both factors (Table 3). In general, regardless of initial soil P availability, cv. Mondial took up higher amounts of nutrients than the other cultivars, and cv. Agata and Atlantic, lower amounts.

Table 3. Nutrient (N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn) uptake by the potato cultivars as affected by rates of P applied in the planting furrow in soils with low, medium, and high P availability

Treatment	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
	kg ha^{-1}						g ha^{-1}				
Cultivar	Low P availability (14 mg dm^{-3})										
Agata	65 b	8 bc	110 b	14 b	7 b	4 b	42 bc	123 ab	2374 a	81 bc	86 b
Asterix	62 bc	8 bc	97 bc	14 b	7 b	4 b	45 b	95 c	1821 b	80 bc	78 bc
Atlantic	55 c	7 c	85 c	12 c	6 b	4 b	37 c	96 c	1749 b	92 b	65 c
Markies	67 b	9 ab	104 b	14 b	7 b	4 b	39 bc	103 bc	1607 b	70 c	81 b
Mondial	79 a	10 a	137 a	18 a	9 a	5 a	56 a	142 a	2540 a	113 a	103 a
	F probability										
Cultivar (C)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Furrow-applied P rate (P)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
C × P	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Cultivar	Medium P availability (36 mg dm^{-3})										
Agata	87 d	10 c	153 d	22 bc	11 c	7 c	88 c	96 c	1592 c	123 b	135 d
Asterix	118 bc	13 b	202 b	25 b	14 b	8 b	129 a	129 b	2161 b	194 a	200 b
Atlantic	107 c	11 c	164 cd	21 c	12 bc	7 c	102 bc	117 b	2232 b	146 b	172 c
Markies	123 b	13 b	180 bc	25 b	14 b	8 b	109 b	114 b	2204 b	184 a	207 b
Mondial	148 a	17 a	247 a	30 a	17 a	10 a	144 a	165 a	3000 a	204 a	253 a
	F probability										
Cultivar (C)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Furrow-applied P rate (P)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.026	0.030
C × P	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Cultivar	High P availability (70 mg dm^{-3})										
Agata	113 a	14 ab	226 ab	26 ab	13 a	7 a	98 b	78 a	2589 a	170 c	119 c
Asterix	125 a	15 a	253 a	27 a	14 a	8 a	121 a	74 a	2717 a	228 a	148 a
Atlantic	97 b	12 b	213 b	21 c	13 a	8 a	81 c	66 bc	2871 a	178 bc	127 bc
Markies	116 a	14 ab	229 ab	27 a	14 a	7 a	93 bc	57 c	2661 a	198 b	140 ab
Mondial	118 a	14 ab	250 a	22 bc	14 a	8 a	105 b	70 a	2731 a	178 bc	150 a
	F probability										
Cultivar (C)	<0.001	0.011	<0.001	<0.001	ns	ns	<0.001	<0.001	ns	<0.001	<0.001
Furrow-applied P rate (P)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.006	ns
C × P	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Means followed by the same letter in a column are not significantly different at p≤0.05 by Tukey's test. ns: not significant at p≤0.05.

In the soil with low P availability, the uptake of N, K, Ca, Mg, and S was about 3.1-4.3 times as much with P fertilizer application, up to the rate of 500 kg ha^{-1} P_2O_5, while in the other soils there was no significant increase in the uptake of these nutrients at rates above 250 kg ha^{-1} P_2O_5 (Figures 3a, 3c, 3d, 3e, and 3f). In the most P-fertile soils, the N, K, Ca, Mg, and S uptake was approximately 1.3 times as much in response to P application. When averaged over potato cultivars, phosphate fertilization increased the plant P uptake up to the rate of 500 kg ha^{-1} P_2O_5, in all soils. However, in the low P availability soil, the increase in P uptake was more expressive than in the average of the other soils (Figure 3b).

The amounts of B, Cu, and Fe taken up by the plants grown in soils with medium and high P availability increased significantly (1.3-1.4 times) up to the rates of 250 and 125 kg ha^{-1} P_2O_5, respectively (Figures 4a, 4b, and 4c). In the low P availability soil, B uptake showed increases up to approximately 500 kg ha^{-1} P_2O_5 (Figure 4a), Cu uptake increased 5.7 times up to the 500 kg ha^{-1} P_2O_5 rate, and Fe uptake increased 4.0 times up to the highest P rate tested (Figures 4b and 4c).

Regardless of soil P availability, phosphate fertilization increased Mn uptake up to rates estimated at 474 to 554 kg ha^{-1} P_2O_5 (Figure 4d). In soils with higher P availability, the highest rate of phosphate fertilizer reduced Mn uptake in potato by approximately 10 %. The Zn uptake increased 1.1-2.5 times in soils with low and medium P availability up to the estimated P fertilization rates of 500 and 546 kg ha^{-1} P_2O_5, respectively (Figure 4e).

Tuber yield, nutrient concentrations, and nutrient removal

At the three levels of initial soil P availability, the fresh tuber yield and tuber DM yield were, like nutrient uptake, influenced by the cultivar and P rate factors (Table 4). In general, the tuber DM yields of cv. Mondial were highest and those of cv. Atlantic lowest. Phosphate fertilization in the planting furrow significantly increased fresh tuber yield and tuber DM yield up to the rates of 500, 250, and 125 kg ha^{-1} P_2O_5 in soils with low, medium, and high initial P availability, respectively (Figures 5a and 5b).

Despite variations, the nutrient concentrations in most tubers were influenced by the cultivar in the three soils, but the P rates affected only the P, S, and Mn concentrations in all three soils, and the Zn concentration in the soil with low initial P availability (Table 4). In general, in low P availability soil, the tuber concentrations of P, K, Ca, Mg, S, Fe, and Zn of cv. Agata were high. In the soil with medium P availability, the tuber concentrations of K and Mg in cv. Agata were high, while cv. Mondial had high Fe and Mn concentrations. At high soil P availability, cultivar Agata had high concentrations of P, Fe, and Mn in its tubers and cv. Atlantic had tubers with lower concentrations of K, Mg, B, and Cu than the other cultivars.

Phosphate fertilization in the planting furrow led to a linear increase in P concentrations in the tubers in soil with medium initial P availability, and up to application rates estimated at 818 and 875 kg ha^{-1} P_2O_5 in soils with low and high initial P soil, respectively (Figure 5c). In soils with low and medium P availability, the S concentration in tubers decreased up to the rate of 250 kg ha^{-1} P_2O_5 (Figure 5d). In the soil with high P availability, the opposite occurred and the S concentration in tubers increased up to the rate of 250 kg ha^{-1} P_2O_5. The Mn concentrations in tubers exhibited a significant decrease up to 500 kg ha^{-1} P_2O_5 in the soil with low P availability and decreased in a linear manner in the soil with high P availability (Figure 5e). In the soil with medium P availability, phosphate fertilization increased the tuber Mn concentrations up to the rate estimated at 515 kg ha^{-1} P_2O_5. The Zn concentration in tubers from soil with low initial P availability decreased by about 24 % up to the highest P rate studied (Figures 5f).

Only the cultivar and P rate factors had an effect on nutrient removal at the three levels of initial soil P availability (Table 5). In the soils with low and medium P availability, nutrient removal by cv. Mondial was higher than removal by the other cultivars (except for Ca in the soil with medium P availability). However, in the high P availability soil, the

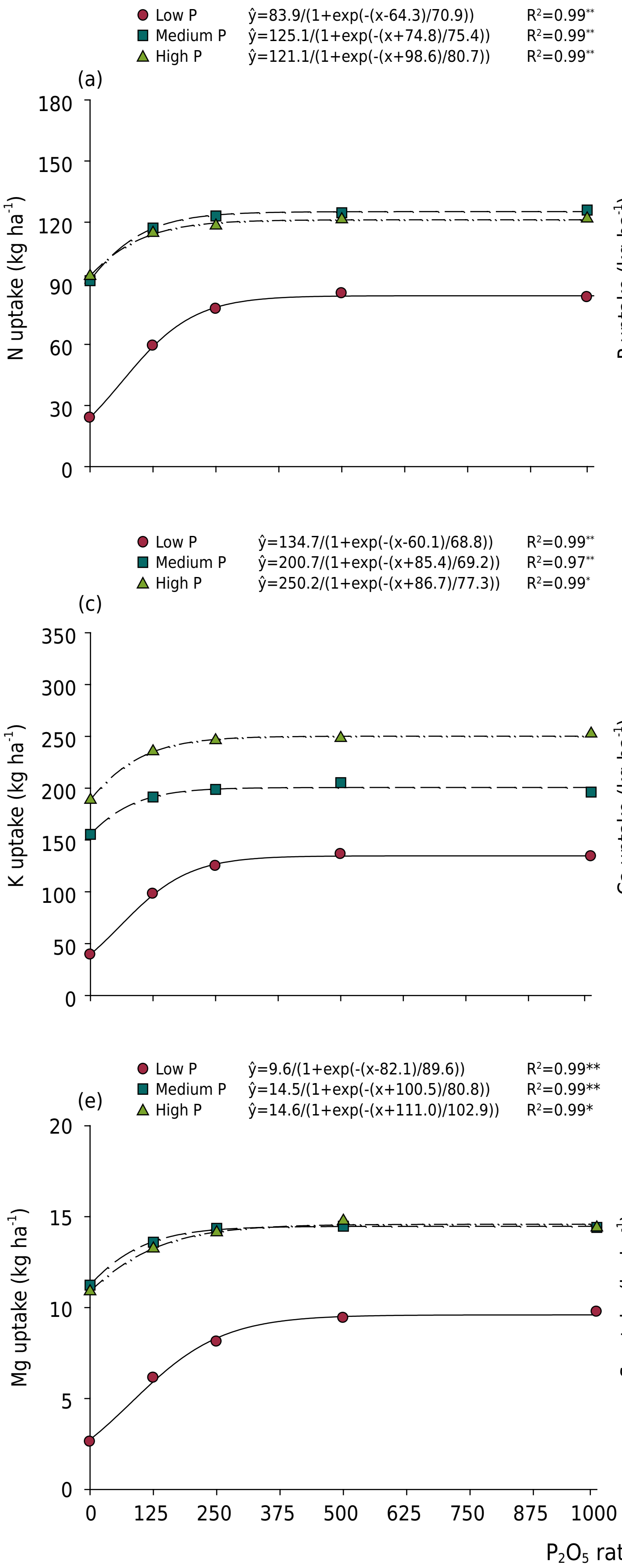

Figure 3. Uptake of N (a), P (b), K (c), Ca (d), Mg (e), and S (f) by potato plants as affected by rates of P applied in the planting furrow in soils with low, medium, and high P availability. Means of five cultivars. * and **: significant at 5 and 1 % by the F test.

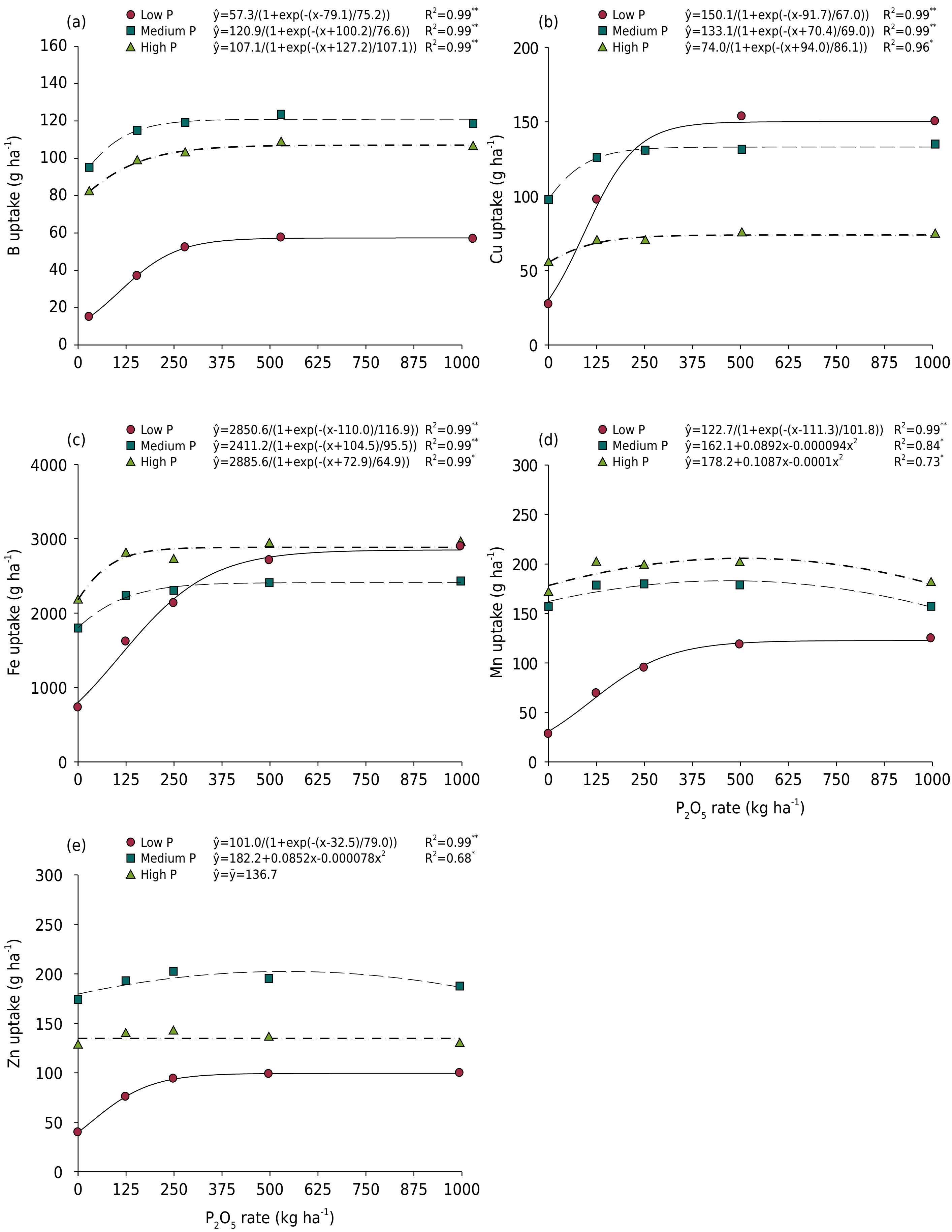

Figure 4. Uptake of B (a), Cu (b), Fe (c), Mn (d), and Zn (e) by potato plants as affected by rates of P applied in the planting furrow in soils with low, medium, and high P availability. Means of five cultivars. * and **: significant at 5 and 1 % by the F test.

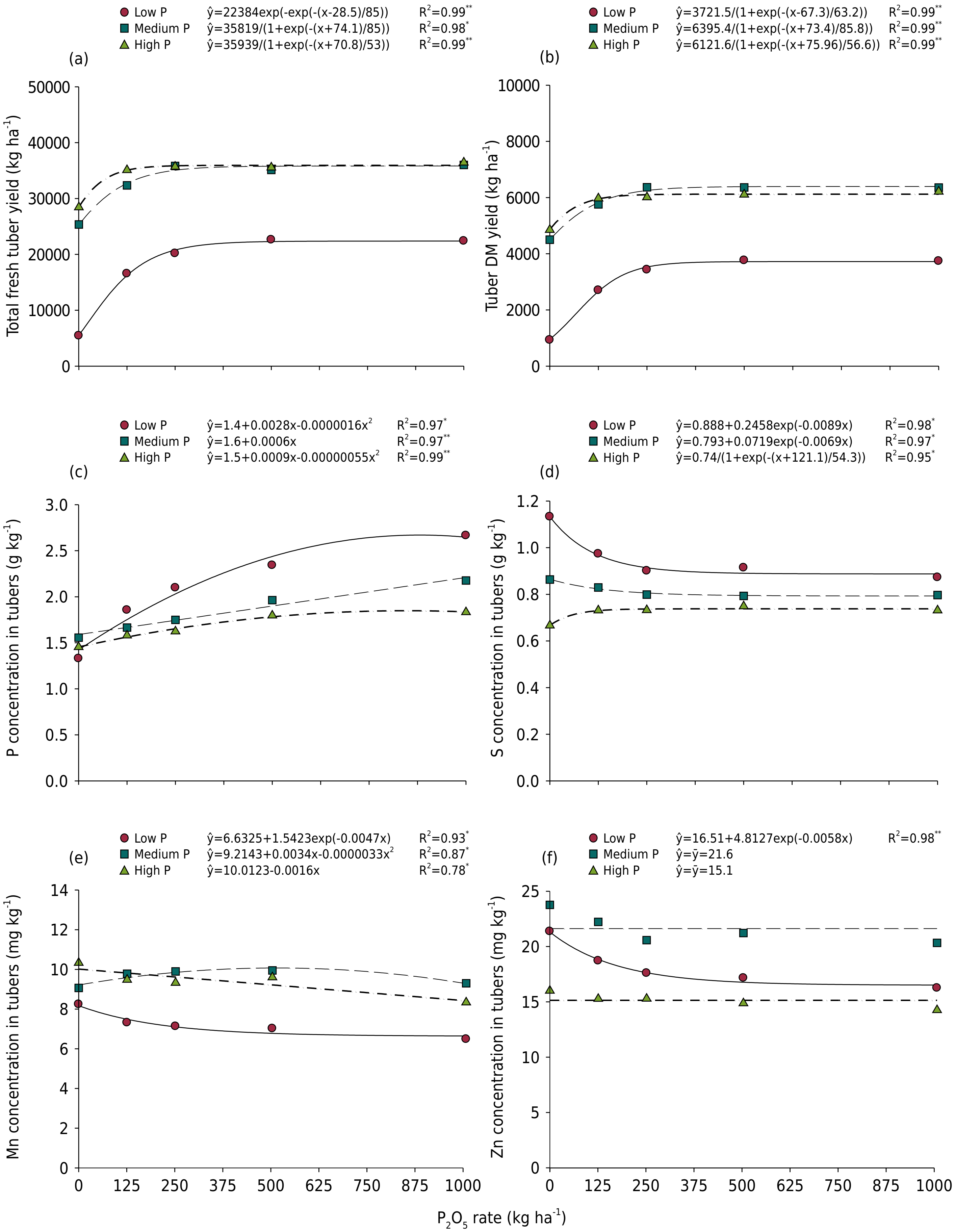

Figure 5. Total fresh tuber yield (a), tuber dry matter (DM) yield (b), and concentrations of P (c), S (d), Mn (e), and Zn (f) in potato tubers as affected by rates of P applied in the planting furrow in soils with low, medium, and high P availability. Means of five cultivars. * and **: significant at 5 and 1 % by the F test.

Table 4. Total fresh tuber yield (TFTY), tuber dry matter yield (TDMY), and nutrient (N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn) concentrations in tubers of five potato cultivars as affected by rates of P applied in the planting furrow in soils with low, medium, and high P availability

Treatment	TFTY	TDMY	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
	kg ha^{-1}		g kg^{-1}						mg kg^{-1}				
Cultivar	Low P availability (14 mg dm^{-3})												
Agata	18,569 b	2,651 bc	20.4 b	2.2 a	27.6 a	0.8 a	1.3 a	1.0 a	8.5 a	6.3 a	174.4 a	7.7 a	19.6 a
Asterix	16,897 b	2,951 b	17.9 c	1.9 b	25.6 ab	0.7 b	1.3 a	0.9 ab	9.2 a	7.2 a	139.9 c	7.1 a	19.0 ab
Atlantic	12,776 c	2,408 c	18.0 c	2.0 ab	25.6 ab	0.6 c	1.1 c	1.0 a	8.7 a	6.9 a	164.3 ab	6.9 a	16.5 c
Markies	14,590 c	2,527 bc	22.7 a	2.3 a	27.0 ab	0.7 b	1.4 a	1.0 a	9.2 a	6.6 a	141.9 bc	7.8 a	18.8 abc
Mondial	24,342 a	4,028 a	16.9 c	1.8 b	25.2 b	0.6 c	1.2 b	0.8 b	9.7 a	6.9 a	144.9 bc	6.7 a	17.2 bc
	F probability												
Cultivar (C)	<0.001	<0.001	<0.001	<0.001	0.016	<0.001	<0.001	<0.001	ns	ns	<0.001	ns	0.001
Furrow-applied P rate (P)	<0.001	<0.001	ns	<0.001	ns	ns	ns	<0.001	0.032	ns	ns	0.001	<0.001
C × P	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Cultivar	Medium P availability (36 mg dm^{-3})												
Agata	27,919 c	4,076 d	18.2 ab	1.9 a	29.8 a	0.4 c	1.7 a	0.9 a	10.8 abc	6.8 b	96.4 b	9.2 bc	19.7 a
Asterix	35,614 b	6,649 b	16.4 c	1.8 a	26.2 bc	0.8 a	1.6 ab	0.8 a	11.6 a	5.5 c	102.4 ab	8.2 c	23.2 a
Atlantic	25,456 c	5,307 c	16.7 bc	1.8 a	25.3 c	0.4 c	1.3 d	0.9 a	9.7 c	8.4 a	99.4 ab	9.2 bc	22.6 a
Markies	28,833 c	5,554 c	19.4 a	1.9 a	27.7 b	0.3 d	1.4 c	0.8 a	10.0 bc	8.8 a	101.6 ab	10.0 ab	20.4 a
Mondial	46,840 a	7,757 a	17.7 bc	1.8 a	27.2 b	0.5 b	1.4 bc	0.8 a	11.2 ab	6.8 b	114.4 a	11.4 a	22.3 a
	F probability												
Cultivar (C)	<0.001	<0.001	<0.001	ns	<0.001	<0.001	<0.001	ns	<0.001	<0.001	0.033	<0.001	ns
Furrow-applied P rate (P)	<0.001	<0.001	ns	<0.001	0.013	0.013	ns	ns	ns	0.032	ns	ns	ns
C × P	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Cultivar	High P availability (70 mg dm^{-3})												
Agata	37,556 b	5,303 ab	18.0 b	1.8 a	28.6 a	0.4 a	1.4 a	0.7 a	10.3 a	7.7 a	94.4 ab	11.5 a	14.1 b
Asterix	35,952 b	6,493 a	17.2 bc	1.6 b	28.0 a	0.4 a	1.5 a	0.7 a	10.3 a	6.0 bc	79.5 c	10.2 b	16.2 a
Atlantic	25,507 d	5,168 b	16.4 c	1.6 b	26.3 b	0.4 a	1.2 b	0.8 a	8.5 b	4.9 c	105.6 a	9.5 bc	13.7 b
Markies	30,457 c	5,736 b	19.4 a	1.7 ab	28.7 a	0.3 a	1.4 a	0.7 a	9.0 b	7.4 a	89.6 bc	8.2 cd	15.0 ab
Mondial	41,748 a	6,450 a	16.8 bc	1.6 b	28.5 a	0.4 a	1.4 a	0.7 a	10.4 a	6.5 ab	80.5 bc	7.7 d	16.6 a
	F probability												
Cultivar (C)	<0.001	<0.001	<0.001	0.002	<0.001	ns	<0.001	ns	<0.001	<0.001	<0.001	<0.001	<0.001
Furrow-applied P rate (P)	<0.001	<0.001	ns	<0.001	ns	ns	ns	ns	ns	ns	ns	0.002	ns
C × P	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Means followed by the same letter in a column are not significantly different at $p \leq 0.05$ by Tukey's test. ns: not significant at $p \leq 0.05$.

removal of N, P, and Cu by cv. Mondial did not differ from cv. Asterix and Markies, while removal of K, Ca, Mg, B, and Zn was similar to that of cv. Asterix.

Phosphate fertilization increased the removal of all nutrients under all conditions of initial soil P availability (Figures 6 and 7). The removal of N increased up to 500 kg ha^{-1} P_2O_5 in the soil with low initial P availability, and up to 250 kg ha^{-1} P_2O_5 in the other soils, while removal of Mg from all soils increased up to 250 kg ha^{-1} P_2O_5 (Figures 6a and 6e). The removal of K increased up to 250 kg ha^{-1} P_2O_5 in the soil with low P availability, but only up to 125 kg ha^{-1} P_2O_5 in the other soils (Figure 6c). In soil with high P availability, removal of S increased up to 125 kg ha^{-1} P_2O_5, but it increased up to twice that rate of P application in the other soils (Figure 6f).

The amounts of P removed by tubers from soils with low and medium P availability increased up to the highest P rate studied (Figure 6b). In the soil with high P availability, there was an increase in the removal of this nutrient only up to the rate of 500 kg ha^{-1} P_2O_5. The maximum P removal was 10, 11, and 14 kg ha^{-1} P in soils with low, high, and medium initial P availability, respectively. In the soils with low and

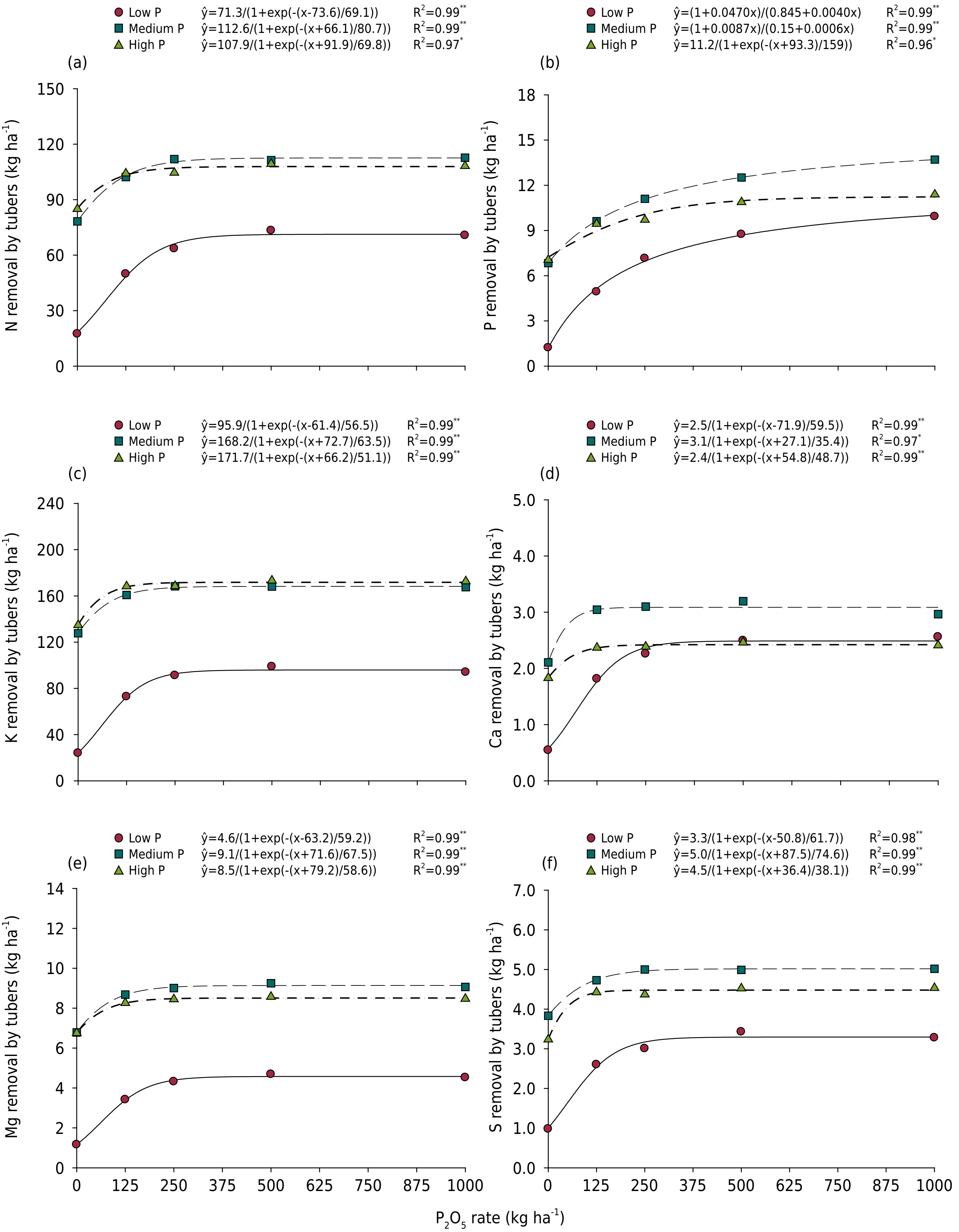

Figure 6. Removal of N (a), P (b), K (c), Ca (d), Mg (e), and S (f) by potato tubers as affected by rates of P applied in the planting furrow in soils with low, medium, and high P availability. Means of five cultivars. * and **: significant at 5 and 1 % by the F test.

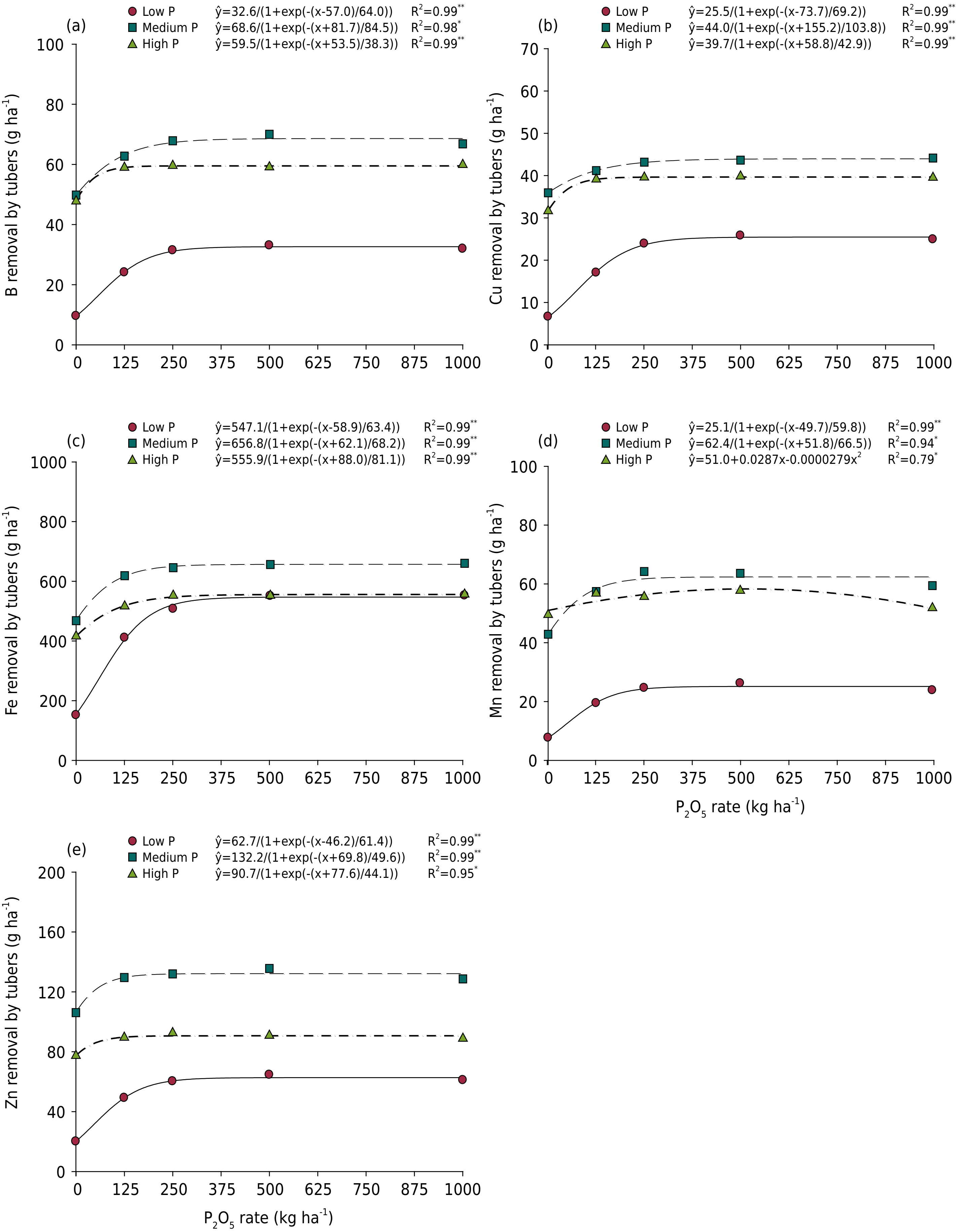

Figure 7. Removal of B (a), Cu (b), Fe (c), Mn (d), and Zn (e) by potato tubers as affected by rates of P applied in the planting furrow in soils with low, medium, and high P availability. Means of five cultivars. * and **: significant at 5 and 1 % by the F test.

Table 5. Nutrient (N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn) removal by tubers of the potato cultivars as affected by rates of P applied in the planting furrow in soils with low, medium, and high P availability

Treatment	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
	kg ha^{-1}						g ha^{-1}				
Cultivar	Low P availability (14 mg dm^{-3})										
Agata	54 b	6 b	73 b	2.1 b	3.4 b	2.5 b	22 bc	17 c	472 b	20 b	49 b
Asterix	53 b	6 b	74 b	2.1 b	3.8 b	2.7 b	26 b	21 b	400 c	20 b	54 b
Atlantic	43 c	5 b	62 b	1.4 c	2.7 c	2.3 b	20 c	17 c	387 c	15 c	38 c
Markies	57 b	6 b	68 b	1.6 c	3.4 b	2.5 b	23 bc	16 c	340 c	20 b	46 b
Mondial	68 a	8 a	103 a	2.5 a	4.8 a	3.3 a	38 a	27 a	574 a	26 a	67 a
	F probability										
Cultivar (C)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Furrow-applied P rate (P)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
C × P	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Cultivar	Medium P availability (36 mg dm^{-3})										
Agata	75 d	8 d	122 c	1.6 c	6.7 c	3.5 c	44 d	28 d	394 d	38 c	79 c
Asterix	111 b	12 b	173 b	5.1 a	10.3 a	5.1 b	78 b	36 c	683 b	55 b	153 a
Atlantic	88 c	9 c	132 c	2.1 c	6.8 c	4.6 b	52 c	44 b	523 c	50 b	117 b
Markies	106 b	10 c	154 b	1.6 c	7.9 b	4.5 b	56 c	48 ab	574 c	55 b	112 b
Mondial	137 a	14 a	211 a	3.9 b	11.1 a	5.9 a	88 a	52 a	875 a	89 a	171 a
	F probability										
Cultivar (C)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Furrow-applied P rate (P)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.002	<0.001	<0.001	0.001
C × P	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Cultivar	High P availability (70 mg dm^{-3})										
Agata	95 b	9 ab	151 b	2.0 b	7.5 b	3.9 b	55 b	41 a	502 a	60 a	74 bc
Asterix	112 a	10 a	182 a	2.8 a	9.6 a	4.7 a	67 a	39 a	517 a	67 a	105 a
Atlantic	84 b	8 b	136 c	2.0 b	6.4 c	3.9 b	44 c	25 b	546 a	48 b	70 c
Markies	111 a	10 a	165 b	2.0 b	8.2 b	4.0 b	52 bc	42 a	511 a	47 b	86 b
Mondial	109 a	11 a	184 a	2.7 a	8.8 ab	4.5 b	67 a	42 a	516 a	49 b	106 a
	F probability										
Cultivar (C)	<0.001	<0.001	<0.001	<0.001	<0.001	0.002	<0.001	<0.001	ns	<0.001	<0.001
Furrow-applied P rate (P)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	<0.001	0.032	0.006
C × P	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Means followed by the same letter in a column are not significantly different at p≤0.05 by Tukey's test. ns: not significant at p≤0.05

medium P availability, the Ca removal increased up to rates estimated at 500 and 561 kg ha^{-1} P_2O_5, respectively, while in the soil with high P availability, Ca removal only increased up to 125 kg ha^{-1} P_2O_5 (Figure 6d).

In the soil with low P availability, the removal of B, Cu, Fe, Mn, and Zn increased up to the rate of 500 kg ha^{-1} P_2O_5 (Figures 7a, 7b, 7c, 7d, and 7e). In soils with medium and high P availability, the removal of most micronutrients increased up to rates estimated from 125 to 250 kg ha^{-1} P_2O_5. In soil with high P availability, Mn was the only micronutrient that was removed, with a small increase up to the rate estimated at 514 kg ha^{-1} P_2O_5 (Figure 7d).

DISCUSSION

Regardless of the initial soil P availability, phosphate fertilization increased leaf P concentration up to values within and/or above the adequate ranges proposed for potato by Lorenzi et al. (1997). In general, with the exception of P, phosphate fertilization had little influence on the nutritional status of plants for most nutrients, and the leaf nutrient concentrations were normally within the above ranges. This indicates that the crop was not affected by stress due to nutrient deficiency, except for P in the soil that had low soil P availability and no P application in the planting furrow. Although phosphate fertilization decreased the leaf Mn and Zn concentrations of plants grown in the soil with low initial P availability, these concentrations were within the ranges of 30-250 mg kg^{-1} Mn and 20-60 mg kg^{-1} Zn. These results demonstrate that initial soil P availability and phosphate fertilization in the planting furrow do not significantly affect the nutritional status of the plants by interactions with the other nutrients to the point of causing nutrient deficiency (Fernandes et al., 2015).

The plants of cv. Mondial accumulated more DM in the whole plant than the other cultivars (Table 2). This higher DM accumulation is a result of the high growth rates of the cultivar during the development cycle (Fernandes et al., 2010). Potato plants with adequate P supply develop more lateral branches, more leaves, and a larger photosynthetically active leaf area (Jenkins and Mahmood, 2003; Fleisher et al., 2013). Thus, in the soils more fertile in P, the plant growth responses to P application in the planting furrow were weaker and occurred in response to lower P application rates (125 to 250 kg ha^{-1} P_2O_5) (Figure 2a), because in the soils with higher P availability, the residual P concentrations in the soil were sufficient for generating satisfactory plant growth (Fontes et al., 1997; Ali and Anjum, 2004). This indicates that there is no need to apply high P rates to more P-fertile soils, contrary to the traditional custom of growers in Brazil.

In general, the nutrient concentrations of cv. Mondial plants were lower than those of the other cultivars (Table 2). These lower nutrient concentrations were associated with the higher DM production of the plants of this cultivar, resulting in a dilution effect (Jarrell and Beverly, 1981). At all levels of initial soil P availability, phosphate fertilization increased P concentrations in potato plants to rates exceeding those that resulted in maximum plant DM production (Figures 2a and 2b); this indicates that applications of high P rates in the planting furrow can cause luxury uptake of this nutrient. Under high P availability, the plant use efficiency of the P taken up decreases (Fernandes and Soratto, 2012b), which results in P uptake higher than necessary for DM production (Alvarez-Sánchez et al., 1999; Rosen and Bierman, 2008; Fernandes and Soratto, 2012b; Soratto and Fernandes, 2016). Especially in P-deficient soil, phosphate fertilization reduced the plant Mg and S concentrations because of nutrient dilution in the plants, caused by the highly significant increase in DM production of the plants cultivated in this soil (Figures 2a, 2c, and 2d).

In the soil with low initial P availability, the application of this nutrient increased plant Cu concentrations, but when P was supplied at high rates, it reduced Cu concentrations in the potato plants (Figure 2e) because high P availability led to the formation of Cu phosphate in the soil, which is unavailable to plants (Islam et al., 2009). The literature states that excessive P availability can inhibit root Fe uptake, and the root-to-shoot transport of Fe (Fageria, 2001). However, in more P-fertile soils, phosphate fertilization did not significantly affect the Fe concentration in potato plants, and when soil P availability was low, the P applications even increased plant Fe concentrations (Table 2 and Figure 2f).

Mainly at higher soil P availability, the plant Mn concentrations decreased with phosphate fertilization (Figure 2g). This indicates that soil P availability interferes with plant Mn concentrations (Barben et al., 2010a; Fernandes and Soratto, 2012b), possibly by influencing root Mn uptake and transport in the plants (Barben et al., 2010b). There was a reduction in plant Zn concentrations in response to phosphate fertilization in all soils (Figure 2h), which can be explained by the increase in plant DM production in response to P application, which resulted in a dilution effect (Fageria et al., 1997; Soratto and Fernandes, 2016).

The cv. Agata and Atlantic, in general, took up smaller amounts of nutrients than cv. Mondial did (Table 3), in part due to their less developed root systems, with shorter root length and smaller root surface area (Fernandes et al., 2014), and also due to their reduced growth and DM production (Table 2). However, particularly in soil with high P availability, cv. Mondial did not always take up larger amounts of nutrients (Table 3), indicating that cultivars with higher DM accumulation do not always take up larger amounts of all nutrients (Fernandes et al., 2015).

The uptake of N, K, Ca, Mg, and S was 3.1 to 4.3 times greater up to the rate of 500 kg ha^{-1} P_2O_5 in the soil with low P availability, and 1.3 times greater up to 250 kg ha^{-1} P_2O_5 in other soils, which indicates that the crop demand for these nutrients was higher because phosphate fertilization increased the biomass production of the potato plants, with little or no effect on plant nutrient concentrations (Figures 2 and 3, and Table 2). Higher soil P availability increased the uptake of the N and K nutrients by increasing the DM production of potato plants (Munda et al., 2015; Soratto and Fernandes, 2016). In all soils, an increase of 1.7 to 5.8 times in P uptake by the potato plants up to the 500 kg ha^{-1} P_2O_5 rate occurred because, especially in the more P-fertile soils, the plant P concentrations increased beyond the P rates necessary to ensure maximum plant DM production (Figures 2b and 3b). This suggests that under higher soil P availability, the application of high P rates caused luxury uptake of P (Alvarez-Sánchez et al., 1999; Rosen and Bierman, 2008; Fernandes and Soratto, 2012b; Soratto and Fernandes, 2016) and decreased P use efficiency of the plants (Fernandes and Soratto, 2012b).

In soils with medium and high P availability, the B, Cu, and Fe uptake in potato plants increased 1.3 to 1.4 times, up to the same P rates that obtained maximum DM accumulation (125-250 kg ha^{-1} P_2O_5) (Figures 2a, 4a, 4b, and 4c). In these soils, since phosphate fertilization did not alter the plant nutrient concentrations, the increase in B, Cu, and Fe uptake reflected the increase in DM production (Figures 2 and 4, and Table 2). However, at low soil P availability, Cu uptake that was 5.7 times greater up to 500 kg ha^{-1} P_2O_5 and Fe uptake that was 4 times greater up to the highest P rate was related to the increases in biomass and plant concentrations of these nutrients, indicating that under this condition, the increase in the uptake of these nutrients was not solely due to the increase in plant DM production (Figures 2a, 2e, 2f, 4b, and 4c). Most likely, in P-deficient soil, the P supply improved the root environment and favored plant Cu and Fe uptake by plants.

The application of high P rates reduced Mn uptake only in the most P-fertile soils, by 10 % (Figure 4d). This reduction in Mn uptake occurred because phosphate fertilization led to a linear decrease in the Mn concentrations of plants grown in the most P-fertile soils, indicating that the high soil P availability may have interfered with Mn uptake (Figure 2g). Studies have shown that high P availability compromises Mn root uptake and its transport to the plant shoot (Barben et al., 2010b) because at high P availability, Mn-P complexes can be formed in root tissues (Barben et al., 2010a).

In soils with lower initial P availability, Zn uptake was 1.1 to 2.5 times greater up to rates between 500 and 546 kg ha^{-1} P_2O_5 because phosphate fertilization increased plant DM production, which consequently increased the crop Zn demand (Figures 2a and 2e). However, in soil with high P availability, phosphate fertilization, regardless of increases in the plant biomass, did not significantly affect Zn uptake, because in this soil the plant Zn concentrations decreased linearly with increasing P rates (Figures 2a and 2h, and Table 3). This is an indication that excessive P applications may reduce Zn uptake by potato, as observed by other authors (Christensen and Jackson, 1981; Hopkins et al., 2003). Phosphate fertilization increased the plant biomass without increasing Zn uptake. However, since the P and Zn availability in this soil was high, P fertilization induced no deficiency of Zn (Tables 1 and 3, and Figure 2a). This indicates that the P-Zn interaction becomes relevant when the soil availability of one of these elements is low (Fageria, 2001; Araújo and Machado, 2006). The maximum ranges of nutrient uptake per hectare observed in response to P applications were 85-123 kg N, 11.5-15.4 kg P, 136-246 kg K, 19-26 kg Ca, 9.4-14.3 kg Mg, 5.3-8.7 kg S, 57-124 g B, 75-154 g Cu, 2,409-2,929 g Fe, 118-201 g Mn, and 100-198 g Zn.

The absence of a cultivar × P rate interaction for fresh tuber yield and tuber DM yield in the three soils indicates that, at each of the initial soil P availability, the five potato cultivars responded to the same P rate (Table 4). The increase in fresh tuber yield and tuber DM yield up to the rates of 500, 250, and 125 kg ha^{-1} P_2O_5 in soils with low, medium, and high initial P availability, respectively, indicates that at high soil P availability, there is no need to apply high P rates to potato (Figures 5a and 5b). Other studies have indicated no increase and/or only small increases in potato tuber yield in response to the application of high P rates in soils with high initial P availability (Rykbost et al., 1993; Hochmuth et al., 2002; Rosen and Bierman, 2008; Luz et al., 2013; Rosen et al., 2014; Fernandes and Soratto, 2016). However, Brazilian producers still commonly apply rates higher than 600 kg ha^{-1} P_2O_5 in potato-growing areas (Sangoi and Kruse, 1994; Fernandes et al., 2011).

Cultivars differed in nutrient removal (Table 5). The cv. Mondial removed many nutrients from soils with low and medium P availability because of its high tuber DM yield (Table 4). This cultivar did not remove more nutrients from the soil with high P availability because, in general, the nutrient concentrations in its tubers were not higher than the concentrations in the tubers of the other cultivars (Tables 4 and 5). This shows that the high tuber yield of cv. Mondial is not necessarily associated with a higher removal of all nutrients (Fernandes et al., 2010; Soratto et al., 2011).

When potato cultivars were averaged, phosphate fertilization increased the removal of all nutrients in all soils and the highest increase was for P removal, especially in the soil with low level of initial P availability (Figures 6 and 7). The maximum nutrient removal ranges per hectare were 73-111 kg N, 9.9-13.7 kg P, 99-173 kg K, 2.5-3.2 kg Ca, 4.7-9.2 kg Mg, 3.4-4.9 kg S, 33-70 g B, 26-44 g Cu, 551-656 g Fe, 26-64 g Mn, and 65-136 g Zn. Nutrient removal in response to phosphate fertilization increased mainly due to the increase in tuber yield since, in general, the removal of most nutrients from each soil increased up to the P rate that induced the maximum tuber DM yield (Figures 5a, 5b, 6, and 7). The amounts of N, P, and K accumulated in potato tubers are more related to the tuber DM yield than the concentrations of these nutrients in the tuber (Šrek et al., 2010).

The increase in S removal only up to 250 kg ha^{-1} P_2O_5 in the soil with low initial P availability, where the tuber yield increased up to double this rate, reflected the reduction in tuber S concentration induced by phosphate fertilization (Figures 5a, 5c, and 6f). This indicates that P may affect S translocation to potato tubers. In common bean, the reduction in plant S uptake in response to high P rates was attributed to the competition of sulfate and phosphate anions at root uptake sites, or to the competition for the same uptake pathways within roots and stem (Aulakh and Pasricha, 1977).

The amounts of P removed by tubers increased up to 8.3 times in the soil with low initial P availability because of the increase in tuber DM yield and tuber P concentrations; P removal increased from the less P-fertile soils up to the highest P rate applied (Figures 5b, 5c, and 6b). The application of high P rates may unnecessarily increase P removal because P removal increased beyond the rate of phosphate fertilization that induced the highest fresh tuber yield, i.e., a high P supply increases P translocation to the tubers.

When potato cultivars were averaged, the removal of Mn and Zn were increased by P fertilization in all soils (Figures 7d and 7e), even with slight decreases in tuber Mn concentrations in all soils with low and high initial P availability and in tuber Zn concentrations in P-deficient soil (Figures 5e and 5f).

CONCLUSIONS

Under low, medium, and high soil P availability, phosphate fertilization increased plant growth and tuber DM yield up to 500, 250, and 125 kg ha^{-1} P_2O_5, respectively. However, for each level of initial soil P availability, all potato cultivars responded to the same P rate applied in the planting furrow for plant growth, tuber yield, and nutrient uptake and removal.

Regardless of the soil P availability levels, leaf analysis showed that the nutritional status of potato plants was not significantly changed and no nutritional deficiency was induced by the highest P fertilization rates; however, in soils with higher P availability, P fertilization linearly decreased the plant Mn and Zn, and tuber Mn concentrations.

Increases in N, K, Ca, Mg, S, B, Cu, and Fe uptake and in the removal of most nutrients in response to phosphate fertilization were more related to increases in plant biomass and tuber DM yield than to changes in concentrations of these nutrients in the plants.

At a high level of soil P availability, high application rates caused luxury P uptake, reducing Mn uptake by 10 %, and due to a decrease in plant Zn concentrations, Zn uptake was not increased by increases in the plant biomass.

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