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Crop growth and macronutrient extraction and export curves for two arrowroot cultivars

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ABSTRACT. Curves of crop growth and nutrient extraction and export are essential to develop fertilization strategies and management plans to maximize yield and reduce environmental impacts. Our study aimed to evaluate dry matter production and both extraction and export of macronutrients by arrowroots (*Maranta arundinacea* L.) to be used in further crop fertilization plans. To this purpose, two experiments were carried out in field conditions using the varieties Viçosa and Seta. The experimental design was randomized with four replications and nine periods of analysis, which were defined as days after planting (105, 135, 165, 195, 225, 255, 285, 315, and 345 DAP). Dry matter, extraction, and export of macronutrients by arrowroot seed-rhizomes, aerial parts, roots, and storage roots (rhizomes) were determined. The exports of N, P, K, Ca, Mg, and S of storage rhizomes of the variety Viçosa were 104.6, 51.83, 412.24, 15.85, 36.14, and 64.36 kg ha^{-1}, while those of the seta variety were 160.6, 71.62, 521.31, 17.57, 60.09, and 160.41 kg ha^{-1}, respectively. Both varieties proved to be efficient soil macronutrient extractors, mainly for K. The variety Seta had higher shoot, root, seed-rhizome dry matter contents, as well as greater macronutrient extractions and exports.

Keywords: extraction; fertilization; *Maranta arundinacea* L.; mineral nutrition.

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Introduction

The growing demand for food due to population increase has served as a warning for agricultural intensification with less, irrigation and processing water, fertilizers and chemicals, and energy in operations (Beyer, Cuneo, Alvaro, & Pedreschi, 2021), as well as to diversify staple food types. For example, productions of starchy tropical fruits and tubers have been concentrated on banana, cassava, yams, and sweet potatoes, which is 2.7 times less than the world production of cereals (Rinaldo, 2020).

Arrowroot (*Maranta arundinacea* L.) is an herbaceous plant of the Marantaceae family, originally from tropical regions in South America (Amante, Santos, Correia, & Fante, 2020). As seed multiplication is rare due to its low germination capacity, it mainly reproduces asexually through rhizomes (Daquinta, Brown, Silva, & Sagarra, 2009). This is a rhizomatous plant, erect, with pointed leaves, and heights between 0.6 to 1.5 m (Guilherme et al., 2019). Its starchy rhizomes measure between 5 to 25 cm (Reddy, 2015) and are the most used organ for propagation, human consumption, or starch extraction industry (Brito et al., 2019).

Consumption of *M. arundinacea* can reduce dependence on staple foods due to its biological and industrial properties, which are mainly attributed to its high starch concentrations. Moreover, arrowroot crops are resistant to drought and to pathogen and insect attacks. It is also highly efficient in transforming solar energy into food, with average yield of 20 tons of rhizome per hectare (Mukherjee et al., 2015; Vilpoux, Brito, & Cereda, 2019).

In recent years, arrowroot has conquered the food and chemical industry for having a high-quality, gluten-free, and easy-to-digest starch, given its round and oval granules and amylose rates of 20-30% (Waterschoot, Gomand, Fierens, & Delcour, 2015; Charles et al., 2016). A high amylose concentration is also a notable trait of this species because it decreases the energy required to start gelatinization. Starches with higher amylose contents have fewer crystalline regions and, consequently, lower gelatinization temperatures (Denardin & Silva, 2009). Arrowroot consumption has been related to positive effects in preventing diabetes, cardiovascular diseases, high blood pressure, and oxygen free radical neutralization (Collado, Dupuy, Morero, & Minahk, 2016; Radomska-Lesniewska et al., 2016).

Depending on the plant age, starch contents in arrowroot rhizomes can vary from 18 to 23% of the total plant (Amante et al., 2020). In one of the pioneering studies with arrowroot, Erdman and Erdman (1984) showed that arrowroot silage and processing residues contain 10.8-21.1% crude protein, 11.1-30.2% crude fiber, 3.8-17.0% ash, and 38.5-60.3% *in vitro* dry matter digestibility.

As arrowroot has not received due attention from researchers, the knowledge and use of this species are still limited. Therefore, further studies are needed to help expand cultivation areas, identify more productive genotypes, and determine better agricultural practices for its production, envisioning a proper mineral nutrition of plants (Sediyama et al., 2020).

Crop yields can be improved by fertilizer application and are directly associated with the applied rates. Studies on other cultivated plants have shown that fertilization management is directly related to crop quality and yield. When fertilizer inputs are above crop needs, nutrient amounts can be lost by water leaching, resulting in low use efficiency (Salim & Raza, 2020). For example, despite being considered tolerant to drought and low-fertility soils, cassava can have its yield increased by irrigation when grown under water restriction conditions (Oliveira, Coelho, & Nogueira, 2006). However, higher water availability and soil N concentrations generally generates plants with excessive shoot development and low root production (Guo et al., 2019). As already observed in other cultivated plants, N is a fundamental nutrient for vegetative growth and starch accumulation. Sediyama, et al. (2020) observed that a bovine manure application at 778 kg N ha^{-1} results in a commercial rhizome production of 47.9 t ha^{-1} for the variety Seta, while an application of 900 kg N ha^{-1} provides a production of 43.2 t ha^{-1} for the variety Viçosa or Common. Nevertheless, there are still few technical recommendations and indications for fertilization and nutrition of arrowroot crops.

Curves of growth and nutrient extraction and export have not yet been determined for arrowroot plants. These findings could be useful as theoretical and practical bases for fertilization plans focused on maximum yields, lower costs, less energy input, and less environmental risk. Such tools could also help develop less expensive and time-consuming procedures to reach nutrition indices, allowing farmers to adjust nutrient applications as a function of crop demands, growth rates, and season duration. Therefore, our general objective was to determine the curves of crop growth and macronutrient extractions and exports for two arrowroot varieties, namely Viçosa and Seta, which are commonly grown in Brazil.

Material and methods

Study area

This study was carried out in the vegetable garden at the Universidade Federal de Viçosa (UFV), Viçosa city, Minas Gerais State, Brazil. The area is at the geographical coordinates of 20°45’ S, 42°51’ W, and 693-m altitude. The climate of the region is *Cwb* type (Alvares, Stape, Sentelhas, Goncalves, & Sparovek, 2013), with an average annual temperature of 19.4ºC and rainfall of about 1,200 mm.

Field experiments

Two separate experiments were performed in field conditions from September 2016 to August 2017. The arrowroot varieties used were Viçosa (also known as Common) and Seta, which were provided by the Vegetable Germplasm Bank of the UFV (BGH/UFV). The experimental unit was composed of four 4.0-m rows spaced 1 m apart. We considered as borders the rows at the edges of the plots and the last two plants at the central row ends, totaling 20 plants per plot. The soil of the area is classified as Cambisolic Red-Yellow Argisol (Santos et al., 2018). The chemical properties of the topsoil layer (0-20 cm) were determined and are shown in Table 1.

Soil preparation was carried out by plowing and harrowing. Then, planting furrows were fertilized with 78.6 kg P ha^{-1} using simple superphosphate fertilizer as source (18% P_2O_5). Arrowroot seed-rhizomes of both varieties (Viçosa and Seta) averaged 10.0 g and 16.0 cm and were placed at 0.12 m depth every 0.30 m, resulting in a population of 33,333 plants ha^{-1}. No topdressing was performed due to the local history of high soil fertility and lack of information on arrowroot nutritional needs.

Table 1. Chemical characteristics of the soil in the experimental areas (Viçosa, Minas Gerais State, Brazil).

Soil Depth (cm)	0–20
pH_{Water}	6.40
P (mg dm^{-3})	113.80
K (mg dm^{-3})	440.00
Ca^{2+} (cmolc dm^{-3})	5.00
Mg^{2+} (cmolc dm^{-3})	1.20
S (mg dm^{-3})	4.30
Al^{3+} (cmolc dm^{-3})	0.00
H + Al (cmolc dm^{-3})	3.30
BS(1) (cmolc dm^{-3})	7.30
CEC(2) (cmolc dm^{-3})	10.30
V (%)	69.00
OM(3) (dag kg^{-1})	5.00
P-rem (mg L^{-1})	34.00
Ds (g cm^{-3})	1.12

Irrigations were performed weekly by conventional spraying, applying a 40-mm irrigation depth, considering the rainfall volume.

Plant collection and biomass analysis

Plants were harvested every 30 days (105, 135, 165, 195, 225, 255, 285, 315, and 345 days after planting - DAP). After removing plants from soil (n = 3), roots and rhizomes were washed, and plants divided into seed-rhizomes, shoots, roots, and storage rhizomes. After weighing fresh matter, plants were dried in a forced-air circulation oven at 65 ± 5°C until constant weight (dry matter - DM). Subsequently, dry tissues were ground in a Wiley mill with a 20 mesh (0.841 mm) sieve to determine nutrient accumulations in plant organs.

Nutrient analysis

Dry tissues were mineralized with perchloric nitric digestion (Johnson & Ulrich, 1959). Phosphorus was determined by colorimetry, using the vitamin C method (Braga & Defelipo, 1974), K by flame emission photometry, Ca and Mg by atomic absorption spectrophotometry (AOAC, 1975), and S by sulfate turbidimetry (Jackson, 1958). To determine NH_4^+ and total N (NT) concentrations, plant dry tissues were submitted to sulfuric digestion and quantified by the Kjeldahl method (Malavolta et al., 1997). Finally, NO_3^- contents were quantified by the salicylic acid method (Cataldo, Haroon, Schrader, & Youngs, 1975). Only pa reagents were used for all determinations, and a blank test was made with deionized water. Nutrient accumulations in plant organs were calculated by multiplying the nutrient concentration by the dry matter (DM) content of each organ.

Experimental design and statistical analysis

The experiment was arranged in a completely randomized design, with four replications. Treatments consisted of nine evaluation times (105, 135, 165, 195, 225, 255, 285, 315, and 345 DAP) and two arrowroot varieties (Viçosa and Seta), which were analyzed separately.

Data were subjected to regression analysis. Model equations were chosen based on the significance of regression coefficients, using the t-test at 1% level of probability for determination coefficient (R^2 = SSReg/SStrat) and biological significance.

Results and discussion

Plant dry biomass

Seed-rhizome DM decreased throughout the DAP (Figure 1A). Therefore, the reserves in these organs were used by plants for their initial growth. The Viçosa variety had the highest DM consumption throughout the cycle. Similar results were seen in potato seed tubers (Fernandes, Soratto, & Silva, 2011). Arrowroot initial growth and storage rhizome yield vary with biomass production and the proportion of nutrients allocated to this organ. Thus, nutrient contents in such a propagule are important for the allocation of DM in storage rhizomes.

Root DM production of both arrowroot varieties increased over the evaluation period, showing maximum values of 65.5 and 53.3 g $plant^{-1}$ at 345 DAP for Viçosa and Seta, respectively (Figure 1B). Oliveira, Araujo, and

Guerra (2011) observed a maximum root DM accumulation in taro plants (*Colocasia esculenta*) at 120 DAP. This difference indicates that arrowroot roots grow continuously throughout the cycle, which may be related to their higher nutrient-extraction efficiency from soil.

Regarding shoot DM production, both varieties presented a quadratic behavior, with maximum for Viçosa at 236 DAP (325.84 g plant^{-1}) and Seta at 235 DAP (516.00 g plant^{-1}) (Figure 1C). Afterwards, there was a decrease in shoot DM, which coincides with the increase in root and storage rhizome DM accumulations (Figure 1B-D). Therefore, the reserve compounds were transported from the shoot to storage rhizomes in arrowroot plants. The variety Seta has larger plants than does Viçosa, besides producing several flower stems, which may explain its more significant DM accumulation in shoot.

Both varieties showed exponential DM accumulations in storage rhizomes (Figure 1D), increasing as shoot DM accumulations reduced (Figure 1C). Seta was more efficient than Viçosa in accumulating DM in storage rhizomes, with a maximum of 882 g plant^{-1} against 534 g plant^{-1} for Viçosa at 345 DAP; therefore, the former exceeded the latter by 65%. This increased DM production in storage rhizomes may be explained by the larger shoot area of Seta plants, which increases the synthesis of photoassimilates that are later transported to storage rhizomes.

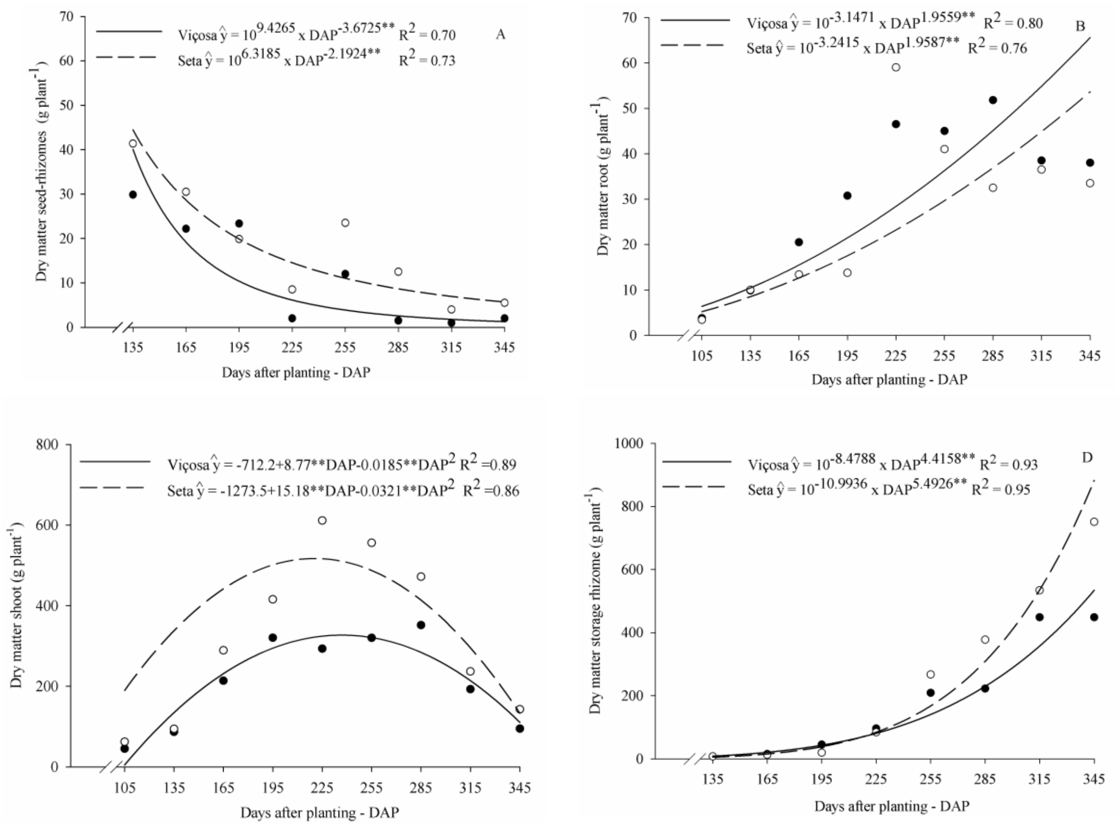

Figure 1. Dry matter of seed-rhizomes (A), roots (B), shoot (C), and storage rhizomes (D) of arrowroot plants of the varieties Viçosa and Seta throughout the cultivation cycle. **Significant at 1% probability by the t-test.

Macronutrients in seed-rhizomes

Accumulations of N, P, K, Ca, Mg, and S in the seed-rhizomes of both varieties reduced throughout plant development. Therefore, these macronutrients were mobilized during the establishment of the plants (Figure 2). Nutrient reductions in propagation organs occurs because the reserves in such structures are used for the initial growth of plants, thus allocating these resources for the development of shoots (stems and leaves) and roots (Franco, Bologna, Faroni, Vitti, & Trivelin, 2007; Bindraban, Dimkpa, Nagarajan, Roy, & Rabbinge, 2015). Over the 345-day cycle, Ca contents were reduced in seed-rhizomes. It is well-known that this element is rarely translocated through the phloem (Paiva, 2019). However, our findings suggest the opposite, or even that a Ca transporter in the rhizome may have been connected to the xylem to transport it and other nutrients absorbed by the roots. If Ca had not been translocated, its accumulation would have increased (concentration effect) as CHO was exported and DM reduced, without reducing Ca accumulation. This result can be explained by the several families of ion channels and transporters already identified. Such structures contribute to Ca^{2+} transport across plasma membrane and intracellular membranes. Regulation of these transport systems at cell and whole-plant levels governs Ca^{2+} and Mg^{2+} nutrition and ensures a proper Ca^{2+} control, which acts as a second messenger in response to various developmental and environmental cues. This nutrient sensing network was exemplified by the existence of a Ca^{2+} – dependent CBL (calcineurin B-like) – CIPK (CBL-interacting protein kinase) pathway, which serves as a major link between environmental nutrient status and transport activities (Tang & Luan, 2017).

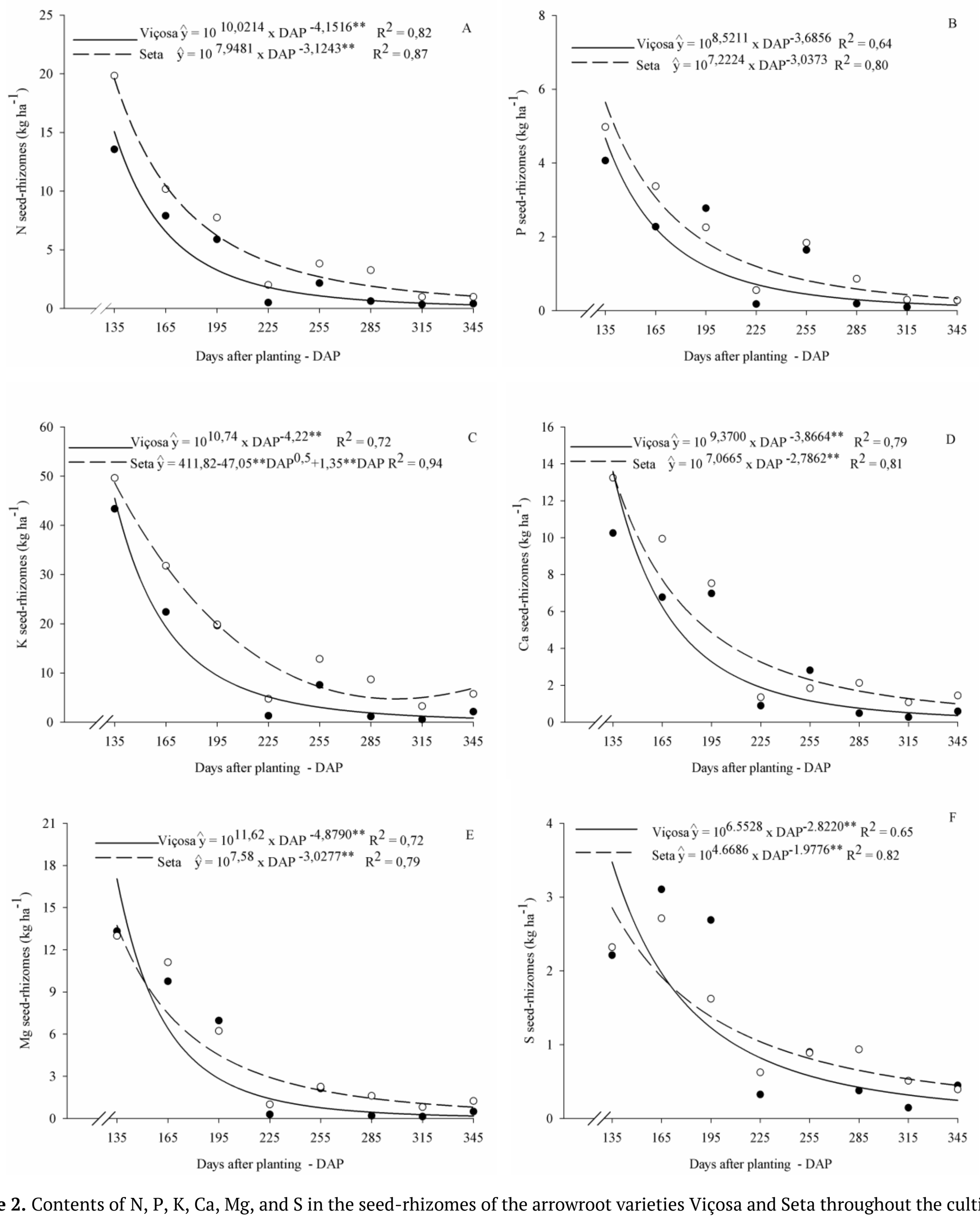

Figure 2. Contents of N, P, K, Ca, Mg, and S in the seed-rhizomes of the arrowroot varieties Viçosa and Seta throughout the cultivation cycle. **Significant at 1% probability by the t-test.

Macronutrients in roots

Accumulations of N, P, K, Ca, Mg, and S increased in the roots of both varieties throughout the cycle (Figure 3). In Viçosa plants, these accumulations showed a quadratic behavior for N, P, and K, with maximum values of 14.6 (255 DAP), 2.20 (275 DAP), and 26.6 (265 DAP) kg ha^{-1}, respectively. Whereas for Ca, Mg, and S, they had an exponential increase at 345 DAP, with maximum accumulations of 28.0, 17.5, and 11.90 kg ha^{-1}, respectively. Yet, macronutrient accumulations in the Seta plants presented a linear behavior for N and Ca and exponential for the other macronutrients, with maximum values at 345 DAP of 10.6, 2.15, 31.0, 26.4, 20.2, and 11.7 kg ha^{-1} for N, P, K, Ca, Mg, and S, respectively (Figure 3).

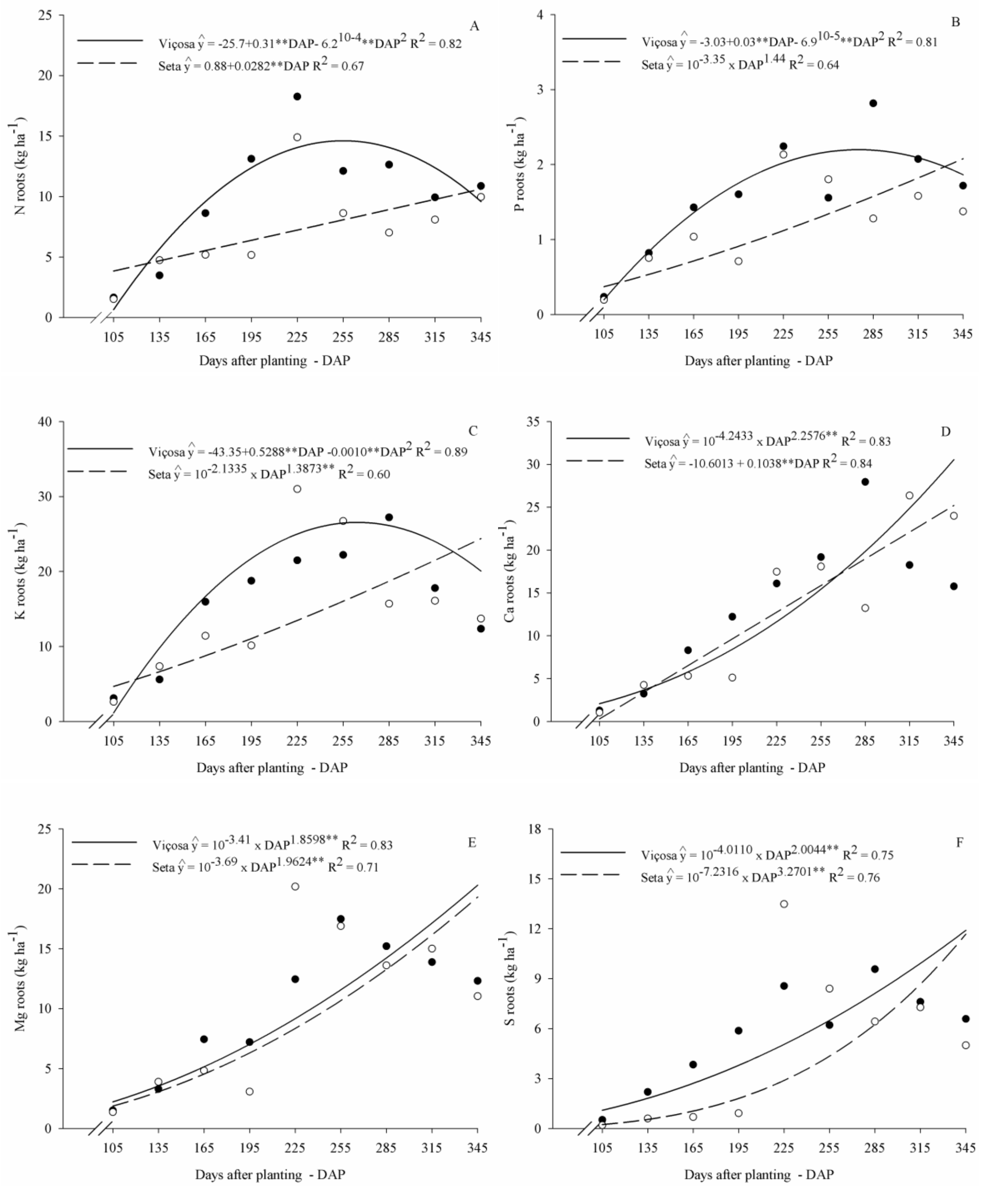

Figure 3. Contents of N, P, K, Ca, Mg, and S in the roots of the arrowroot varieties Viçosa and Seta throughout the cultivation cycle. **Significant at 1% probability by the t-test.

As there was no decrease in root DM throughout the cycle (Figure 3B), the quadratic behavior of N, P, and K accumulations in Viçosa roots (Figure 3A, B, and C) indicates that these nutrients continued to be translocated after 255, 275, and 265 DAP, respectively. Besides, this nutrient-extraction efficiency, mainly for P, may explain the remarkable adaptation of arrowroot plants to P-poor soils, which are pervasive in the tropics. This nutrient plays an essential role in carbohydrate synthesis and storage, as already observed in potato tubers (Fernandes et al., 2015). The differences in root macronutrient accumulation reflect the variability in shoot growth rate between both varieties, and hence demand for nutrients. When analyzing root and shoot DM values (Figure 1B and C), we can infer that the variety Seta, which has a larger size, showed a lower root: shoot ratio and, therefore, a lower investment of carbon in roots more effective in absorbing and transporting nutrients to the shoot. The high nutrient accumulation in roots of the variety Viçosa (Figure 2) suggests the presence of a mechanism that compensates for the lower efficiency in nutrient extraction by its roots. Cultivar differences in absorption from soil solution and transport of nutrients have also been reported for potatoes (Barben, Hopkins, Jolley, Webb, & Nichols, 2010; Fernantes, Soratto, & Pilon, 2015).

Macronutrients in plant shoot

For both varieties, shoot accumulations of N, P, and K were adjusted to a quadratic model (Figure 4A, B and C), just as DM accumulation in the variety Seta (Figure 1C). The maximum N accumulation for Viçosa was 148.2 kg ha^{-1} at 215 DAP, while for Seta it was 239 kg ha^{-1} at 222 DAP. For P, the maximum accumulation for Viçosa was 47.47 kg ha^{-1} at 239 DAP, while for Seta it was 56.70 kg ha^{-1} at 225 DAP. For K, it was 77.84 kg ha^{-1} at 184 DAP for Viçosa, and 94.70 kg ha^{-1} at 177 DAP for Seta. Plant shoot metabolic and structural compounds and changes in their proportions during growth explain the decrease in nutrient accumulation, as previously described for potatoes (Giletto, Calvo, Sandaña, Echeverría, & Bélanger 2020). Finally, the reduction in macronutrient accumulations in plant shoots suggests their remobilization to underground reserve structures (storage rhizomes - Figure 5), as these nutrients are efficiently mobilized and readily redistributed from older leaves to new growing organs (Sediyama et al., 2020).

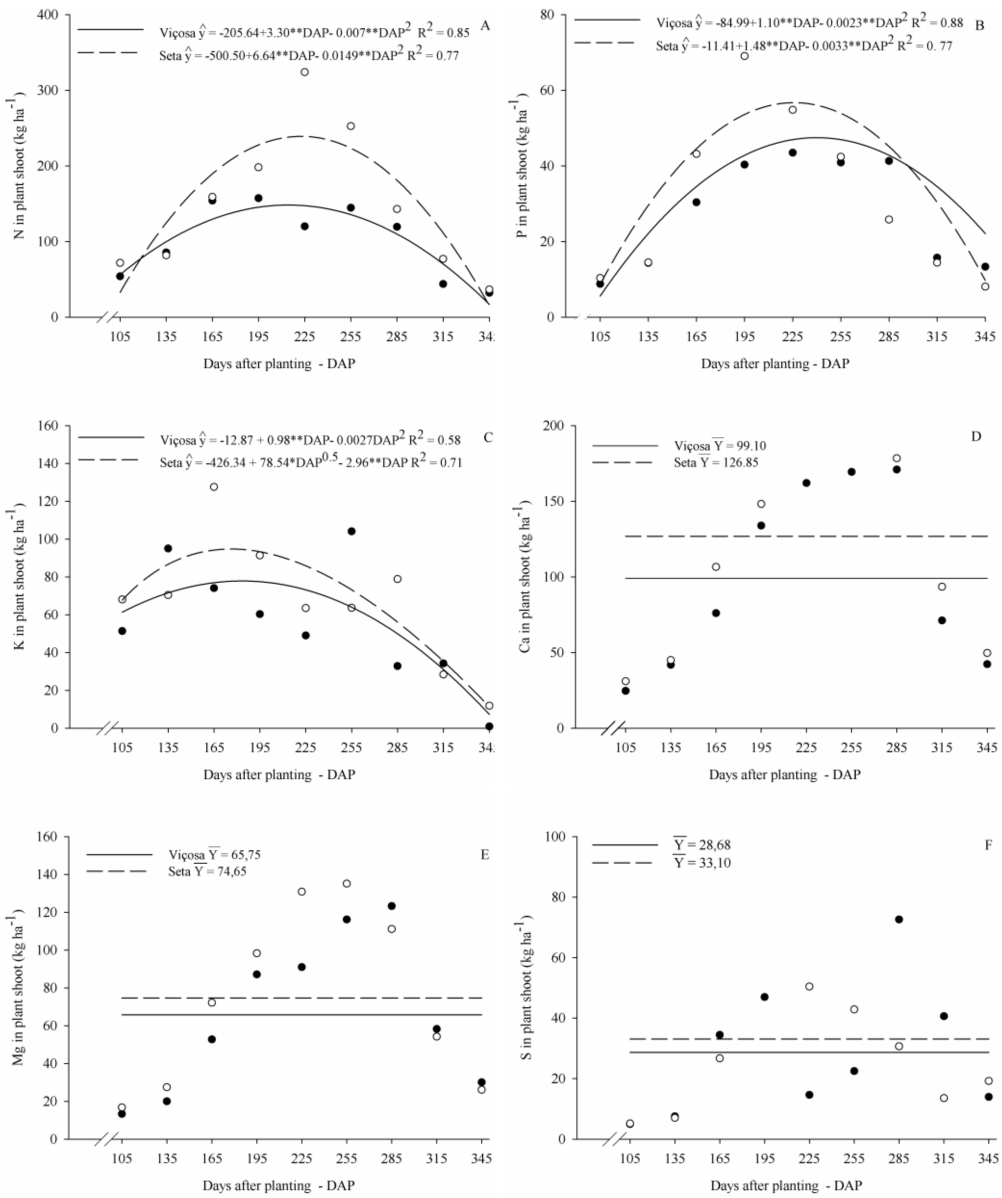

Figure 4. Contents of N, P, K, Ca, Mg, and S in the shoot of the arrowroot varieties Viçosa and Seta throughout the cultivation cycle. **Significant at 1% probability by the t-test.

Although there are no defined values in the literature regarding nutritional requirements of N, P, and K for arrowroot shoot, our results are in line with those already reported for potatoes (Westerman, 2005). Our findings also indicate that the N retranslocation of the aerial part met the rhizomes' demand, making them independent of N in the soil. The most striking observation resulting from the comparison of nitrogen data was that the retranslocation of nutrients from the shoot to the rhizomes might have provided independence from the soil quantities. These results contribute to the improvement of arrowroot fertilization programs. Thus, on average, for both varieties, N and K topdressing can be applied within the first 105 DAP, as these macronutrients showed linear accumulations up to 180 DAP. Splitting N and K topdressing may be appropriate to decrease potential nutrient losses by leaching, which vary with soil sand content and rainfall frequency and intensity in the cultivation site (Zheng, Qu, Kilasara, Mmari, & Funakawa, 2019). The amounts of P absorbed by arrowroots in our study were above those reported for potatoes, which had a total P uptake of 31 kg ha^{-1} for the whole plant (Westerman, 2005). Such an increased P accumulation in the arrowroot varieties may be a consequence of their higher DM production compared to potato plants.

Nevertheless, we could not adjust any equation to explain Ca, Mg, and S accumulations in both arrowroot varieties throughout the cycle. For Viçosa, accumulations were 99.10, 126.85, and 28.68 kg ha^{-1} for Ca, Mg, and S, respectively. Conversely, for Seta, the values were 65.75, 74.65, and 33.10 kg ha^{-1} for Ca, Mg, and S, respectively. As these nutrients were not retranslocated from arrowroot shoots to rhizomes, they should be supplied through soil over the cycle.

Macronutrients in storage rhizomes

Both arrowroot varieties showed exponential increases in N, P, K, Ca, Mg, and S accumulations in storage rhizomes throughout the cycle (Figure 5). Such accumulations started increasing from the 225 DAP on, coinciding with the decreases in DM accumulations in shoots (Figure 1C) and reductions in N, P, and K (Figure 4A, B, and C). At 345 DAP, the amounts of macronutrients exported by rhizomes (kg ha^{-1}) were: 104.6 and 160.6 (N), 51.83 and 71.62 (P), 412.24 and 521.31 (K), 15.85 and 17.57 (Ca), 36.14 and 60.09 (Mg), and 64.36 and 160.41 (S) for the varieties Viçosa and Seta, respectively (Figure 5).

In a fertilization study using cattle manure in the same varieties with N doses up to 900 kg ha^{-1}, but in another soil type (city of Oratórios-MG), Sediyama et al. (2020) found the following values extracted by the varieties Viçosa and Seta: 107.06 and 168.90 (N), 34.79 and 38.85 (P), 272.99 and 320.91 (K), 2.68 and 3.38 (Ca), 10.71 and 13.51 (Mg), and 14.72 and 16.89 (S), respectively. As observed in our study, Seta showed greater extraction of macronutrients than did Viçosa, with both studies showing similar exported N values. However, the exported values of the other macronutrients were much higher in our study, which may be due to the higher soil fertility, leading to higher rhizome yields than those obtained by Sediyama et al. (2020). By applying the highest N dose (900 kg ha^{-1}), these authors found rhizome DM values of 13.1 and 17.0 t ha^{-1} for Viçosa and Seta, respectively. In contrast, we found rhizome DM values of 17.8 and 29.4 t ha^{-1} for Viçosa and Seta, respectively.

Studies on on nutrient exportation by arrowroot rhizomes are scarce in the literature (Vieira, Colombo, Puiatti, Cecon, & Silvestre, 2015; Sediyama et al., 2020). However, for Japanese taro, which is a rhizomatous plant of the family Araceae, N, P, and K exports by corms were 132.9, 24.0, and 206.2 kg ha^{-1}, respectively (Sediyama, Santos, Salgado, Puiatti, & Vidigal, 2009). Moreover, these authors found a yield of commercial rhizomes of 29.1 t ha^{-1}. Another study conducted with Japanese taro showed that N, P, and K exports by rhizomes were 193, 47.0, and 443 kg ha^{-1}, respectively, with a yield of 66.0 t ha^{-1} (Puiatti, Greeman, Katsumoto, & Favero, 1992). These findings indicate that the amounts of nutrients exported by arrowroot and taro rhizomes are high and similar, especially for K and N. The amount of Mg exported by arrowroot rhizomes was relatively high, especially for the variety Seta. The presence of Mg in arrowroot starch may explain its widespread use in the treatment of ulcers, diarrhea, and intestinal pain (Lim, 2016).

In short, arrowroots have a high extraction capacity for macronutrients from the soil and export to rhizomes, especially K and N. Such extraction occurs during a large part of the cycle, what must be considered when fertilizing the crop with nutrients with high soil mobility. Our findings evidence that there are differences between the varieties, of which Seta showed greater extraction and rhizome production capacities than did Viçosa. Therefore, this crop should be fertilized to accumulate nutrients as a function of the variety to be grown. This approach may increase these crops' productive potential and maintain soil fertility.

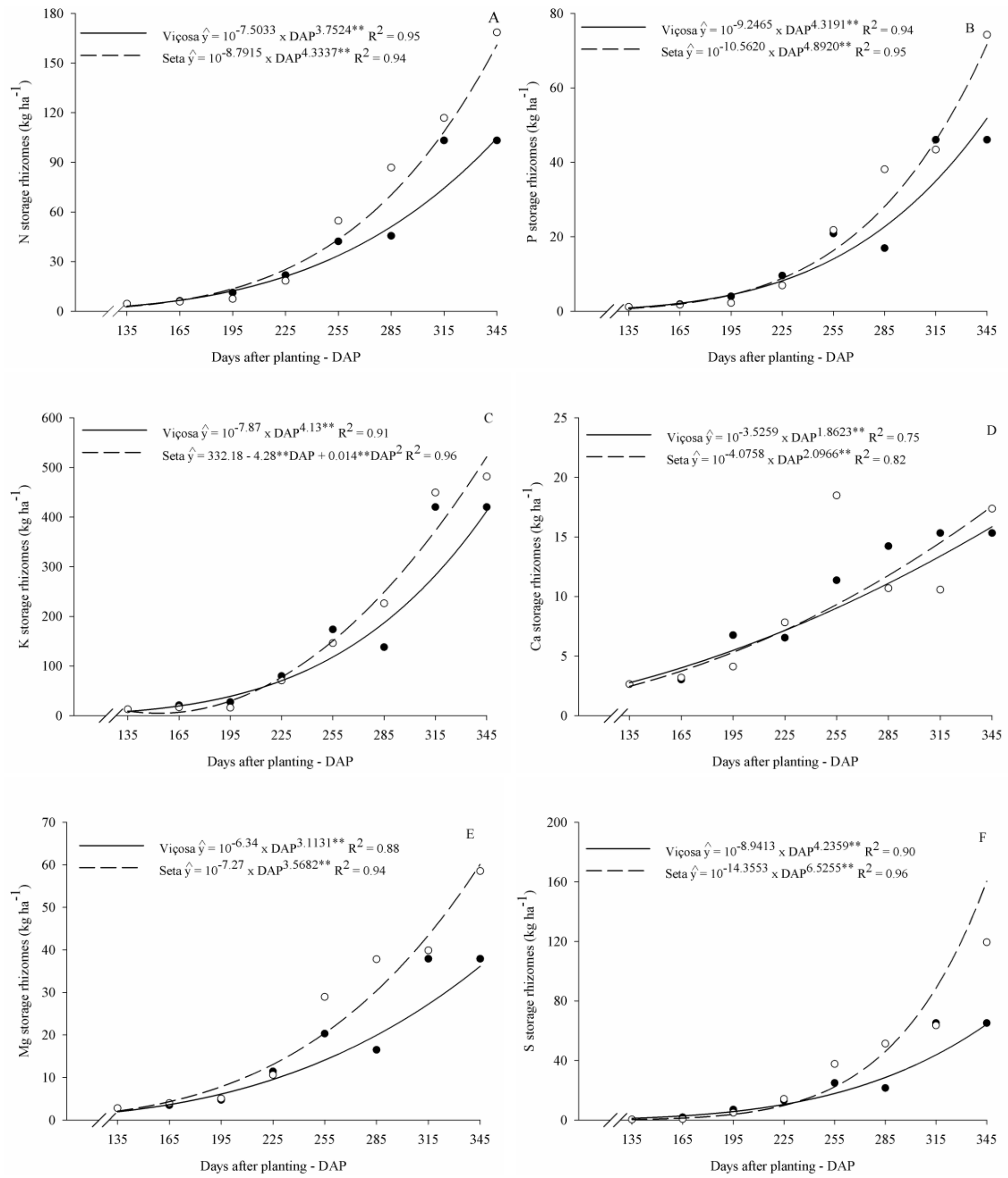

Figure 5. Contents of N, P, K, Ca, Mg, and S in the storage rhizomes of the arrowroot varieties Viçosa and Seta throughout the cultivation cycle. **Significant at 1% probability by the t-test.

Conclusion

Arrowroot plants absorbed the following amounts (kg ha^{-1}) of macronutrients from the soil: 267.4 and 410.2 (N), 101.5 and 130.47 (P), 516.68 and 647.0 (K), 142.95 and 109.72 (Ca), 180.5 and 154.94 (Mg), and 102.94 and 205.2 (S) for the varieties Viçosa and Seta, respectively. From these total absorbed amounts, the rhizomes (kg ha^{-1}) of Viçosa and Seta exported: 104.6 and 160.6 (N), 51.83 and 71.62 (P), 412.24 and 521.31 (K), 15.85 and 17.57 (Ca), 36.14 and 60.09 (Mg), and 64.36 and 160.41 (S), respectively. This characterizes that arrowroots have high demand and export of nutrients, besides differences between the varieties. Nitrogen and potassium topdressings should be applied up to 105 days after planting, which is when these nutrients present linear accumulations in plant shoots.

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