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Nutrient uptake and removal by runner peanut cultivars of different maturity groups

Carlos Felipe dos Santos Cordeiro[(1)]*, Leonardo Vesco Galdi[(2)] and Fábio Rafael Echer[(2)]

[(1)] Universidade Estadual Paulista "Júlio de Mesquita Filho", Faculdade de Ciências Agronômicas, Departamento de Ciência Agrícola, Botucatu, São Paulo, Brasil.
[(2)] Universidade do Oeste Paulista, Departamento de Agronomia, Presidente Prudente, São Paulo, Brasil.

ABSTRACT: Modern runner-type peanut cultivars have high yield potential, but little is still known about the dynamics of nutrient uptake by these cultivars and whether nutrient uptake differs between maturity groups. This study evaluated the growth, nutrient uptake, and nutrient removal of runner-type peanut cultivars with early and late maturity. The study was conducted in the field in the 2021/2022 season, in a sandy soil environment in southeastern Brazil. Treatments consisted of runner-type peanut cultivars (early and late maturity) and the phenological stage of sampling (V4/V5, R2/R3, R4, R5, R6, R7, and R8). Average pod yields were 4.0 and 5.9 Mg ha^{-1} for the early and late-maturity cultivars, respectively. Uptake of P, Cu, and Zn was linearly increased until stage R8. Nitrogen uptake continued until stage R7 for the early-maturity cultivars and stage R8 for the late-maturity cultivar. Potassium and B uptake did not increase after stages R5 and R6, respectively. For all other nutrients, maximum uptake occurred between stages R3 and R7. Leaf contents of all nutrients were within the sufficiency range, except Fe, which was higher than needed. Maximum macronutrient uptake (late-maturity cultivar) rates were 300, 28, 215, 76, 31, and 19 kg ha^{-1} for N, P, K, Ca, Mg, and S, respectively, and the maximum micronutrient uptake rates were 2350, 95, 391, 659, and 414 g ha^{-1} for Fe, Cu, Zn, Mn, and B, respectively. Maximum macronutrient removal rates were 210, 20, 48, 15, 7, and 12 kg ha^{-1} for N, P, K, Ca, Mg, and S, respectively, and the maximum micronutrient removal rates were 967, 59, 236, 153, and 136 g ha^{-1} for Fe, Cu, Zn, Mn, and B, respectively. Late-maturity cultivar had higher biomass production and greater uptake of all nutrients except K and Fe. The uptake of K and Fe was the same for both maturity groups.

Keywords: sandy soil, nutrient dynamics, macronutrients, micronutrients, plant nutrition.

*** Corresponding author:**
E-mail: cordeirocfs@gmail.com

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INTRODUCTION

Peanut (*Arachis hypogaea* L.) production and yields have risen in Brazil in the last decade. Peanut cultivation now covers approximately 260,000 ha, with yields ranging between 4,000 and 5,000 kg ha^{-1} (Aparecido et al., 2021; Conab, 2024). Peanut cultivation expansion in Brazil is primarily attributable to the introduction of new high-oleic runner-type cultivars with high yields and good grain quality (Godoy et al., 2017; Suassuna et al., 2019, 2020). Adopting new technologies such as high-performance mechanized harvesting and improved fertilization and plant nutrition management has also contributed to this increase.

Historically, peanut production has been considered unresponsive to fertilization, mainly due to the widespread use of low-yield Valencia and Spanish cultivars (Nakagawa and Rosolem, 2011) and cultivation predominantly in fertile soils, often in a system of sugarcane renewal in Brazil. However, approximately 70 % of peanut production in Brazil (Aparecido et al., 2021) and 80 % worldwide now occurs in low-fertility sandy soils (Rachaputi et al., 2021). Studies of nutrient uptake and removal by peanuts are essential for a better understanding of nutrient dynamics in peanuts and improvements in peanut fertilization management. Therefore, knowing how much the runner-type peanuts uptake and removal of each nutrient, and the timing of the highest uptake rate will improve fertilizer management, nutrient use efficiency by peanut farmers and technicians.

Recent studies about nutrient uptake and removal by peanut have mainly focused on high-fertility, clayey soils and paid little attention to the differences between cultivars belonging to different maturity-cycle groups (Bertino et al., 2022; Crusciol et al., 2021, 2023). In Brazil, peanut production is split approximately evenly between early-maturing (EM) cultivars, which have maturity cycles of 120–130 days, and late-maturing (LM) cultivars, which have maturity cycles of 140–150 days (Godoy et al., 2017; Nawade et al., 2018; Suassuna et al., 2019). Late-maturing cultivars have a more indeterminate growth pattern than EM cultivars (Stalker et al., 2016) and exhibit greater root growth, which may enhance phosphorus (P) acquisition (Cordeiro et al., 2024a). However, EM cultivars have a more concentrated flowering and pod formation period (Rachaputi et al., 2021), which may accelerate nutrient uptake. This study evaluated biomass production and nutrient uptake and removal by EM and LM cultivars to improve our understanding of nutrient dynamics in modern runner-type peanut. We hypothesize that late-maturity cultivar have higher uptake of nutrients and biomass production.

MATERIALS AND METHODS

Site description

Field experiment was carried out in the 2021/2022 season at Presidente Prudente, São Paulo, Brazil (22° 07’ 10” S, 51° 26’ 59” W, 475 m elevation). The region has a tropical climate with dry winters (Aw in the Köppen classification system). Total rainfall during the crop season was 819 mm; Figure 1 presents the distribution of rainfall and minimum and maximum temperatures during the season. Over the last 30 years, the average total rainfall during the crop season was 827 mm. The soil of the area is classified as Oxisols (Soil Survey Staff, 2014), which corresponds to a *Latossolo Vermelho-Amarelo Distrófico* (Santos et al., 2013), with low fertility, low iron oxide and aluminum oxide contents, and sandy texture (6.2 % clay, 0.00-0.20 m). Chemical properties of the soil (0.00-0.20 m) are as follows: pH: ($CaCl_2$) 5.1, organic carbon: 11 g dm^{-3}, phosphorus (P resin): 28 mg dm^{-3}, sulfur (S): 3 mg dm^{-3}, potassium (K): 1.6 $mmol_c$ dm^{-3}, exchangeable calcium (Ca): 12 $mmol_c$ dm^{-3}, exchangeable magnesium (Mg): 7 $mmol_c$ dm^{-3}, cation exchange capacity (CEC): 42 $mmol_c$ dm^{-3}, boron (B): 0.09 mg dm^{-3}, copper (Cu): 1.5 mg dm^{-3}, iron (Fe): 47 mg dm^{-3}, manganese (Mn): 4 mg dm^{-3}, and zinc (Zn): 1.3 mg dm^{-3}. Interpretation of soil analysis results and recommendations was carried out in accordance with Quaggio et al. (2022).

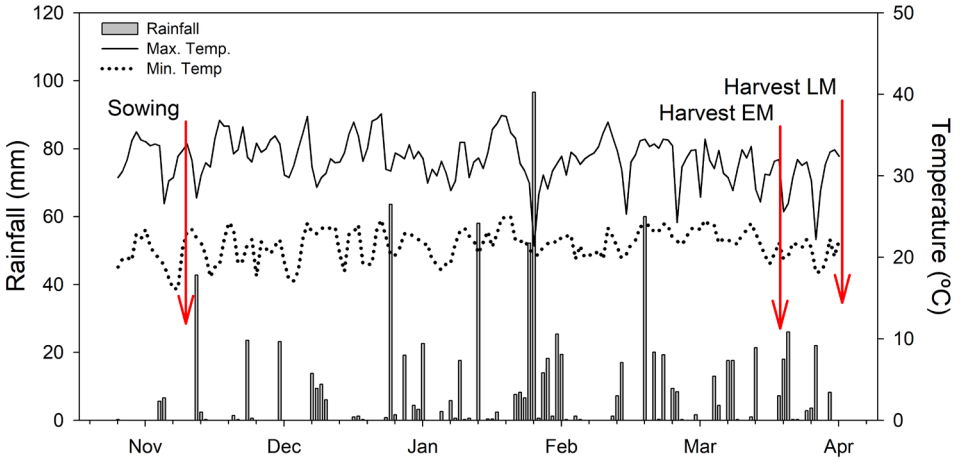

Figure 1. Rainfall and maximum and minimum temperatures during the study. Presidente Prudente-São Paulo, Brazil, 2021/2022. EM: early-maturing, LM: late-maturing.

Experimental design

The experiment followed a complete randomized block design with four replications. The treatments consisted of three modern runner-type peanut cultivars and different shoot sampling times (phenological stages). The cultivars were: BRS 423 OL (EM), Granoleico (EM), and BRS 421 OL (LM). The EM cultivars were sampled seven times: 24, 48, 62, 76, 90, 104, and 120 days after emergence (DAE), which correspond to phenological stages V5, R3, R4, R5, R6, R7, and R8, respectively, according to Boote (1982). The LM cultivar was sampled eight times: 24, 48, 62, 76, 90, 104, 120, and 134 DAE, which correspond to phenological stages V4, R2, R3, R4, R5, R6, R7, and R8, respectively (Boote, 1982). The plots were 3.6 m wide and 6.0 m long. Each plot had four rows, with a spacing of 0.9 m between rows and 15 plants per meter.

Peanut management

Soil tillage was carried out with a medium harrow in October 2021. Limestone (31 % CaO and 21 % MgO) was then applied at a rate of 1 Mg ha^{-1} and incorporated – 0.20 m deep - with a light harrow. Three peanut cultivars were sown on November 17, 2021, and emergence occurred on November 23. Immediately before sowing, fertilizer was mechanically applied using the seeder. Sowing was carried out manually at a rate of 20 seeds per meter and row spacing of 0.9 m. Basal fertilization was 8, 28, 16, and 30 kg ha^{-1} of N, P, K, and S, respectively, using urea (45 % N), triple superphosphate (41 % P_2O_5), potassium chloride (60 % K_2O), and elemental sulfur (90 % S). Micronutrients were applied at rates of 540 g ha^{-1} B, 240 g ha^{-1} Cu, 600 g ha^{-1} Mn, 30 g ha^{-1} Mo, and 2700 g ha^{-1} Zn. Top dressing fertilization was carried out at 25 DAE with 25 kg ha^{-1} K (potassium chloride), 2.0 kg ha^{-1} B (ulexite), and 500 kg ha^{-1} phosphogypsum. In addition, Mo and Co were applied via foliar application at 20 DAE, rates of 80 and 10 g ha^{-1}, respectively. Recommendations for fertilization and soil correction were carried out in accordance with Quaggio et al. (2022). Pesticides (fungicides, insecticides, and herbicides) were applied as needed throughout the peanut cycle according to common practices employed by local peanut farmers.

Nutrient uptake and yield measurements

To determine leaf nutrient content, 20 leaves (the first fully expanded leaf from the top of the plant) were collected from each plot at 42 DAE [R2, beginning of gynophore formation; Boote (1982)], washed in running water, dried at 65 °C for 72 h, and ground. Leaf nutrient content was then determined by acid digestion using nitric acid (Chapman and Pratt, 1962). Nutrient concentrations were determined using inductively coupled

plasma optical emission spectroscopy (ICP-OES) equipment. Nitrogen was determined by acid titration. Plant sampling to determine biomass and nutrient concentrations in stems, leaves, and reproductive organs (flowers, gynophores, and pods) occurred at 24, 48, 62, 76, 90, 104, 120, and 134 DAE. Four vigorous competitive plants were collected and separated into leaves, stems, and reproductive organs at each sampling time. Leaves, stems, and reproductive organs samples were weighed separately on a scale with an accuracy of 0.01 g, placed in paper bags, and dried in a forced-air oven at 65 °C (until constant weight) for moisture determination. The fresh matter and moisture content were used to quantify the dry biomass accumulation of each plant organ in kg ha^{-1}. After drying, the nutrient content of the samples was analyzed (Chapman and Pratt, 1962).

Nutrient uptake by each plant organ was calculated by multiplying the nutrient content of the respective plant tissue by its corresponding dry matter. Mean values of the analyzed variables (pod yield, dry matter, and macro- and micronutrients) at each sampling time were used to determine the rates of uptake and nutrient removal. Data were analyzed by non-linear regression, and the model parameters were estimated using the dynamic curve fitting function in SigmaPlot version 10.0 (Systat Software, San Jose, CA).

We selected the three-parameter Gaussian sigmoidal model to fit the non-linear regression model, which provided the highest statistical significance and the highest coefficient of determination (R^2). The model is described by equation 1.

$$y = ae^{\left[-0.5\left(\frac{x-x0}{b}\right)^2\right]} \quad \text{Eq. 1}$$

in which: y is the nutrient accumulation, in kg ha^{-1} or g kg^{-1}; a is the maximum accumulation value, in kg ha^{-1} or g kg^{-1}; $x0$ is the value of x in DAE that provides the maximum accumulation; and b is the difference in the value of x in number of DAE between the inflection point and the maximum point. From the fitted model, the inflection point (IP) of the curve was determined according to equation 2.

$$IP = x0 - b \quad \text{Eq. 2}$$

in which: IP is the value of x at which the model curve changes sign; in practice, this corresponds to the value of x in DAE at which the daily accumulation rate, although positive, begins to decrease.

To determine the time of maximum nutrient uptake by peanut, the accumulation of nutrients by shoots and pods was fit to a model using an adapted form of the methodology described by Vieira et al. (2018). Nutrient uptake by pods determined at harvest was considered to calculate nutrient removal. At pod maturity (70 % mature pods – R8 and R9 stages), two linear meters were hand-harvested from each plot to evaluate the plant stand (final density of 15 plants per linear meter) and pod yield. Seed moisture was adjusted at 7 % (peanut marketing standard).

Data analysis

After testing for homogeneity and normality, data (dry matter, uptake and removal of macronutrients and micronutrients) were subjected to analysis of variance (ANOVA). Statistical analysis was performed using variance analysis and regression. A two-way factorial design (cultivars × collection time) was considered for nutrient uptake and removal data for statistical analysis. Treatment averages were compared by the t-test (LSD) at 5 % probability ($p<0.05$). Analyses were performed using Sisvar® statistical software and SigmaPlot®; the latter was also used to generate figures.

RESULTS

Pod yield

Cultivars Granoleico (EM), BRS 423 OL (EM), and BRS 421 OL (LM) produced, on average, 4.1, 4.0, and 5.9 Mg ha^{-1} of pods, respectively. As the pod yield was practically the same between the EM cultivars, the average yield, nutrient uptake, and removal data between the two EM cultivars were considered.

Dry matter accumulation

Total dry matter accumulation was 34 % higher in the late-maturing (LM) cultivar than in the early-maturing (EM) cultivars ($p<0.05$). The LM cultivar had a higher average daily dry matter accumulation, except for leaf dry matter (Table 1). For the EM cultivars, the maximum accumulation of total dry matter occurred around 109 DAE (stages R6–R7). The LM cultivar accumulated dry matter until harvest, mainly in the stem and pods (Table 1 and Figure 2). However, for both maturity groups, dry matter accumulation in flowers and pods continued until harvest. Interestingly, in stage R6, leaf dry matter accumulation began to decrease in both maturity groups, but this decrease was more pronounced in the LM cultivar (Figure 2).

Macronutrient uptake

Nitrogen (N) accumulation was 210 and 300 kg ha^{-1} for the EM and LM cultivars, respectively, and approximately 65 and 70 % of this N was allocated to pods and, therefore removed by harvest. The remaining N (35–30 %) accumulated in leaves and stems (crop residues). The EM cultivars exhibited a high N uptake rate until stage R7, whereas the LM cultivar continued to absorb N until harvest, especially in pods (Table 2 and Figures 3a and 3b).

Both maturity groups-maintained P uptake until harvest (Figures 3b and 3c). The maximum P uptake was 23 and 28 kg ha^{-1} for the EM and LM cultivars, respectively (Table 2), approximately 67 and 73 % of which was removed in the harvested pods. Thus, high-yield crops can remove up to 19 kg ha^{-1} P (Figure 3).

After stage R5, which began at 75 and 90 DAE for the EM and LM cultivars, respectively, no further increase in K uptake occurred (Figures 3c and 3d). The maximum K uptake was similar between cultivars, reaching approximately 200 kg ha^{-1}. By contrast, K removal was dependent on maturity group and yield and ranged from 40 kg ha^{-1} for the EM cultivars to 50 kg ha^{-1} for the LM cultivar (Table 2). Thus, only approximately 20 to 25 % of the K absorbed by peanuts was removed from the field. Interestingly, after stage R6, K uptake by stems decreased in the EM cultivars but continued to increase until harvest in the LM cultivar (Figures 3c and 3d).

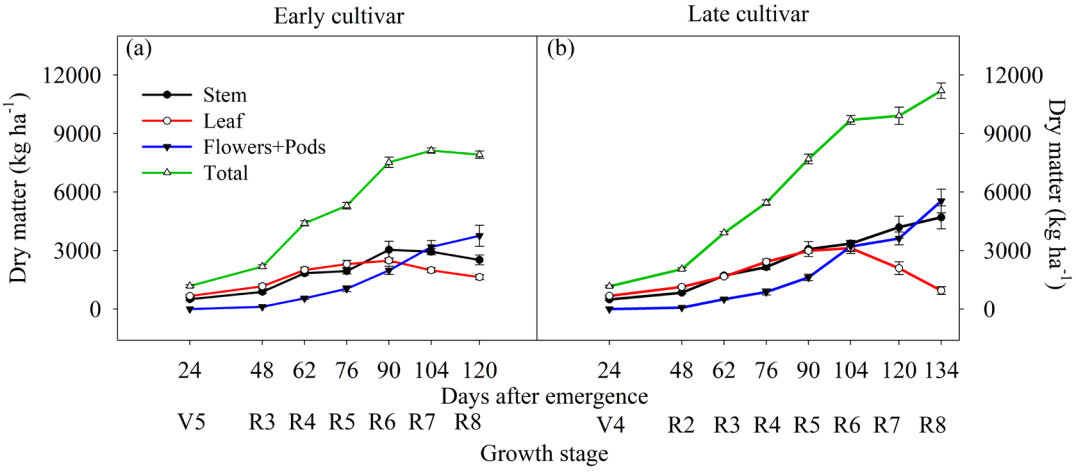

Figure 2. Dry matter accumulation (shoot and pods) by the early-maturing peanut cultivars (BRS 423 OL and Granoleico) (a) and late-maturing peanut cultivar (BRS 421 OL) (b) as a function of days after emergence. Vertical bars represent standard deviation.

Table 1. Estimated model fit parameters for shoot and pod dry matter accumulation and corresponding inflection point (IP), mean daily accumulation rate (MDAR), and coefficient of determination (R^2)

Organ	Cultivar	Model parameters[1]			IP	MDAR	R^2
		a[2]	b[3]	x_0[4]			
		kg ha^{-1}		days after emergence		kg ha^{-1} day^{-1}	
Stem	Early	2,939**	36**	101**	65	29	0.96
	Late	4,755**	56**	134**	78	35	0.96
Leaf	Early	2,419**	35**	86**	51	28	0.96
	Late	2,613**	35**	93**	58	28	0.83
Reproductive structures	Early	3,787**	29**	120**	91	31	0.98
	Late	7,271**	47**	134**	87	54	0.96
Total	Early	8,214**	40**	109**	69	75	0.98
	Late	11,022**	50**	134**	84	82	0.97

[1] Values for the early-maturing cultivar represent the average of the two early-maturing cultivars. [2] Value of maximum dry matter accumulation. [3] Amplitude in value of x in DAE between the inflection point and the maximum point. [4] Days after emergence (DAE) that provided the maximum accumulation. **, *, and ns: significant at 1 % or 5 % or not significant ($p>0.05$) by the t-test, respectively.

Table 2. Estimated model fit parameters for N, P, K, Ca, Mg, and S uptake and the corresponding inflection point (IP), mean daily accumulation rate (MDAR), and coefficient of determination (R^2)

Organ	Cultivar	Model parameters[1]			IP	MDAR	R^2
		a[2]	b[3]	x_0[4]			
		kg ha^{-1}		days after emergence		kg ha^{-1} day^{-1}	
				Nitrogen			
Stem	Early	33**	40**	92**	52	0.35	0.84
	Late	56**	69**	134**	65	0.41	0.88
Leaf	Early	71**	36**	81**	45	0.87	0.93
	Late	85**	36**	90**	54	0.94	0.79
Reproductive structures	Early	137**	25**	116**	91	1.18	0.99
	Late	215*	48**	134**	86	1.61	0.94
Total	Early	210**	42**	112**	70	1.87	0.97
	Late	299**	55**	134**	79	2.23	0.94
				Phosphorus			
Stem	Early	5**	44**	99**	55	0.05	0.87
	Late	6**	63**	134**	71	0.04	0.84
Leaf	Early	5**	35**	82**	47	0.06	0.94
	Late	6**	36**	90**	54	0.06	0.81
Reproductive structures	Early	17**	33**	120**	87	0.14	0.98
	Late	19*	52**	134**	82	0.14	0.95
Total	Early	23**	51**	120**	69	0.19	0.98
	Late	28**	58**	134**	76	0.20	0.95
				Potassium			
Stem	Early	92**	31**	85**	54	1.08	0.85
	Late	118**	72**	134**	62	0.88	0.76
Leaf	Early	108**	22**	80**	58	1.35	0.90
	Late	111**	24**	82**	58	1.35	0.81
Reproductive structures	Early	39**	48**	120**	72	0.32	0.94
	Late	50**	77*	134**	57	0.37	0.88
Total	Early	215**	29**	85**	56	2.52	0.91
	Late	207**	44**	103**	59	2.00	0.83

Continue

Continuation

Organ	Cultivar	Model parameters[1]			IP	MDAR	R^2
		a[2]	b[3]	x_0[4]			
		kg ha^{-1}		days after emergence		kg ha^{-1} day^{-1}	
				Calcium			
Stem	Early	20**	35**	95**	60	0.21	0.90
	Late	29**	51**	134**	83	0.21	0.89
Leaf	Early	36**	38**	93**	55	0.38	0.95
	Late	44**	32**	98**	66	0.44	0.75
Reproductive structures	Early	12**	34**	120**	86	0.10	0.98
	Late	16**	51**	134**	83	0.16	0.95
Total	Early	62**	39**	99**	60	0.62	0.96
	Late	82**	38**	109**	71	0.69	0.90
				Magnesium			
Stem	Early	7**	44**	97**	53	0.07	0.85
	Late	9**	66**	134**	68	0.06	0.87
Leaf	Early	13**	36**	81**	45	0.16	0.91
	Late	13**	35**	86**	51	0.15	0.79
Reproductive structures	Early	9**	33**	120**	87	0.06	0.98
	Late	7**	31**	123**	92	0.05	0.96
Total	Early	28**	43**	97**	54	0.25	0.95
	Late	31**	44**	103**	59	0.24	0.90
				Sulfur			
Stem	Early	5**	51**	120**	69	0.04	0.93
	Late	5**	85**	134**	49	0.11	0.93
Leaf	Early	4**	40**	87**	47	0.04	0.91
	Late	5**	36**	96**	60	0.05	0.65
Reproductive structures	Early	7**	26**	120**	94	0.06	0.98
	Late	9**	40**	134**	94	0.11	0.95
Total	Early	16**	51**	105**	69	0.14	0.96
	Late	19**	55**	124**	79	0.17	0.94

[1] Values for the early-maturing cultivar represent the average of the two early-maturing cultivars. [2] Value of maximum nutrient uptake. [3] Amplitude in value of x in DAE between the inflection point and the maximum point. [4] Days after emergence (DAE) that provided the maximum uptake. **, *, and ns: significant at 1 or 5 % or not significant ($p>0.05$) by the t-test, respectively.

The maximum Ca uptake occurred between 100 (EM) and 110 (LM) DAE at stage R7 and ranged from 60 kg ha^{-1} for the EM cultivars to 75 kg ha^{-1} for the LM cultivar (Figures 4a and 4b). However, the EM and LM cultivars only removed 12 and 20 kg ha^{-1} Ca, respectively, in harvested pods (Figure 4). The EM and LM cultivars absorbed 28 and 31 kg ha^{-1} Mg, respectively; Mg uptake peaked at 97 in the EM cultivars and 103 DAE in the LM cultivar and decreased thereafter (Figures 4c and 4d). Furthermore, the EM cultivars continued accumulating Mg in the pods until harvest, but the LM cultivar did not show significant Mg accumulation after stage R7. Magnesium removal ranged from 7 kg ha^{-1} for the EM cultivars to 8 kg ha^{-1} for the LM cultivar, which had yields of approximately 4 and 5.9 Mg ha^{-1}, respectively (Figure 4). The maximum S uptake occurred at maturity stage R7, regardless of maturity group. Total S uptake by the EM and LM cultivars was 16 and 19 kg ha^{-1} of S, respectively. Approximately 50 % of the absorbed S was removed in the pod harvest, regardless of the maturity group (Figures 4e and 4f).

Interestingly, pronounced reductions in Ca, Mg, and S uptake in leaves were observed in the LM cultivar starting at stage R6. These declines were less pronounced in the EM

cultivars (Figure 4). By contrast, the accumulation of these nutrients in stems increased until harvest for the LM cultivar but peaked at stage R7 for the EM cultivars (Figure 4).

Micronutrient uptake

Maximum Fe uptake occurred at stage R7, which corresponded to 96 DAE (EM cultivars) and 114 DAE (LM cultivar), and the total uptake was approximately 2350 g ha^{-1}, regardless of maturity group. However, Fe removal in harvested pods ranged from 760 g ha^{-1} for the EM cultivars to 830 g ha^{-1} for the LM cultivar (Figures 5a and 5b and Table 3).

In all cultivars, Cu uptake increased until harvest. Total Cu uptake was 76 g ha^{-1} (EM cultivars) and 95 g ha^{-1} (LM cultivar), and total removal was 45 g ha^{-1} (EM cultivars) and 58 g ha^{-1} (LM cultivar). Additionally, after stage R5 (80 or 90 DAE), Cu uptake by leaves decreased (Figure 5c and 5d).

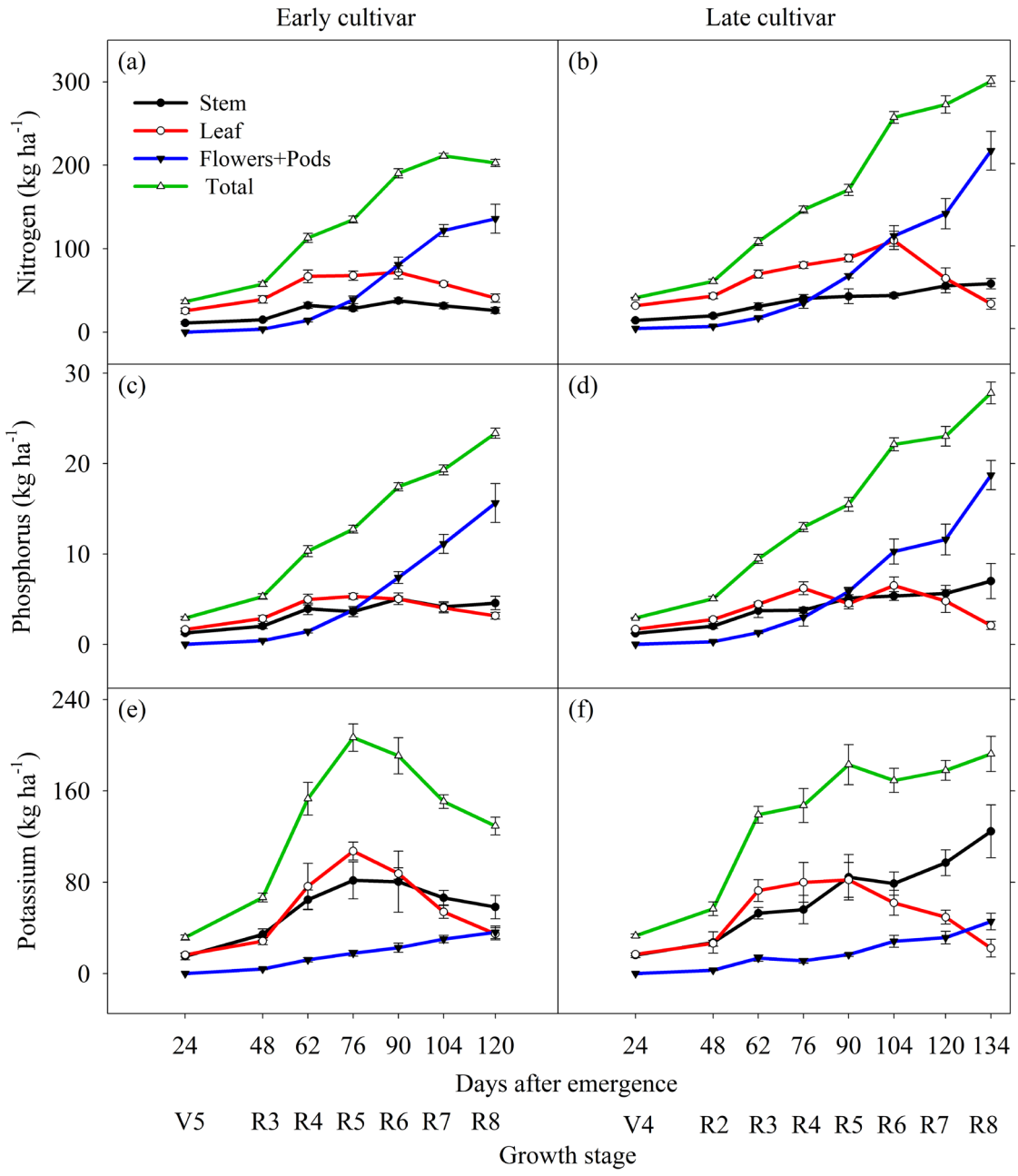

Figure 3. Nitrogen, phosphorus, and potassium uptake by early-maturing (a, c, and e) and late-maturing (b, d, and f) peanut cultivars as a function of days after emergence or phenological stage. Vertical bars represent standard deviation.

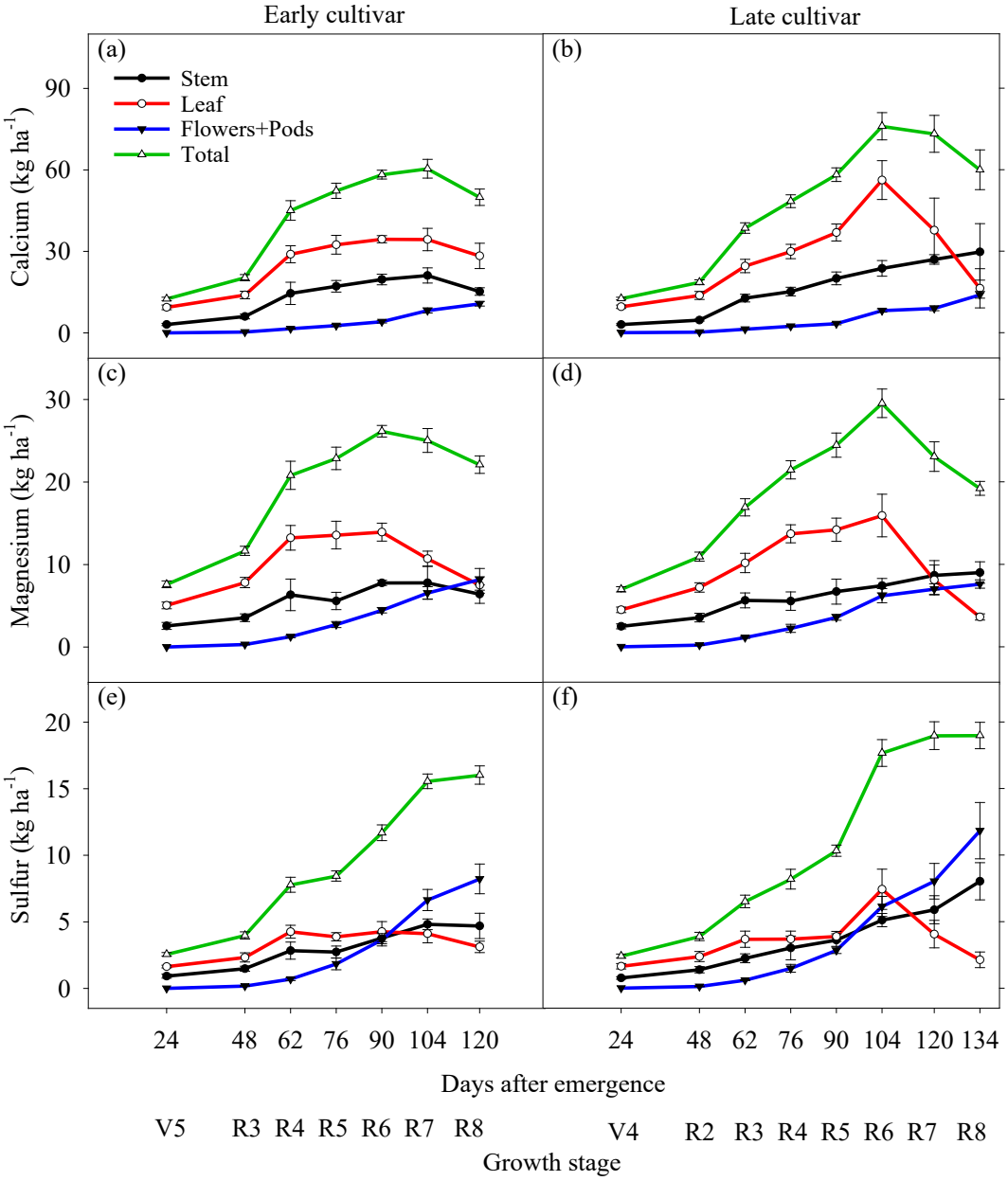

Figure 4. Calcium, magnesium, and sulfur uptake by early-maturing (a, c, and e) and late-maturing (b, d, and f) peanut cultivars as a function of days after emergence and phenological stage. Vertical bars represent standard deviation.

Approximately 60 % of absorbed Zn was removed in the pod harvest. Moreover, Zn was absorbed and redistributed from leaves to pods until harvest. The EM and LM cultivars absorbed 294 and 391 g ha^{-1} at daily rates of 2.45 and 2.92 g ha^{-1} day^{-1} (Table 3), respectively, and removed 190 g ha^{-1} Zn and 240 g ha^{-1} Zn (Figures 5e and 5f).

The maximum uptake of B occurred between stages R6 and R7 (98–113 DAE) and was redistributed from leaves to pods thereafter. Total B uptake was 364 g ha^{-1} (EM cultivars) and 414 g ha^{-1} (LM cultivar), with an average B uptake rate of 3.7 g ha^{-1} day^{-1}. Additionally, B removal in the harvested pods ranged from 100 g ha^{-1} (EM cultivars) to 145 g ha^{-1} (LM cultivar). Boron absorption by stems decreased in the EM cultivar after stage R7 but continued in the LM cultivar until harvest (Figures 5i and 5j; and Table 3).

Leaf nutrient concentration

All nutrients were within the sufficiency range recommended for peanuts, with no nutritional deficiency (Table 4).

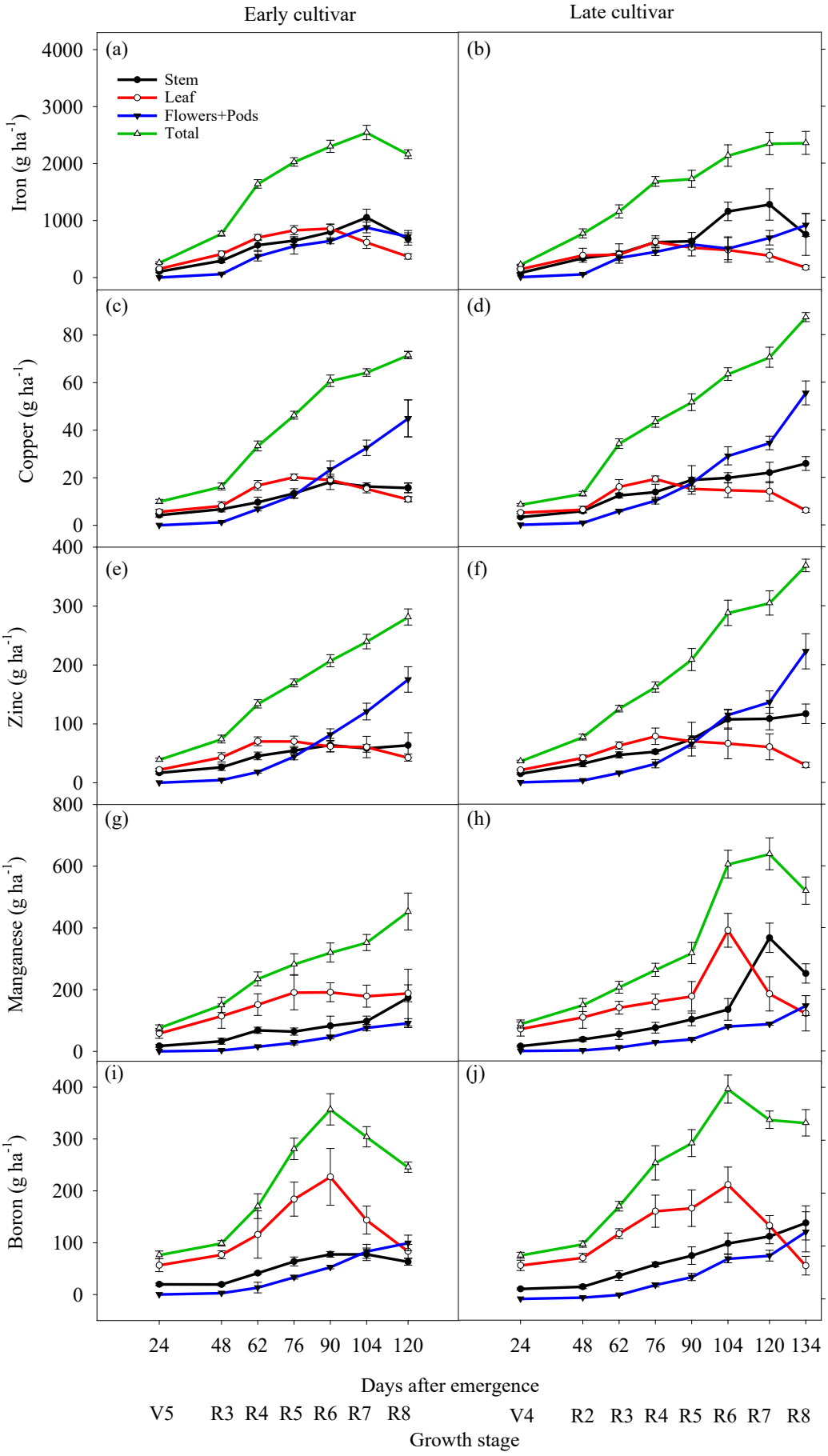

Figure 5. Iron, copper, zinc, manganese, and boron uptake by early-maturing (a, c, e, g, and i) and late-maturing (b, d, f, h, and j) peanut cultivars as a function of days after emergence and phenological stage. Vertical bars represent standard deviation.

Table 3. Estimated model fit parameters for uptake of the micronutrients B, Cu, Fe, Mn, and Zn and corresponding inflection point (IP), mean daily accumulation rate (MDAR), and coefficient of determination (R^2)

Organ	Cultivar	Model parameters[1]			IP	MDAR	R^2
		A[2]	B[3]	x_0[4]			
		g ha^{-1}		days after emergence		g ha^{-1} day^{-1}	
				Iron			
Stem	Early	875**	38**	99**	61	8.83	0.82
	Late	1,241**	68**	134**	66	9.26	0.70
Leaf	Early	839**	30**	82**	52	10.23	0.96
	Late	752**	29**	92**	63	8.17	0.61
Reproductive structures	Early	767**	37**	113**	76	6.78	0.84
	Late	832**	47**	134**	87	6.20	0.74
Total	Early	2,346**	36**	96**	60	24.43	0.91
	Late	2,350**	44**	114**	70	20.61	0.75
				Copper			
Stem	Early	16**	43**	100**	57	0.17	0.90
	Late	24**	57**	134**	77	0.17	0.89
Leaf	Early	14**	33**	83**	50	0.22	0.90
	Late	17**	35**	86**	51	0.19	0.81
Reproductive structures	Early	45**	36**	120**	84	0.40	0.98
	Late	58**	63**	134**	71	0.43	0.97
Total	Early	76**	45**	118**	73	0.64	0.96
	Late	95**	60**	134**	74	0.71	0.95
				Zinc			
Stem	Early	63**	48**	105**	57	0.60	0.85
	Late	111**	58**	134**	76	0.82	0.84
Leaf	Early	73**	37**	83**	46	0.87	0.88
	Late	84**	35**	91**	56	0.92	0.72
Reproductive structures	Early	190**	36**	120**	84	1.58	0.98
	Late	240**	55*	134*	79	1.79	0.95
Total	Early	294**	52**	120**	68	2.45	0.97
	Late	391**	55**	134**	79	2.92	0.92
				Manganese			
Stem	Early	250*	17**	120**	103	2.08	0.82
	Late	354**	11**	119**	108	2.97	0.78
Leaf	Early	194**	47**	99**	52	1.95	0.85
	Late	257**	33**	99**	66	2.59	0.49
Reproductive structures	Early	93**	31**	120**	89	0.77	0.96
	Late	155**	61*	134*	73	1.15	0.93
Total	Early	455**	63**	120**	57	3.79	0.89
	Late	659**	35**	115**	80	5.71	0.79
				Boron			
Stem	Early	85**	33**	101**	68	0.84	0.94
	Late	151**	60**	134**	74	1.12	0.91
Leaf	Early	191**	28**	87**	59	2.19	0.83
	Late	191**	33**	92**	59	2.07	0.75
Reproductive structures	Early	100**	30**	120**	90	0.83	0.97
	Late	145**	47**	134**	87	1.08	0.89
Total	Early	364**	33**	98**	65	3.71	0.93
	Late	414**	43**	113**	70	3.66	0.90

[1] Values for the early-maturing cultivar represent the average of the two early-maturing cultivars. [2] Value of maximum nutrient uptake. [3] Amplitude in value of x in DAE between the inflection point and the maximum point. [4] Days after emergence (DAE) that provided the maximum uptake **, *, and ns: significant at 1 or 5 % or not significant ($p>0.05$) by the t-test, respectively.

Table 4. Leaf nutrient concentrations of peanut cultivars at stage R2 – beginning of gynophore formation

Nutrients	N	P	K	Ca	Mg	S
	g kg^{-1}					
Early-maturing	33.4	2.4	24.2	11.8	6.7	2.0
Late-maturing	34.6	2.4	23.3	12.0	6.3	2.1
CV%	8.9	9.9	10.1	7.8	6.9	9.8
Sufficiency range[(1)]	30-45	2.0-5.0	17-30	12-20	5.0-8.0	2.0-3.5
	B	Cu	Fe	Mn	Zn	
	mg kg^{-1}					
Early-maturing	30.6	16.9	345.9	96.2	36.4	
Late-maturing	50.7	15.6	333.1	96.6	36.7	
CV%	9.1	6.8	7.1	10.8	11.9	
Sufficiency range[(1)]	25-60	5-20	50-300	50-150	20-60	

[(1)] (Quaggio et al., 2022). CV: coefficient of variation.

Table 5. Uptake and removal of nutrients per unit produced by early-maturing and late-maturing modern peanut cultivars

Dry matter and nutrients	DM	N	P	K	Ca	Mg	S
	Mg ha^{-1}	kg Mg^{-1}					
Early-maturing cultivars (4 Mg ha^{-1} – pod yield)							
Uptake	7.9	54	6.2	51	16	7.0	4.0
Removal	3.8	36	4.2	9.6	2.8	1.5	1.5
% removal	48	66	68	19	18	21	44
Crop residues	4.2	18	2.0	41.4	13.2	5.5	2.5
Late-maturing cultivar (5.9 Mg ha^{-1} – pod yield)							
Uptake	11.2	54	5.0	35	14	5.3	3.2
Removal	5.5	39	3.4	8.2	2.7	1.2	1.5
% removal	49	72	68	24	19	22	47
Crop residues	5.7	15	1.6	26.8	11.3	4.1	1.7
Micronutrients							
	DM	B	Cu	Fe	Mn	Zn	**
	Mg ha^{-1}	g Mg^{-1}					
Early-maturing cultivars (4 Mg ha^{-1} – pod yield)							
Uptake	7.9	95	19	677	120	75	**
Removal	3.8	26	13	216	24	48	**
% removal	48	28	64	32	20	64	**
Crop residues	4.2	69	6.0	461	96	27	**
Late-maturing cultivar (5.9 Mg ha^{-1} – pod yield)							
Uptake	11.2	72	16	424	115	66	**
Removal	5.5	25	10	154	26	40	**
% removal	49	35	62	36	23	61	**
Crop residues	5.7	47	6.0	270	89	26	**

DM: dry matter; crop residues = leaf + stem.

Nutrient uptake and removal vs. yield

For each Mg (megagram) of peanut pods produced, the uptake of N, K, Ca, Mg, P, and S was 54, 43, 16, 6.2, 5.6, and 4.1 kg, respectively (average of the three cultivars) (Table 5). Approximately 70, 22, 19, 21, 68, and 45 % of the total N, K, Ca, Mg, P, and S uptake

was removed in the pod harvest (average of the three cultivars), respectively, while the rest was returned to the soil through crop residues (stems and leaves). For macronutrients, the amounts absorbed and removed did not differ significantly between the maturity groups, except for K uptake, which was 45 % higher in the EM cultivars than in the LM cultivar. The uptake of the micronutrients Fe, Mn, B, Zn, and Cu was 550, 118, 84, 70, and 18 g (average of the three cultivars) for each Mg of peanut pods produced (Table 5). The removal of total Fe, Mn, B, Zn, and Cu uptake was 37, 22, 30, 61, and 63 %, respectively. For all micronutrients, uptake by the EM cultivars was higher than uptake by the LM cultivar.

DISCUSSION

This study demonstrates that peanut yield level affects nutrient uptake, consistent with prior reports (Singh, 1999; Wang et al., 2021; Crusciol et al., 2021, 2023). However, this study is the first to show that the cultivar maturity group affects nutrient uptake dynamics. It was estimated by Singh (1999) that by 2050 the peanut pods yield would reach 5.0 Mg ha^{-1} in India, which has calcareous and alkaline soils, with maximum uptakes of 300 kg ha^{-1} N, 150 kg ha^{-1} K and Ca, 60 kg ha^{-1} Mg, 40 kg ha^{-1} P and S, 10000 g ha^{-1} Fe, 800 g ha^{-1} Mn, 600 g ha^{-1} Zn, 300 g ha^{-1} B, and 100 g ha^{-1} Cu. Recent genetic improvements in Brazil have produced cultivars with high pod yield potential (9.0 Mg ha^{-1}) and average yields of 5.0 Mg ha^{-1} (Godoy et al., 2017; Suassuna et al., 2019, 2020), similar to the maximum yield achieved in this study. Singh's (1999) estimates of nutrient uptake for this yield level were accurate only for N and Cu; K and B uptake were higher than estimated, whereas the uptake of other nutrients was lower. These results suggest that the shift from Valencia and Spanish botanical types to higher-yield, higher-quality runner cultivars in most peanut-producing countries has altered nutrient uptake dynamics.

Although our study was carried out in a sandy soil with low natural fertility, all nutrients were provided, and there was no deficiency or excess, as shown by the foliar diagnosis (Table 4). Studies in high-fertility clayey soils of cultivars with yields similar to those in our study have reported higher nutrient uptake, especially of N, Ca, Mg, and Cu (Crusciol et al., 2021, 2023). The higher uptake observed by Crusciol et al. (2021) is attributable to luxury consumption, as high soil fertility improves nutrient availability to plants. However, approximately 80 % of global peanut production occurs in low-fertility sandy soil environments (Aparecido et al., 2021; Rachaputi et al., 2021), similar to the environment in which our study was conducted.

Water availability during peanut growth can also affect nutrient absorption (Djaman et al., 2013). Although precipitation during season was within the region's historical climatic data, between the end of January and the beginning of February there was 250 mm of precipitation in 11 days (Figure 1). This period corresponds from 65 to 76 DAE of peanuts – stages R4-R5. High precipitation can lead to nutrient leaching and affect nutrient uptake, especially in sandy soils. Interestingly, the accumulation of potassium and boron in peanut leaves reduced after the R5 and R6 stages, respectively (Figures 3 and 5). However, this reduction appears to be associated with the peanuts phenological age and not the chronological age, since the reduction occurs when each cultivar group reaches a certain stage and not when it reaches a certain age. Therefore, high precipitation was apparently not a key factor in reducing the accumulation of these nutrients in peanut leaves.

For most nutrients, the absorption performances of the cultivars were similar. However, the LM cultivar accumulated N until harvest, with a maximum uptake of 300 kg ha^{-1}, whereas the EM cultivars ceased N uptake after stage R7, with a maximum uptake of 210 kg ha^{-1}. All peanut cultivars are indeterminate plants, meaning that they continue to grow and produce new branches until harvest, which generates a demand for N until harvest. However, LM cultivars have a higher degree of indeterminacy than EM cultivars

(Stalker et al., 2016; Suassuna et al., 2020). Crusciol et al. (2021) did not observe differences in N absorption performance between cultivars of different maturity groups, possibly because they did not consider the phenological stage at sampling, which may have resulted in the collection of pods in different stages of maturity. The present study found that approximately 30 % of the total N absorbed was allocated in crop residues (leaves + stems) and thus returned to the soil. Therefore, a high-yield peanut crop leaves up to 100 kg ha^{-1} N in the crop system after harvest. By contrast, soybean returns only 25 % of absorbed N to the system, with a maximum return of 70 kg ha^{-1} in high-yield areas (Bender et al., 2015).

Phosphorus absorption was 25–30 kg ha^{-1} in our study, similar to the results of studies in clayey soils in Brazil (Crusciol et al., 2021; Bertino et al., 2022) and China (Xie et al., 2020; Wang et al., 2021). However, we found that P accumulation increased linearly until the harvest, whereas in clayey soils, P uptake ceases after 100 DAE. High-yield peanuts crops have high removal of P (approximately 60 kg ha^{-1} of P_2O_5), and fertilization programs should consider this high removal.

Responses of peanut yield to K fertilization have been observed at K fertilization rates of 25 kg ha^{-1} in sandy soils in Brazil and the USA (Cordeiro et al., 2023) and 25–75 kg ha^{-1} in Vietnam (Hoang et al., 2019). We observed high K uptake (~200 kg ha^{-1}), similar to that reported by Bertino et al. (2022) (173 kg ha^{-1}) and Crusciol et al. (2021) (200–280 kg ha^{-1}). In addition, we found that only 27 % of total K uptake was removed (53 kg ha^{-1} K_2O), consistent with the removal rates observed by Sarawatx et al. (1988) (31 %), Xie et al. (2020) (34 %), Zhao et al. (2021) (28 %), and Bertino et al. (2022) (25 %). By contrast, Crusciol et al. (2021) observed 70 % removal of total K uptake. Because the rate of K uptake increases until stage R5, late K fertilization is not recommended. Another important fact is that peanuts are also able to use non-exchangeable forms of K (Xu et al., 2021), this may help explain the low response to the application of higher rates of K. However, new studies should investigate the K balance in soils with peanut cultivation and seek strategies to supply K.

Calcium, Mg, and S also had low uptake rates after stage R6. This may impact the gypsum recommendation. For United States conditions, it has been reported that the best strategy for applying gypsum is to split the rate into two applications at the beginning and middle of flowering (Yang et al., 2022). However, in the environmental conditions of countries such as the United States and Argentina, the peanuts cycle is longer compared to Brazil. Therefore, new studies should investigate the best strategy for applying gypsum to peanuts in Brazilian conditions.

Crusciol et al. (2021) reported much higher Ca and Mg uptake rates (approximately 60 % higher) than those reported by us and Bertino et al. (2022). However, S uptake in our study was similar to those of Bertino et al. (2022) and Crusciol et al. (2021). The higher Ca uptake in Crusciol et al. (2021) may be related to high soil fertility and luxury consumption by peanut. In the present study, Ca uptake by pods increased slightly, beginning in stage R6. This highlights the importance of adequate Ca soil availability throughout the peanut cycle, as pods directly take up Ca (Yang et al., 2022). Perhaps more important than the concentrations of Ca and Mg in the soil is the balance of these nutrients in the pod formation zone, as high Mg availability can reduce the uptake of Ca and Zn by pods (Zharare et al., 2010).

Copper and Zn uptake remained constant until harvest, regardless of the cultivar maturity group, in contrast to Crusciol et al. (2023) findings. Additionally, total Cu uptake was lower in our study than in Crusciol et al. (2023) in clayey soil. This discrepancy may reflect the higher initial soil Cu content in the clayey soil. However, Zn uptake was similar to that observed by Crusciol et al. (2023). In our study and Crusciol et al. (2023), total Cu and Zn uptake removal was approximately 60 %. Interestingly, after the R6 stage, the accumulation of Zn in the pods was linearly increased, while the accumulation in the

stem practically did not change, and in the leaves, there was a slight reduction. This suggests that pods absorbed Zn directly, as reported by Chahal et al. (1979).

Boron dynamics, i.e., uptake, removal, and phenological stage of maximum uptake, were similar to those observed by Crusciol et al. (2023). In Crusciol et al. (2023), soil B content was medium; in our study, although soil B content was very low, B was applied at a rate of 2 kg ha^{-1}, preventing B deficiency and improving yield (Cordeiro et al., 2024b). Although LM has a higher B uptake compared to EM, the daily uptake rate is higher for EM due to the shorter development cycle. Additionally, the early-maturing cultivar had lower leaf B content than was recently suggested by Cordeiro et al. (2024b), but the late-maturing cultivar was within this sufficiency range. Thus, there appear to be differences in the acquisition and efficiency of B use by peanut cultivars, requiring further studies.

We observed higher Fe uptake and removal rates than Crusciol et al. (2023). The leaf Fe concentration was above the crop sufficiency range (Table 4) due to the high soil Fe content, which is typical of acidic soils. By contrast, soil Mn content was low in this study, but Mn uptake and removal rates were similar to those observed in high-fertility soil by Crusciol et al. (2023).

CONCLUSION

Cultivar maturity group affected nutrient uptake and removal. Late maturing cultivar had a higher pod yield (5.9 Mg ha^{-1}) and nutrient requirements than the early maturing cultivars (4.1 Mg ha^{-1}). Late maturing cultivars had high N demand until harvest, whereas the early cultivars ceased N uptake after stage R7. Potassium uptake peaked between stages R3 and R5, whereas the uptake of other nutrients peaked between stages R3 and R7. For these runner-type peanut cultivars, macronutrient uptake (in kg) per Mg of pods was 54 (N), 43 (K), 16 (Ca), 6.2 (Mg), 5.6 (P), and 4.1 (S), of which approximately 70, 22, 19, 21, 68, and 45 % was removed in pods at harvest, respectively. Micronutrient uptake (in g) per Mg of pods was 550 (Fe), 118 (Mn), 84 (B), 70 (Zn), and 18 (Cu), of which approximately 37, 22, 30, 61, and 63 % was removed in pods at harvest, respectively.

DATA AVAILABILITY

Datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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AUTHOR CONTRIBUTIONS

Conceptualization: Carlos Felipe dos Santos Cordeiro (lead) and Fábio Rafael Echer (supporting).

Data curation: Carlos Felipe dos Santos Cordeiro (lead) and Leonardo Vesco Galdi (supporting).

Formal analysis: Carlos Felipe dos Santos Cordeiro (lead) and Leonardo Vesco Galdi (supporting).

Investigation: Carlos Felipe dos Santos Cordeiro (lead) and Leonardo Vesco Galdi (supporting).

Methodology: Carlos Felipe dos Santos Cordeiro (lead) and Leonardo Vesco Galdi (supporting).

Project administration: Carlos Felipe dos Santos Cordeiro (equal) and Fábio Rafael Echer (equal).

Resources: Carlos Felipe dos Santos Cordeiro (equal) and Fábio Rafael Echer (equal).

Writing – original draft: Carlos Felipe dos Santos Cordeiro (lead).

Writing – review & editing: Carlos Felipe dos Santos Cordeiro (lead) and Fábio Rafael Echer (supporting).

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