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Yield and nutritional requirements of cassava in response to potassium fertilizer in the second cycle

Adalton Mazetti Fernandes, Bruno Gazola, Jesion Geibel da Silva Nunes, Emerson Loli Garcia, and Magali Leonel

Center for Tropical Roots and Starches (CERAT), São Paulo State University (UNESP), Botucatu, São Paulo, Brazil

ABSTRACT

Potassium (K) is one of the most absorbed nutrients by cassava because it acts on the synthesis and starch accumulation in the storage roots. Here, we show that K application at the beginning of the second vegetative cycle of cassava submitted to shoot pruning increased the yield of roots and starch, and the nutrient demand of plants. Application of 45–89 kg ha^{-1} dipotassium oxide (K_2O) in the second cycle increased the yield of storage roots and starch from 36–49% and K applied at this time had a greater effect on the synthesis and allocation of starch in the storage roots. K supply increased the accumulation of N and S by 2.0- to 3.0-fold and the accumulation of other nutrients by 1.4- to 1.7-fold. The removal of phosphorus (P), manganese (Mn), and zinc (Zn) by storage roots was not affected by K application, whereas the removal of other nutrients increased by 1.3- to 4.3-fold.

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KEYWORDS
Manihot esculenta; mineral nutrition; root weight; root yield; starch yield

Introduction

Potassium (K) is one of the nutrients absorbed in large amounts by cassava plants (*Manihot esculenta* Crantz) and removed from the field by storage roots of this crop (Howeler and Cadavid 1983; Ternes 2002; Imas and John 2013). On an average, to achieve a storage root yield of 25 Mg ha^{-1}, cassava crop absorbs between 146 and 167 kg ha^{-1} K (Ternes 2002; Souza, Silva, and Souza 2009) and removes with the storage roots approximately 87.8 kg ha^{-1} K (Souza, Silva, and Souza 2009), demonstrating that cassava roots contain large amounts of K. In cassava roots, the nitrogen, phosphorus, and potassium (N:P:K) ratio is approximately 5:1:10 compared to the typical relationship of 7:1:7 in other crops (Imas and John 2013). Thus, the supply of K in adequate amounts for cassava is essential to increase the root yield and the starch quality (Mehdi, Sarfraz, and Hafeez 2007; Okpara, Agoha, and Iroegbu 2010; Uwah et al. 2013).

In Brazil, cassava for industrial use involves growing cultivars with higher levels of hydrocyanic acid (HCN) in the roots (Otsubo and Lorenzi 2002), which are usually harvested with two growing cycles, between 16 and 24 months, due to increased profitability (Takahashi 2002) as the yield and quality of the starch and the flour are larger (Otsubo and Lorenzi 2002). In this case, between the first and second vegetative cycles, cassava goes through a physiological rest period that occurs in the cold and dry season of the year (Conceição 1981; Lorenzi 2003; El-Sharkawy 2006; Aguiar et al. 2011).

The second growing season begins with the regrowth of the stems, stimulated by increased temperature and return of the rains, and the plants go through another period of intense vegetative growth (Aguiar et al. 2011). In large areas of cassava growing for industrial use, between the first and second vegetative cycles, the pruning of the aboveground of plants is made to facilitate the control of weeds

CONTACT Adalton Mazetti Fernandes adalton@cerat.unesp.br Center for Tropical Roots and Starches (CERAT), Lageado Experimental Farm, São Paulo State Univ. (UNESP), P.O. Box 237, 18610-307, Botucatu, São Paulo Brazil.

with herbicide in the second cycle (Takahashi 1998; Lorenzi 2003; Aguiar et al. 2011), and also to obtain propagating material for new planting (Takahashi 2002). In some situations, this pruning of the aboveground of plants may even increase the dry matter (DM) yield of the roots (Takahashi 1998). To obtain improvements in starch yield, some producers have done the fertilization of cassava crop after pruning to stimulate the regrowth of the aboveground of plants and the reconstitution of the leaf area, increasing the photosynthetic activity.

Potassium is the nutrient required in larger amounts by cassava crop (Howeler and Cadavid 1983; Ternes 2002; Imas and John 2013). Potassium plays an important role in several biochemical and physiological processes of plants (Viana and Kiehl 2010), besides being involved with N metabolism (Marschner 1995; Xu, Wolf, and Kafkafi 2002), it can help in the quick reestablishment of the leaf area of crop, and contributes in improving crop yield. As K exercises influence on the mineral nutrition of other nutrients, such as calcium (Ca) (Fageria 2001; Silva and Trevizam 2015), magnesium (Mg) (Hannaway, Bush, and Leggett 1982; Fageria 2001; Silva and Trevizam 2015), and manganese (Mn) (Fageria 2001), it may be that its application in the second cycle of pruned cassava can also change the plant's nutritional demand. Therefore, there is a need for a more thorough examination of the impact that K application at the beginning of the second cycle of pruned cassava can exert on agronomic performance and nutritional demand of the crop, as the knowledge of the interactions between elements is fundamental to understanding the dynamics of nutrients in the soil and in the plant and hence to the increasing crop yield (Silva and Trevizam 2015).

Thus, the aim of this study was to evaluate the yield of storage roots and starch, and the accumulation and removal of nutrients by cassava crop in response to K fertilizer at the beginning of the second vegetative cycle.

Materials and methods

Location, soil properties analysis, and experimental design

The field experiment was performed between 2013 and 2015 in the experimental area of the Center for Tropical Roots and Starches (CERAT), located at the Experimental Farm of São Manuel (48° 57′ W, 22° 77′ S and 740 m asl). The region has a Cwa climate (tropical with a dry winter and a hot, rainy summer) according to the Köppen classification system. Daily rainfall, irrigation, and temperatures were measured during the experimental period (Figure 1). The soil in the experimental area was classified as a sandy-textured dystroferric Red Latosol (Santos et al. 2006) corresponding to a dystrophic Typic Hapludox (Soil Survey Staff 2015). Before the installation of the experiment, soil samples in the experimental area were collected at a depth of 0–0.20 m and were analyzed (Table 1). The soil of the experimental area has low P and K availability, medium pH value, base saturation, and Mg, copper (Cu), and zinc (Zn) availability and has high Ca, iron (Fe), and Mn availability according to van Raij et al. (1997).

The experiment was conducted in an experimental design of randomized complete block with eight replications. The treatments were represented by four rates of potassium oxide (K_2O) (0, 45, 90, and 180 kg ha^{-1}) applied at the beginning of the second vegetative cycle of cassava crop. The plots comprised five 5-m-long rows with 1.20-m row spacing. The three central rows were considered for data collection; the 0.5 m at the end of each row and the two outer rows of the plot were disregarded. The pruning of the aboveground of plants occurred at 12 months after planting (MAP) and K application rates were performed only once at 13 MAP.

Cassava planting and management

The soil preparation was done with plowing and harrowing in accordance with the recommendations of Souza and Souza (2006). For planting, furrows were mechanically opened to 10 cm deep and spaced 1.20 m between furrows. After the opening of the furrows of all treatments, the application and incorporation of 142 kg ha^{-1} of formulated fertilizer NPK 8-28-16 [8% of N, 28% of phosphorus pentoxide (P_2O_5), and 16% of K_2O] in the furrow was made. There was no fertilization with micronutrients.

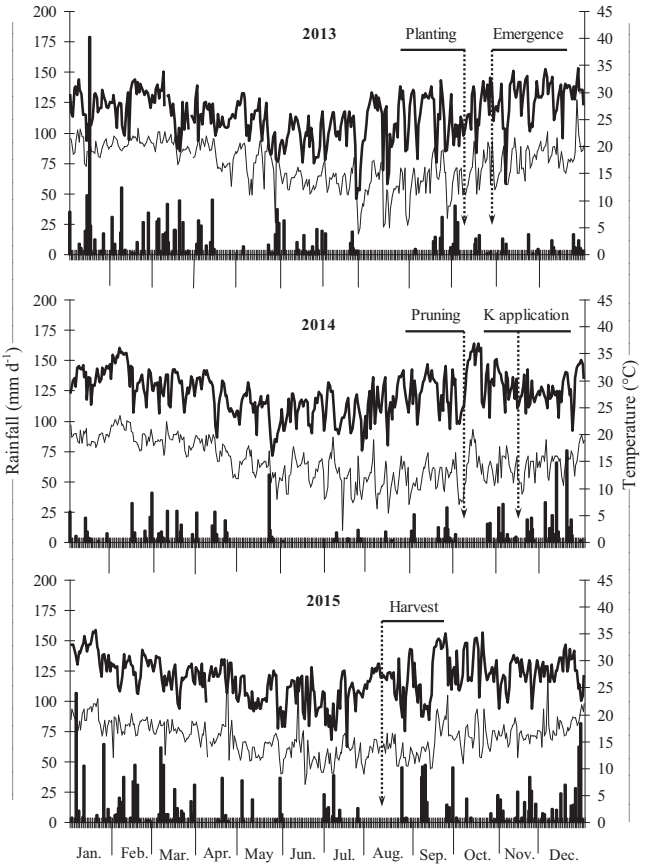

Figure 1. Daily rainfall (▮), and maximum (▬) and minimum (—) temperatures at the experimental area during the period of cassava growing in the field; and the times of planting, emergence, aboveground pruning, K application in the second vegetative cycle, and harvest of cassava crop.

The planting of cassava cv. IAC 13 was performed on 10 October 2013 using stem cuttings, 20-cm long, taken from the middle third of healthy plants of the 12-month cycle. For planting, the stem cuttings were placed manually in a spacing of 0.80 m into the open furrows, which were then closed. The emergence of cassava crop occurred on 30 October 2013 at 20 days after planting (DAP).

Table 1. Chemical and textural characteristics of the soil at the experimental area prior to the cassava planting.

Soil characteristics[†]	Values
pH (1:2.5 soil/$CaCl_2$ suspension 0.01 mol L^{-1})	5.3
Soil organic matter, g dm^{-3}	11
$P_{resin\text{-}extractable}$, mg dm^{-3}	8
K_{ex}, $mmol_c$ dm^{-3}	1.2
Ca_{ex}, $mmol_c$ dm^{-3}	17
Mg_{ex}, $mmol_c$ dm^{-3}	8
ECEC, $mmol_c$ dm^{-3}	45
Base saturation, %	59
Cu, mg dm^{-3}	0.8
Fe, mg dm^{-3}	17
Mn, mg dm^{-3}	12
Zn, mg dm^{-3}	0.9
Sand, g kg^{-1}	854
Silt, g kg^{-1}	58
Clay, g kg^{-1}	89

[†]K_{ex}, Ca_{ex}, and Mg_{ex} indicate basic exchangeable cations; ECEC, effective cation exchange capacity.

The pest and weed control in the experimental area was performed in accordance with the technical recommendations for cassava crop in the region where appropriate.

On 10 October 2014, at 12 MAP, the pruning of the aboveground of plants was carried out, which consisted of cutting the aboveground of plants to a height of 10 cm above the ground (Lorenzi 2003). Pruning was performed manually with a machete and the pruned aboveground of plants was chopped and kept in the plots. The application of K fertilizer treatments was made with potassium chloride (KCl) and occurred on 17 November 2014, at approximately 13 MAP.

Plant measurements and sampling

On 14 August 2015, at 22 MAP, the number of plants in the three 3.2-m-long rows of the useful area was counted to determine the final plant population. Then, these plants were collected and the number of storage root per plant and mean length and diameter of storage roots were determined. The aboveground (represented by leaves and haulm), stem cutting, and storage root were weighed (fresh weight) and ground. With the data of plant population and the fresh storage root weight, the fresh storage root yield was calculated. The subsamples of the aboveground, stem cutting, and storage roots were collected, weighed (fresh weight), and dried in an oven with forced-air circulation at 65°C for 96 hr and weighed again. The data of samples' fresh weight, subsamples' fresh and DM weight, and final plant population were used to calculate the amounts of DM accumulated in the aboveground, steam cutting, and storage roots. DM accumulation in the whole plant was obtained by the sum of amounts of DM accumulated in the plant organs. The dried subsamples of storage roots were ground in a Wiley mill and the starch percentage was determined, using the method described by ISO-6647 (1987). The starch yield was calculated by multiplying the starch percentage of the storage roots by the amount of DM accumulated per hectare in the storage roots.

Nutrient determination in plant tissues

In the dried subsamples of aboveground (leaves + haulm), stem cutting, and storage root, the concentrations of N, P, K, Ca, Mg, Cu, Fe, Mn, and Zn were determined. The N concentration in the plant tissues was determined by sulfuric acid (H_2SO_4) digestion and quantified using the semi-micro-Kjeldahl method (Malavolta, Vitti, and Oliveira 1997). P, K, Ca, Mg, S, Cu, Fe, Mn, and Zn concentrations were determined by atomic absorption spectrophotometry after nitric acid (HNO_3) – perchloric acid ($HClO_4$) digestion (Malavolta, Vitti, and Oliveira 1997).

The amounts of accumulated nutrients in each plant organ (aboveground, stem cutting, and storage roots) were calculated by multiplying the concentrations of nutrients by the accumulated amount of DM in each plant organ. The amount of nutrients absorbed by cassava crop was represented by the sum of the accumulated nutrients in the aboveground, stem cutting, and storage roots at harvest. Nutrient removal by storage roots was represented only by the amounts of accumulated nutrients in the storage roots (without including the amounts of accumulated nutrients in the aboveground and stem cutting).

Statistical analyses

Data were submitted to analysis of variance (ANOVA). The effect of K rates applied in the second vegetative cycle of cassava was evaluated by regression analysis using the SigmaPlot 10.0 software.

Results and discussion

Yield components, fresh storage root yield, and starch yield

In cassava crop, the maximum number of storage root per plant, mean length, and diameter of storage root are defined during tuberization phase, which occurs between 2 and 6 MAP (Ternes 2002; Alves

2006). Thus, the application of K at 13 MAP, in the beginning of the second vegetative cycle of pruned cassava, did not affect the variable numbers of storage root per plant, mean length and diameter of storage root, and DM percentage of storage root (Figure 2a, b, c, and e), since they are defined at the beginning of cassava cycle. Okpara, Agoha, and Iroegbu (2010) found no effect of K applied at planting furrow on the number of storage roots per plant of cassava harvested up to 14 MAP. Our results showed that cassava crop cv. IAC 13 produced, on average of all K rates, 6.0 roots per plant, with a length of 26.1 cm and diameter of 4.6 cm, with 42.1% DM. Aguiar et al. (2011) in a study conducted in the same region (São Manuel) found that cv. IAC 14 harvested with 22 MAP produced, on average, 5.9 roots per plant with an average DM of 44.8%, i.e., similar to the values obtained in this study.

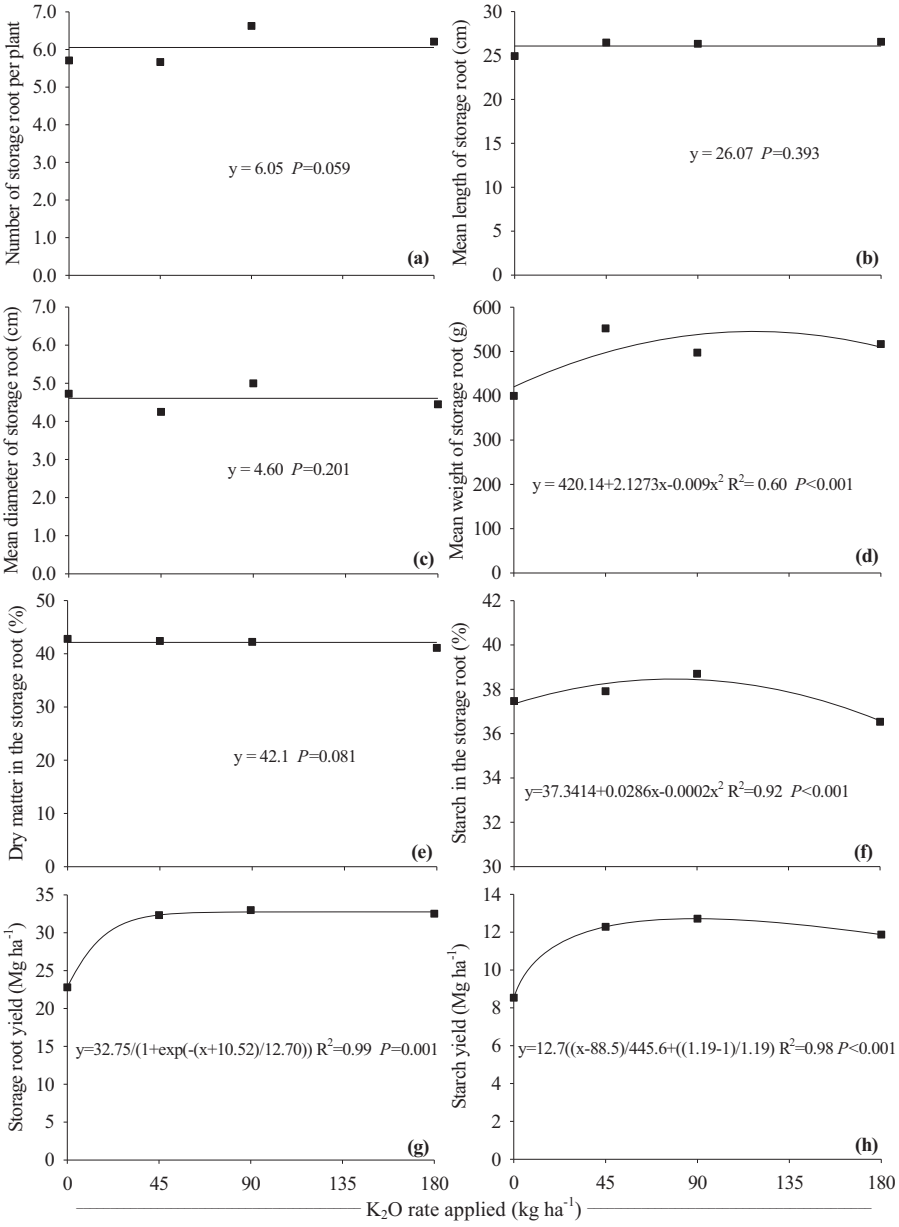

Figure 2. Number (a) and length (b); diameter (c) and mean weight (d) of storage roots; percentage of dry matter (DM) (e) and starch (f) in the storage roots; yield of storage roots (g) and yield of starch (h) of the cassava crop at harvest in response to potassium fertilizer in the second vegetative cycle.

The mean weight of storage roots increased by 37% up to 118 kg ha^{-1} K_2O, whereas the percentage of starch of storage roots increased by 3.7% up to 72 kg ha^{-1} K_2O (Figure 2d and f). These increases occurred because K is a nutrient required for starch synthesis and translocation of sugar to all parts of the plant (Boateng and Boadi 2010), and is essential to promote the translocation of assimilates from leaves to storage roots where they are stored (Howeler 2002; Kanto et al. 2012; Uwah et al. 2013).

The fresh storage root yield increased by 36% up to 45 kg ha^{-1} K_2O when the maximum fresh storage root yield of 32 Mg ha^{-1} was obtained (Figure 2g). These results show that the yield response to K by cassava can be expected when K availability in the soil is low (Kang 1984; Nguyen et al. 2002), as was also observed in this study. The increase in starch yield occurred up to 89 kg ha^{-1} K_2O, which resulted in an increase of 49% and a starch yield of 12.7 Mg ha^{-1} (Figure 2g and h). Our results show that, even when applied after the first vegetative cycle of cassava crop, K increased the fresh storage root yield, the starch content in the storage roots, and the starch yield in this crop (Figure 2f–h). Previous studies have shown that K application in the planting furrow of cassava not only increases the fresh storage root yield but also enhances the starch content in the storage roots (Malavolta et al. 1955; Kanto et al. 2012); however, our study showed that late application of K in cassava crop also increases these variables. The crop response for the starch production occurred up to higher rates of K than for the production of storage roots (Figure 2g and h). This indicates that K application in the second cycle after pruning of the aboveground of plants benefits starch yield because it stimulates more synthesis and allocation of starch in the storage roots than the growth of roots in number and size (Figure 2). Other authors also observed that an adequate K supply is important for the synthesis and translocation of starch in cassava plant in addition to increasing crop yield and quality of storage roots (Mehdi, Sarfraz, and Hafeez 2007; Uwah et al. 2013).

Plant dry matter accumulation and distribution

K application differently increased the growth of the different organs of cassava plants (Figure 3). In the aboveground, stem cutting, and whole plant, DM accumulation increased up to the estimated rates between 105 and 121 kg ha^{-1} K_2O (Figure 3a, b and d), but in the roots the increase occurred only up to 45 kg ha^{-1} K_2O (Figure 3c). This shows that the increase in DM of roots occurred until rates are lower than in the other plant organs, possibly because the increase in DM of roots occurred mainly by the translocation of assimilates from the aboveground of plants to storage roots and not by the formation of new tissue, as it occurred in the aboveground of plants, which at this stage issued new shoots and leaves (Lorenzi, Gallo, and Malavolta 1981). In cassava harvested at 12–14 MAP, other studies have also demonstrated a higher response of cassava to K supply to the growth of the aboveground part than for the growth of storage roots (Boateng and Boadi 2010; Okpara, Agoha, and Iroegbu 2010); although cassava requires relatively large amounts of K for starch formation and root development (Eneji et al. 2001; Kanto et al. 2012). In this study, K application at the beginning of the second vegetative cycle increased the DM production of cassava plants by approximately 43% (Figure 3d), indicating that the late application of K in cassava crop is related to stimulating plant growth and fresh storage root yield.

Plant nutrient concentrations

K fertilizer increased the concentrations of N and K in all parts of cassava plants up to the estimated rates between 102 and 137 kg ha^{-1} K_2O (Table 2) because K is involved in N metabolism (Marschner 1995; Xu, Wolf, and Kafkafi 2002), and both K and N have an important role in many biochemical and physiological processes of plants (Viana and Kiehl 2010). The P concentration in different parts of cassava plants was not affected by K application, which also occurred with Ca and Mg concentrations in the storage roots (Table 2).

K fertilizer linearly increased the Mg concentration in the stem cutting, but in the aboveground of plants, the increase occurred up to 73 kg ha^{-1} K_2O with a later reduction in the higher K rates, indicating that high rates of K decrease the Mg concentration in the aboveground of plants. In other crops,

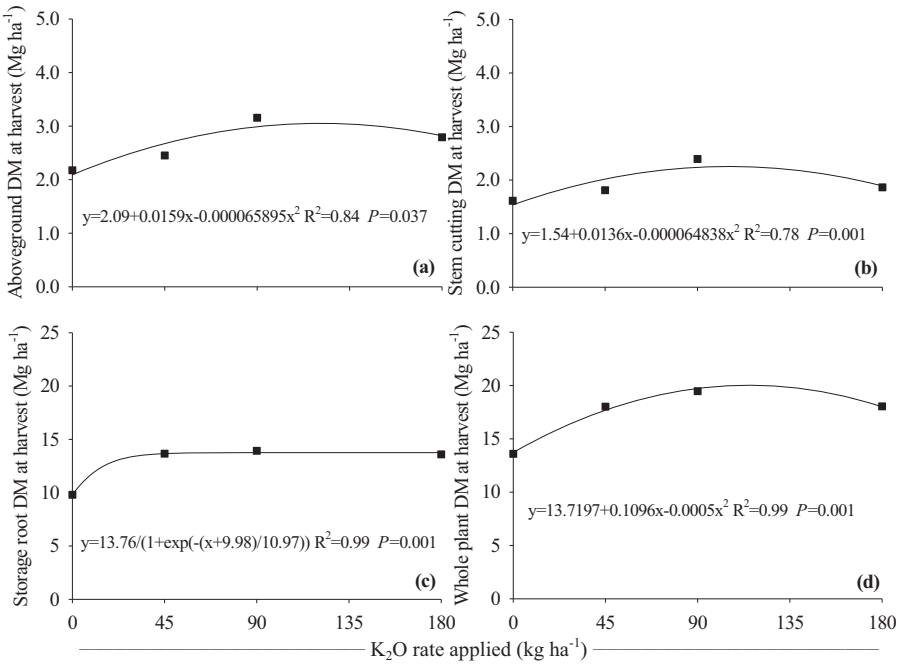

Figure 3. Dry matter (DM) accumulation in the aboveground (a), stem cutting (b), storage roots (c), and the whole plant (d) of the cassava crop at harvest in response to potassium fertilizer in the second vegetative cycle.

the high K supply also decreased the Mg concentration in the aboveground of plants, but it is not changed in the roots (Hannaway, Bush, and Leggett 1982; Fageria 2001). In the aboveground part of plants and in the stem cuttings, Ca concentrations increased up to estimated rates of 109 and 142 kg ha^{-1} K_2O, respectively, and decreased at higher K rates (Table 2). The reduction in the concentrations of Ca and Mg in the aboveground of plants with high K supply can be explained by the dilution effect. A plant well- nourished in K has greater growth, and even with the decrease in Ca and Mg concentration in the plant, many times, there is no loss in growth or yield (Silva and Trevizam 2015), as observed in this study (Table 2 and Figure 2g). However, if K is excessively high, there may be damage in the yield by intensifying the dilution effect (Silva and Trevizam 2015).

In the stem cutting, sulfur (S) concentrations were not altered by K application, but in the aboveground of plants these concentrations increased linearly with K fertilization, whereas in the roots these increases occurred up to 99 kg ha^{-1} K_2O (Table 2). This increase in S concentration in response to K can be an indirect effect of K on the protein synthesis in plants, as K is associated with N metabolism (Viana and Kiehl 2010), and both N and S act in protein synthesis (Silva and Trevizam 2015). The Cu concentration in the aboveground of plants was not affected by K fertilizer, but in the stem cutting and roots they increased up to the estimated rates between 74 and 106 kg ha^{-1} K_2O (Table 2). In the aboveground and roots of plants, Fe and Zn concentrations were not affected by K fertilizer, but in the stem cutting they linearly increased with K application. K fertilizer linearly increased Mn in the aboveground of cassava plants, whereas concentrations of this nutrient in the stem cutting and roots increased up to the estimated rates among 120 and 199 kg ha^{-1} K_2O (Table 2). Cations such as K play a role in the regulation of Mn uptake, promoting an increase in uptake when Mn is in low availability and a decrease when its availability is high or toxic (Fageria 2001).

Total nutrient accumulation at harvest

The amounts of N and S accumulated by the whole plant of cassava increased by 2.0- to 3.2-fold until rates between 118 and 123 kg ha^{-1} K_2O (Figure 4). As K is associated with N metabolism (Viana and Kiehl 2010), and both N and S act in protein synthesis (Silva and Trevizam 2015), improvement in K

Table 2. Concentration of nutrients in the aboveground, stem cutting, and the storage roots of the cassava crop at harvest in response to potassium fertilizer in the second vegetative cycle.

	K_2O rate (kg ha^{-1})						
Plant organ	0	45	90	180	Regression	R^2	p > F
			N concentration (g kg^{-1})				
Aboveground	4.2	6.2	6.7	7.0	$y = 4.30 + 0.043071x - 0.000157x^2$	0.97	<0.001
Stem cutting	3.1	4.8	4.9	4.9	$y = 3.19 + 0.034596x - 0.000139x^2$	0.91	<0.001
Storage root	0.9	2.7	2.6	2.6	$y = 1.10 + 0.032818x - 0.000139x^2$	0.88	<0.001
			P concentration (g kg^{-1})				
Aboveground	1.5	2.1	1.9	1.9	y = 1.9	—	NS
Stem cutting	1.0	0.8	1.1	1.1	y = 1.0	—	NS
Storage root	0.9	1.0	0.8	0.8	y = 0.9	—	NS
			K concentration (g kg^{-1})				
Aboveground	7.0	9.6	8.9	8.3	$y = 7.27 + 0.044124x - 0.000216x^2$	0.72	0.008
Stem cutting	5.0	5.0	4.0	4.4	$y = 5.32 - 0.020202x + 0.000079x^2$	0.94	0.012
Storage root	7.2	7.5	7.9	7.8	$y = 7.16 + 0.01121x - 0.000043x^2$	0.94	0.011
			Ca concentration (g kg^{-1})				
Aboveground	10.5	12.6	12.4	11.9	$y = 10.68 + 0.03954x - 0.000182x^2$	0.85	0.006
Stem cutting	5.5	4.3	3.6	3.5	$y = 5.55 - 0.031717x + 0.000112x^2$	0.99	<0.001
Storage root	0.7	0.7	0.6	0.6	y = 0.65	—	NS
			Mg concentration (g kg^{-1})				
Aboveground	3.0	3.7	3.2	2.9	$y = 3.15 + 0.007129x - 0.000049x^2$	0.50	0.005
Stem cutting	1.6	1.4	1.3	1.2	$y = 1.5250 - 0.002222x$	0.93	<0.001
Storage root	0.8	0.8	0.8	0.8	y = 0.82	—	NS
			S concentration (g kg^{-1})				
Aboveground	0.3	0.3	0.4	0.4	$y = 0.322 + 0.000602x$	0.77	0.002
Stem cutting	0.2	0.2	0.2	0.2	y = 0.18	—	NS
Storage root	0.2	0.2	0.3	0.2	$y = 0.1382 + 0.001975x - 0.000010x^2$	0.61	<0.001
			Cu concentration (mg kg^{-1})				
Aboveground	1.5	2.4	1.2	1.2	y = 1.6	—	NS
Stem cutting	2.1	1.4	1.5	1.7	$y = 2.018 - 0.011816x + 0.000056x^2$	0.83	0.001
Storage root	1.9	1.7	1.8	2.1	$y = 1.91 - 0.004730x + 0.000032x^2$	0.97	<0.001
			Fe concentration (mg kg^{-1})				
Aboveground	93	95	85	97	y = 92.6	—	NS
Stem cutting	225	238	244	250	$y = 228.70 + 0.131587x$	0.88	0.026
Storage root	79	67	73	72	y = 72.7	—	NS
			Mn concentration (mg kg^{-1})				
Aboveground	81.2	109.2	103.3	123.8	$y = 88.31 + 0.204x$	0.79	<0.001
Stem cutting	22.3	18.6	13.5	10.3	$y = 22.77 - 0.125253x + 0.000314x^2$	0.99	0.009
Storage root	5.7	4.5	4.3	4.4	$y = 5.58 - 0.024801x + 0.000103x^2$	0.94	0.022
			Zn concentration (mg kg^{-1})				
Aboveground	20.7	35.4	22.1	20.4	y = 24.7	—	NS
Stem cutting	18.5	21.2	16.6	14.7	$y = 20.05 - 0.029206x$	0.62	0.001
Storage root	9.8	11.9	9.0	9.3	y = 10.0	—	NS

NS: not significant at $p \leq 0.05$.

nutrition stimulated plant growth by increasing protein synthesis and crop's demand by N and S. However, the increase in the accumulation of other macronutrients in response to K fertilizer was 1.4- to 1.7-fold and occurred up to 101–116 kg ha^{-1} K_2O, demonstrating that K fertilizer in the second cycle less increases the plant's demand for P, K, Ca, and Mg. Carsky and Toukourou (2005) also observed that the application of fertilizers in cassava crop increased the uptake of nutrients, such as N, P, and K. There was an increase in crop's demand by macronutrients in response to K supply in the second cycle to the same K rates that provided the maximum DM production of plants (105-121 kg ha^{-1} K_2O) (Figures 3 and 4), demonstrating that the increase in the accumulation of nutrients was primarily a result of higher DM of plants. In potato, Srek, Hejcman, and Kunzova (2010) observed that the nutrient uptake by the plant is determined by the tuber yields rather than by the nutrient concentrations in the tubers.

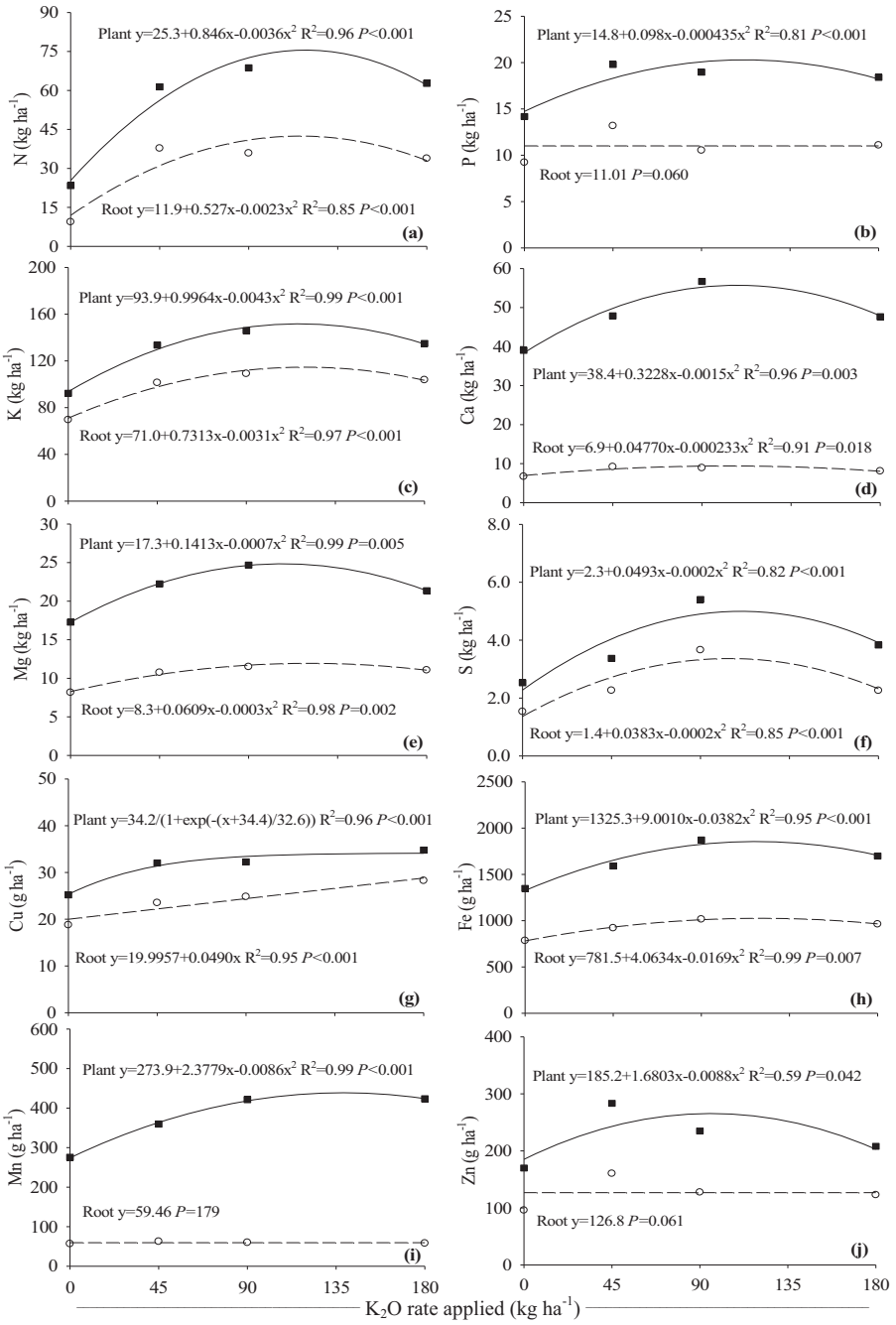

Figure 4. Amounts of N (a), P (b), K (c), Ca (d), Mg (e), S (f), Cu (g), Fe (h), Mn (i), and Zn (j) accumulated in the whole plant, and the amounts removed by storage roots of the cassava crop at harvest in response to potassium fertilizer in the second vegetative cycle.

Cassava plants with 12 MAP that received high levels of fertilization took up more nutrients than unfertilized plants, even those nutrients not applied with the fertilizer (Howeler and Cadavid 1983). According to these authors, the results occurred by the improvement of the root system and higher DM production of plants, i.e., in part similar to our results.

The maximum accumulation of macronutrients in response to K fertilizer in the second cycle was 76, 20, 152, 56, 25, and 5 kg ha^{-1} N, P, K, Ca, Mg, and S, respectively (Figure 4). Lorenzi, Gallo, and

Malavolta (1981), in cassava harvested at 12 MAP, obtained values of macronutrient accumulation per hectare of 113 kg N, 11 kg P, 79 kg K, 62 kg Ca, 19 kg Mg, and 8 kg S, i.e., the amounts of N, Ca, and S even greater than those observed in this study.

There was an increase of 1.4- to 1.6-fold in the accumulation of micronutrients in the whole plant of cassava crop in response to application of K (Figure 4g–j). The amounts of Cu and Zn accumulated in the whole plant of cassava increased up to 95 kg ha^{-1} K_2O, whereas the accumulation of Fe and Mn increased until 118 and 138 kg ha^{-1} K_2O, respectively (Figure 4g–j). This shows that increases in the accumulation of micronutrients occurred up to close to the rates of K that provided the maximum DM yield of plants (105–121 kg ha^{-1} K_2O), confirming that the increase in the uptake of nutrients that were not provided with fertilizer is mainly a result of increased DM production of plants (Howeler and Cadavid 1983). This occurs because the micronutrients are necessary for the biosynthesis of proteins, nucleic acid, growth substance and chlorophyll (Rengel 2007), being essential for the greater development of plants. The maximum accumulation of micronutrients in response to K fertilizer in the second cycle was 34, 1,855, 439, and 265 g ha^{-1} of Cu, Fe, Mn, and Zn, respectively. Silva et al. (2014), in cassava intercropped with banana tree in a 10-months cycle, observed accumulation of Zn in cassava plants of 236 g ha^{-1}, i.e., values similar to those obtained in this study (Figure 4j). However, these same authors obtained values of Cu accumulation in cassava plants of 144 g ha^{-1}, which were greater than that obtained in this study (Figure 4g), possibly due to the differences in the growing conditions.

Nutrient removal at harvest

K fertilizer in the second cycle did not affect P removal, which was on average 11.0 kg ha^{-1} P (Figure 4b). Other authors obtained P removal values in cassava harvested with 12-month cycle between 4.5 kg ha^{-1} P (Lorenzi, Gallo, and Malavolta 1981) and 22 kg ha^{-1} P (Howeler and Cadavid 1983). However, the removal of other macronutrients increased up to rates between 96 and 118 kg ha^{-1} K_2O, i.e., even with the fresh root yield and DM accumulation in the storage roots increasing only up to 45 kg ha^{-1} K_2O, the removal of these nutrients increased until higher K rates, because of the increase in concentrations of these nutrients in storage roots in response to K fertilizer (Figure 4 and Table 2). The removal of N increased by 4.3-fold in response to K application, while the increase in S removal was 2.4-fold (Figure 4). The removal of K, Ca, and Mg had increased by 1.3 to 1.6-fold due to K application. On average, the maximum removal of macronutrient per hectare was 42 kg N, 11 kg P, 114 kg K, 9.3 kg Ca, 11.7 kg Mg, and 3.3 kg S. Howeler (1981) cited that, for a storage root yield of 25 Mg ha^{-1}, the cassava crop removes about 58, 13, 103, 15, and 9 kg ha^{-1} of N, P, K, Ca, and Mg, respectively. It is noteworthy that of Ca total accumulated by plants only 17% was removed by storage roots (Figure 4d), confirming that this is the macronutrient removed in smaller proportions by tuberous roots of cassava crop (Lorenzi, Gallo, and Malavolta 1981). This occurs because Ca is not able to re-translocate from shoot to storage roots due to their high immobility within the plant. In potato, it was observed that Ca taken up by the root system of plants is transported to the shoot with the transpiration flow, but it is not re-translocated via the phloem from the shoot to the storage organ (Busse and Palta 2006).

The removal of Mn and Zn was not influenced by K fertilizer and was, on average, 59.5 and 126.8 g ha^{-1}, respectively (Figure 4i and j). This occurred because K fertilization did not change or even decreased the concentrations of these nutrients in storage roots (Table 2). In cassava harvested at 12-month cycle and that received fertilizer with Zn, the removal of Mn and Zn was higher than in this study (410 g ha^{-1} Mn and 260 g ha^{-1} Zn) (Howeler and Cadavid 1983). However, in cassava unfertilized with micronutrient, the removal of Mn and Zn was similar to this study (50 g ha^{-1} Mn and 112 g ha^{-1} Zn) (Silva et al. 2014).

For the micronutrients Cu and Fe, the application of K fertilizer increased the removal of these nutrients by the storage roots by 1.3- to 1.5-fold (Figure 4g and h). In the case of Cu, the removal increased linearly with increasing K rates, whereas the increase in Fe removal occurred up to 120 kg ha^{-1} K_2O (Figure 4g and h). These increases are the result of the effect of K on DM accumulation in the storage root associated with the changes in nutrient concentration in this plant organ (Figures 3c,

4g and h, and Table 2). The maximum removal of Cu and Fe in response to K application was 28 and 1,025 g ha^{-1}, respectively. Silva et al. (2014), in a study with cassava intercropped with banana tree, obtained a removal of Cu and Fe of 75 and 900 g ha^{-1}, respectively.

Conclusion

K application at the beginning of the second vegetative cycle of cassava increased DM production of plants by 43%. K supply in the second vegetative cycle of cassava increased the storage root yield by 36% up to a rate of 45 kg ha^{-1} K_2O, whereas the starch yield increased by 49% up to an estimated rate of 89 kg ha^{-1} K_2O. The application of K in this phase of cassava crop has a greater effect on starch synthesis and allocation in the storage roots than on their growth.

The greatest plant growth in response to K application in the second vegetative cycle increased the accumulation of N and S by 2.0- to 3.2-fold and the accumulation of the other nutrients in the whole plant of cassava by 1.4- to 1.7-fold. The removal of P, Mn, and Zn by storage roots is not influenced by K application, but the removal of K, Ca, Mg, Cu, and Fe increased by 1.3- to 1.6-fold, whereas the removal of N and S increased by 4.3- and 2.4-fold, respectively.

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