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Nutritional status of 'BRS Rubimel' peach plants in the nursery as a function of the rootstock

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ABSTRACT. Improvements in the traditional production system of peach seedlings, with a focus on the use of selected rootstocks, tend to minimize some of the problems experienced with this crop in the south of Brazil, such as the scarcity of vigorous nursery plants and the lack of a genetic identity for commercial rootstocks. The aim of this study was to investigate the different patterns of nutrient absorption and allocation related to the rootstock in 'BRS Rubimel' peach plants by analyzing growth variables during the post-graft period. The experimental design consisted of randomized blocks in a 3 × 3 factorial scheme, with three peach rootstock varieties (i.e., 'Flordaguard', 'Capdeboscq', and 'Okinawa Roxo') and three post-graft evaluation periods (i.e., 30, 60, and 90 days after the start of budding), corresponding to a total of nine treatments, with three replications, each including five plants. During the three evaluation periods, morphological growth characteristics were measured, and the macronutrient content was determined in the different plant organs (i.e., leaf, stem, and roots). The nutrient content in plants of the 'BRS Rubimel' peach plants was influenced by the rootstock. Despite showing greater N use efficiency, 'Capdeboscq' accumulated a large part of this nutrient in the roots, using it for root growth, which resulted in a smaller scion diameter compared to that of 'Flordaguard'. Comparing the three rootstocks and the evaluated variables, it seems that 'Flordaguard' can be used as a rootstock for the 'BRS Rubimel' peach plants, as it induces a greater scion diameter as well as the uniform allocation of dry matter between organs during the post-graft period, hence ensuring greater initial plant vigor.

Keywords: peach rootstocks; plant nutrition; *Prunus persica*; seedling production.

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Introduction

Despite national recognition, the largest producer of peaches in the country, namely the state of Rio Grande do Sul (Instituto Brasileiro de Geografia e Estatística [IBGE], 2017), has planted and maintained peach orchards formed from seedlings, whose rootstocks are of unknown genotypes, for a long time (Mayer, Ueno, Fischer, & Migliorini, 2015a). One of the explanations for this situation is the ease in obtaining seeds that are discarded by the canning industry and using them to produce rootstocks for scion cultivars (Mayer et al., 2015a; Gonçalves et al., 2019). In addition, there is a lack of research-based evidence to support the use of selected rootstocks for the production of better-quality grafted nursery plants, as well as of studies that consider the absorption efficiency of mineral nutrients (Mayer, Ueno, & Silva, 2015b) and their consequent conversion into growth. Notably, this situation discourages the technification of nurseries and the search for better-quality genotypes.

This context is one of the reasons for the ongoing difficulty in obtaining seedlings with a known genetic rootstock identity or the quality and nutritional status suitable for setting up peach orchards in the state of Rio Grande do Sul; it also partly explains the reason behind the lowest crop yields being observed in the country (Mayer et al., 2015a; IBGE, 2017). Notably, the use of rootstocks from unknown genotypes in the plant propagation stage prevents the application of specific nutrient management systems, which would consider the characteristics intrinsic to each rootstock variety (Almeida, Marodin, Queiroz, & Gonzatto, 2016). As a result, the time needed to obtain nursery plants suitable for the national market is extended (Mayer et al., 2015b), and nursery plants of varied stands, often below commercial standards, are produced, hence reducing the efficiency of the nursery and consequently increasing the production costs (Souza et al., 2019a).

In the orchard, the use of rootstocks with unknown genetic identities results in a diversity of plant sizes in the field and differences in terms of adaptability to the soil and climate, the degree of tolerance to water stress, and resistance to pests and diseases (Jimenez, Mayer, Dias, Scarpare Filho, & Silva, 2018; Gonçalves et al., 2019). These factors limit the application of efficient management techniques, and culminate in failures in the stand, resulting in a low productivity per cultivated area. Studies that characterize the peculiarities of the nutritional efficiency by genotype can contribute to the rational recommendation of fertilizers for nurseries, thus promoting the production of commercial seedlings of excellent nutritional status in less time than that required with traditional production systems. Additionally, these studies can recommend scion/rootstock combinations capable of inducing high productivity in the field and producing high-quality fruits (Mestre, Reig, Betrán, & Moreno, 2017; Gonçalves et al., 2019).

Since the production of commercial peach seedlings is carried out by grafting, a range of selected rootstock varieties has been suggested by researchers as potentially suitable for replacing those obtained from the seeds of the canning industry, or as an alternative to the Capdeboscq cultivar, which is still used as a rootstock in the seedling production by nurseries in the south of Brazil (Mayer et al., 2015a). Among possible materials, the 'Flordaguard' and 'Okinawa Roxo' rootstocks have low chill requirements (Mayer et al., 2015b; Menegatti, Souza, & Bianchi, 2019a; Souza, Ritterbusch, Menegatti, Smirdele, & Bianchi, 2019b), good vigor, and resistance to various species of soil phytonematodes (Mayer et al., 2015a; Souza, Brida, Garcia, & Bianchi, 2019c). However, information related to possible differences in their capacity to absorb, use, and accumulate nutrients is scarce.

As a peach scion cultivar, and with the aim of meeting the demand for fresh fruits with low acidity and high-caliber characteristics, Embrapa launched the 'BRS Rubimel' cultivar in 2007 (Empresa Brasileira de Pesquisa Agropecuária [Embrapa], 2010). This variety is suitable for the production of table peaches in the south of Brazil, as it results in high yield, and produces firm fruits, which is an important characteristic for transport (Embrapa, 2010).

In this context, the aim of the present study was to investigate the different patterns of nutrient absorption and allocation in the various organs of the 'BRS Rubimel' peach tree as a function of the rootstock and post-graft period, by means of chemical analyses and growth variables.

Material and methods

The present study was conducted using propagation materials that were harvested from 8-year-old clonal mother peach trees of the Flordaguard, Capdeboscq, and Okinawa Roxo rootstocks from the Germplasm Collection of the Federal University of Pelotas, located in Capão do Leão, state of Rio Grande do Sul, southern Brazil, between November 2016 and January 2017. The mother peach trees were grown in a 1.5 × 6 meters space, and the cultural treatments were those described in the integrated production standards of Prunus. Fruits were harvested when they reached maturity, with the collection of the Okinawa Roxo selection carried out in November, followed by that of cultivars 'Flordaguard' in December and 'Capdeboscq' in January.

The study, including rootstock production, grafting, and nutritional assessments, was conducted under greenhouse conditions (at Capão do Leão, 31° 52' 00" S and 52° 21' 24" W; altitude of 13.1 m) from April 2017 to March 2018. The average temperature recorded inside the greenhouse during the period of the experiment was 17.9°C. As for the irrigation management of the plants, the field capacity of the substrate was previously determined in the amount of substrate that was used (i.e., 2 dm^3), and this amount was taken as a reference for maintaining an adequate water supply to the plants throughout the experiment.

After harvesting the fruits, the post-harvest handling of the seeds was carried out as described by Picolotto, Bianchi, Gazolla Neto, and Fachinello (2007), and the seeds were then stored in a paper bag at room temperature (25 ± 5°C) for approximately two months. The seed stratification was carried out as per Souza, Spinelli, Souza, Smiderle, and Bianchi (2017). After the stratification period (i.e., 35 days at 7°C), the seeds were sown to a depth of 1 cm in polystyrene trays of 72 cells (114 cm^3 per cell) that contained a substrate composed of orchard soil (i.e., typical dystrophic red yellow Argisol, containing 1.5% organic matter and 17.5% clay), vermiculite, medium sand, and Plantmax® commercial substrate at a 1:1:1:1 ratio, and maintained in a greenhouse.

When the plants were ready for transplantation (i.e., 15 cm in height, from collar to apex), they were transferred to plastic bags with a capacity of 2 dm^3 that contained Carolina Soil® commercial substrate (Table 1), fertilized with 4 g dm^{-3} slow-release encapsulated fertilizer (Osmocote®; NPK formulation 14-14-14), as recommended by Menegatti, Souza, and Bianchi (2020) for the production of peach rootstocks.

Table 1. Chemical composition of the substrate used for the production of 'BRS Rubimel' peach plants grafted onto 'Flordaguard', 'Capdeboscq', and 'Okinawa Roxo'.

Substrate	pH	OM	V	H+Al	SB	t	P	K	Ca	Mg
		%		cmol$_c$ dm^{-3}			mg dm^{-3}			
	6.4	14.9	86.6	4.08	20	20	26.1	151	6.3	12.9

pH: in water; OM: organic matter; V: base saturation index; H+Al: SMP extractor; SB: sum of exchangeable bases; t: effective cation exchange capacity [CEC (t)]; K^+ and P: obtained with Mehlich^{-1} extraction; Ca^{2+} and Mg^{2+}: extracted with 1 mol L^{-1} KCl.

When the rootstocks reached a mean collar diameter of approximately 5.3 mm, during the second half of December 2017, grafting was carried out using vegetative buds from the BRS Rubimel cultivar, which were harvested from mother plants kept in the germplasm collection of *Prunus* rootstocks at the Palma Agricultural Center (Capão do Leão, state of Rio Grande do Sul, Brazil). The grafting method was inverted T-budding at a height of 10 cm from the ground, with subsequent toppling of the scion 10 cm above the grafting point, removing it 15 days later by cutting 5 cm above the graft. Thereafter, the controlled-release fertilizer was reapplied on the substrate surface, at the same dose as initially applied (i.e., 4 g dm^{-3}), since the period stipulated by the manufacturer for the release of nutrients, namely approximately six months after application, had already been exceeded.

The experimental design was of randomized blocks in a 3 × 3 factorial scheme, with three peach rootstocks ('Capdeboscq', 'Flordaguard', and 'Okinawa Roxo') and three evaluation periods following the grafting activity (i.e., 30, 60, and 90 days after the start of the budding [DAB] of the BRS Rubimel cultivar), resulting in a total of nine treatments, with three replications, which included five plants each.

During the three evaluation periods that followed grafting, the growth characteristics and nutritional status of the plants of each treatment were evaluated. The evaluated growth characteristics were graft height (H; measured with a graduated rule), as well as scion collar diameter (GCD at a height of 10 cm from the grafting point) and rootstock collar diameter (RCD; at a height of 10 cm from the ground), both of which were determined using a digital caliper. Additionally, the leaf area (LA in cm^2) was determined using a portable leaf area integrator (model LI-3100, LI-COR, in cm^2), the root length (RL) was measured using a graduated ruler, the root volume (RV) was calculated using the method described by Rossiello, Araújo, Manzatto, and Fernandes (1995), and the number of leaves per plant (NL) was determined by counting the leaves.

The increase in the stem diameter of the rootstocks and grafts was measured 5 cm below and above the grafting point with the aid of a digital caliper; the measurements were taken at two transversal positions, with the final value determined from the average of the two readings.

The plants were then divided into roots, stems, and leaves, and dried to constant weight in a forced air circulation oven at 70 ± 5°C, to determine the dry matter (g per plant) of the individual parts of the plant: the leaves (LDM), stem (SDM) and roots (RDM). The total dry matter (TDM) was determined by summing the individual parts.

For each treatment, the samples from each part of the plant were later ground in a Willey Mill. The macronutrient content (i.e., N, P, K, Ca, Mg, and S) was then determined using the methodology described by the Official Soil and Tissue Analysis Laboratory Network of the states of Rio Grande do Sul and Santa Catarina (Sociedade Brasileira de Ciência do Solo [SBCS], 2016).

Based on the leaf area and the dry matter of the different plant organs, the morphological indices of the leaf area ratio (LAR) and specific leaf area (SLA) were calculated as per Portes and Castro Junior (1991). Finally, the biomass partitioning was analyzed, with the aim of identifying to which plant organ the produced biomass was preferentially allocated, as indicated by the ratio of shoot dry matter to root dry matter.

The data thereby obtained were submitted to normality and homoscedasticity analyses, and differences between treatments were verified using analysis of variance (ANOVA). Variables that showed a significant difference were submitted to Tukey's test at a 5% probability. The data analysis was carried out using the Sisvar statistical package (Ferreira, 2011).

Results and discussion

The ANOVA revealed a significant effect of the interaction between the rootstock (R) and time (T) factors for total dry matter (TDM), and for the accumulation of each macronutrient under evaluation (Table 2). Based on these results, it can be inferred that the peach rootstocks differ in terms of the absorption efficiency of the substrate nutrients, absorbing and accumulating them in varying amounts. The results also showed that this accumulation depends on the amount of days after budding.

Table 2. Analysis of variance for total dry matter (TDM) and nutrient accumulation in 'BRS Rubimel' peach plants as a function of the rootstock (R) (i.e., 'Flordaguard', 'Capdeboscq', and 'Okinawa Roxo') and period of evaluation following grafting (Time; i.e., 30, 60, or 90 days after budding – DAB) and their interactions.

Factor	N	P	K	Ca	Mg	S
	Mean square					
Rootstock (R)	207.47**	2.26**	76.59**	2.12**	2.15**	0.21**
Time (T)	265.96**	1.37**	1375.78**	9.87**	3.32**	0.94**
R × T	287.44**	2.97**	587.12**	6.23**	5.15**	1.23**

Rootstock	DAB 30	DAB 60	DAB 90
	TDM (g plant^{-1})		
Flordaguard	11.7aB	18.7aAB	25.5bA
Capdeboscq	17.3aB	20.6aB	37.2aA
Okinawa Roxo	14.0aB	19.8aB	34.9abA
	N (g kg^{-1} MST)		
Flordaguard	85.6bB	124.3aA	85.0aB
Capdeboscq	80.4cB	84.5bA	80.9cB
Okinawa Roxo	129.0aA	82.5cB	81.4bB
	P (g kg^{-1} MST)		
Flordaguard	13.8bC	14.5cB	15.8bA
Capdeboscq	15.8aC	17.1aA	16.3aB
Okinawa Roxo	15.0aB	16.9bA	13.7cC
	K (g kg^{-1} MST)		
Flordaguard	81.3bA	60.4bB	52.3bC
Capdeboscq	88.7aA	62.1aB	56.7aC
Okinawa Roxo	76.0cA	62.2aB	48.3cC
	Ca (g kg^{-1} MST)		
Flordaguard	15.3aB	18.1bA	19.3aA
Capdeboscq	15.9aB	18.4bA	18.1bA
Okinawa Roxo	13.6bC	19.1aA	15.5cB
	Mg (g kg^{-1} MST)		
Flordaguard	25.2bB	24.3cB	28.0aA
Capdeboscq	27.9aA	25.7bB	25.7bB
Okinawa Roxo	23.9cB	27.4aA	24.6cB
	S (g kg^{-1} MST)		
Flordaguard	7.6aA	6.4bB	6.1aB
Capdeboscq	7.8aA	6.0bB	6.6aB
Okinawa Roxo	6.4bB	9.7aA	6.1aB

**significant at a level of 1%; [ns]not significant. Mean values followed by similar lowercase letters between the rootstocks within each DAB period, and uppercase letters between periods for each cultivar, do not significantly differ from each other, as per Tukey's test at a 5% probability.

In general, the Capdeboscq cultivar resulted in greatest nutrient accumulation in the 'BRS Rubimel' peach plants, especially during the first 30 DAB, when the plants were more efficient in accumulating macronutrients, except for N. As the DAB progressed, nutrient accumulation decreased, and the plants were only more efficient in accumulating P and K. Notably, the greatest values were recorded 60 DAB for P (i.e., 17.1 g kg^{-1} TDM) and at 30 DAB for K (i.e., 88.7 g kg^{-1} TDM). This response suggests that 'Capdeboscq' may have retained more nutrients during the pre-graft phase, a behavior that would explain the superior vigor of this rootstock, which is a differential characteristic that has been mentioned by various authors (Schmitz, Pasa, Fischer, Fachinello, & Bianchi, 2014; Souza et al., 2017; Souza et al., 2019a).

It is important to point out that for the three evaluated periods, 'Capdeboscq' had the lowest mean accumulation of N (i.e., 81.9 g kg^{-1} TDM). In contrast, 'Flordaguard' induced a greater accumulation of N, 60 and 90 DAB; and of Ca and Mg, 90 DAB compared to the other rootstocks that were tested, significantly lower values were obtained for the accumulation of P, K, and Mg, 60 DAB. However, in general, plants grafted onto 'Flordaguard' maintained an intermediate accumulation of macronutrients, with a tendency to greater accumulation during the more advanced periods, that is, 60 and 90 DAB, which may suggest a slower initial growth in the plants grafted onto this rootstock.

As for 'Okinawa Roxo', it induced the lowest accumulation of nutrients in the 'BRS Rubimel' peach plants 30 and 90 DAB. However, this same rootstock was superior in accumulating some quantified nutrients, namely K, Ca, Mg, and S, 60 DAB, but inferior for the nutrients accumulated in greater proportion (i.e., N and P) 30 DAB. Therefore, we infer that this rootstock first induces the absorption and accumulation of greater quantities of N and P, which are both strongly related to the photosynthetic system, in order to guarantee the initial production of energy to be later invested in the absorption and accumulation of the other nutrients.

The differences in total accumulated macronutrients and the production of the corresponding total dry matter induced by the different rootstocks in combination with the 'BRS Rubimel' cultivar for the three periods (in DAB) are outlined in Figure 1. The large accumulation of N induced by the 'Flordaguard' rootstock in the 'BRS Rubimel' plants 60 DAB is highlighted in Figure 1A. It is also worth mentioning the intermediate accumulation of macronutrients during the other periods, with a concurrent increase in total plant dry matter as the DAB progressed.

'Capdeboscq' induced the greatest production of TDM in 'BRS Rubimel' plants, 90 DAB (Figure 1B), which was 30 and 12% higher than the dry matter accumulated during the same period by the 'BRS Rubimel'/'Flordaguard' and 'BRS Rubimel'/Okinawa Roxo combinations, respectively, with a peak phytomass accumulation between 60 and 90 DAB. Notably, this occurred even though 'Capdeboscq' was not superior in accumulating N, and maintained an almost equal amount of the other nutrients throughout the period of plant growth.

N is an essential component of the chlorophyll molecule and participates in increasing the leaf area of the plant, which provides more efficiency in intercepting solar radiation and increases the photosynthetic rate, and, consequently, results in the increase of dry mass (Bassi, Menossi, & Mattiello, 2018). This suggests that 'Capdeboscq' induces greater efficiency in the use of this nutrient.

The 'BRS Rubimel'/'Flordaguard' plants generated a very different result, as shown by the values for N accumulation and total accumulated dry matter (Figure 1A), since this combination not only resulted in the highest overall mean value (i.e., 98.3 g kg^{-1} TDM) for N accumulation between the three rootstocks and across the three periods, but also had the lowest total dry matter per plant (Table 2).

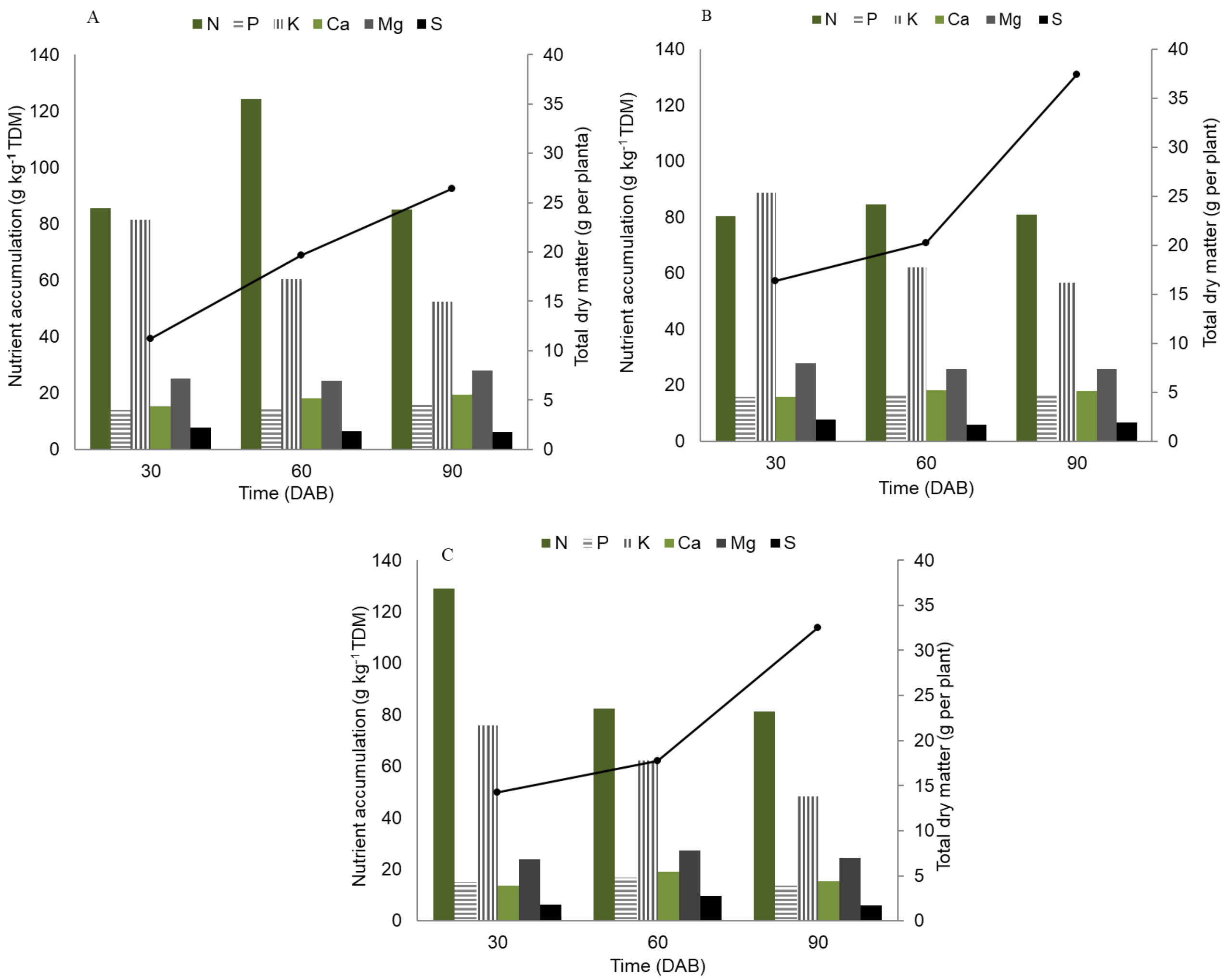

Figure 1. Nutrient accumulation (in g Kg^{-1}) and total dry matter (TDM) (g per plant) in 'BRS Rubimel' peach plants grafted onto (A) 'Flordaguard' (A), (B) 'Capdeboscq', and (C) Okinawa Roxo rootstocks, 30, 60, and 90 days after budding (DAB).

According to Menegatti, Souza, and Bianchi (2019b) and Shahkoomahally, Chaparro, Beckman, and Sarkhosh (2020), the genotypes of *Prunus* rootstocks, in addition to having different nutritional requirements, also accumulate nutrients in different proportions in the various plant organs (i.e., root, stem, and leaves); these are intrinsic characteristics of each genotype, and may compromise recommendations for employing rootstocks that are described as more efficient in the use of any specific nutrient, since usage efficiency does not account for the individual usage of each organ.

The efficient use of a nutrient can be defined as the ratio between the total dry matter of the plant and the total accumulation of that nutrient (Lemaire & Gastal, 2018). As such, rootstocks that efficiently use a certain nutrient in a specific organ such as the roots can induce a nutritional limitation in the shoots, hence restricting the expression of the potential vigor of the graft and, consequently, interfering in results related to growth or productivity.

'Okinawa Roxo' was superior in accumulating N and P at 30 DAB, with a peak in phytomass productivity between 60 and 90 DAB (Figure 1C). Razaq, Zhang, Shen, and Salahuddin (2017) evaluate the influence of N and P on the growth of seedlings of *Acer mono* in a nursery and identified the need for the concurrent accumulation of these nutrients at a level they considered adequate, suggesting that this combination might encourage growth.

P, in appropriate doses, allows the efficient functioning of the electron transport chain and, by producing adenosine triphosphate (ATP), supports the biosynthesis of the principal constituents of the photosynthetic system, such as chlorophylls, which are also dependent on optimal levels of N for their synthesis (Razaq et al., 2017). An increase in the chlorophyll content increases the capacity for light absorption by the leaves, thereby promoting greater carbon fixation, which allows a further increase in energy production. This interdependent interaction is indispensable for maintaining the physiological processes that culminate in biomass production and that result in plant growth (Bassi et al., 2018; Carstensen et al., 2018).

Variations in total nutrient accumulation between peach rootstocks during different growth periods occur to a greater or lesser extent (Nawaz et al., 2016; Mestre et al., 2017; Shahkoomahally et al., 2020), and can mainly be attributed to the characteristics of the kinetic parameters of nutrient absorption, which are genetically influenced and are related to plant growth characteristics (Paula et al., 2018; Raddatz, Ríos, Lindahl, Quintero, & Pardo, 2020). In the present study, the percentage of nutrient accumulation in the different organs of the 'BRS Rubimel' peach plants varied as a function of the rootstock (Figure 2).

Plants grafted onto 'Flordaguard' rootstocks accumulated macronutrients in a similar way between organs, with notable and concurrent increases as the DAB progressed. As for the plants grafted onto 'Capdeboscq' and 'Okinawa Roxo', they accumulated slightly more nutrients in the roots than in the leaves 30 DAB. This response may contribute to increasing the root area to absorb nutrients, with a subsequent reversal in assimilate partitioning 60 DAB. That is, at this point, the preferential sinks for the usage and storage of nutrients, both mineral and photoassimilated, become the shoots, such as the expanding stems and leaves, culminating in a balance between nutrient accumulation in the two organs 90 DAB.

The ANOVA for the accumulated levels of macronutrients in each organ (i.e., leaves, stems, and roots) during the three evaluated periods, revealed significant differences only for the rootstock factor, and just for the accumulation of N, P, and K. A significantly greater accumulation of N was observed 30 DAB in the leaves and stems of the 'BRS Rubimel' peach plants grafted onto 'Okinawa Roxo', and at 60 and 90 DAB in the leaves and stems of the 'BRS Rubimel' peach plants grafted onto 'Flordaguard' (Table 3).

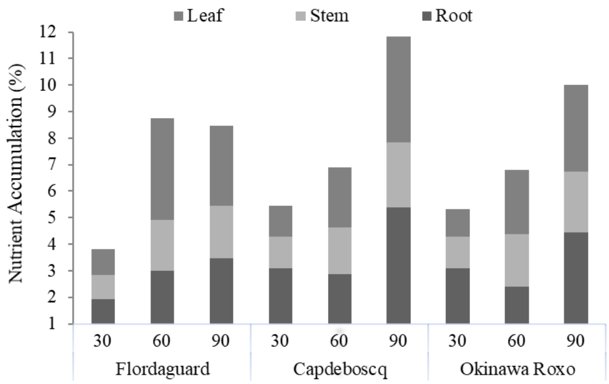

Figure 2. Nutrient accumulation (%) in the different organs of 'BRS Rubimel' peach plants as a function of the rootstock (i.e., Flordaguard, Capdeboscq and Okinawa Roxo) and the period of evaluation following grafting (30, 60, or 90 days after budding).

Table 3. Macronutrient content (i.e., N, P, and K; g kg^{-1}) in the leaves, stems, and roots of 'BRS Rubimel' peach plants grafted onto 'Flordaguard', 'Capdeboscq', and 'Okinawa Roxo' rootstocks for the three periods evaluated following grafting (i.e., 30, 60, and 90 days after budding – DAB).

Rootstock	N			P			K		
	30	60	90	30	60	90	30	60	90
Leaf									
Flordaguard	30.80b	38.89a	25.38a	4.66	4.37a	3.52	23.22a	21.44a	20.22a
Capdeboscq	28.00b	22.96b	22.02b	4.49	3.63ab	3.13	12.80b	10.85b	11.49b
Okinawa Roxo	37.75a	24.12b	23.28b	4.37	3.90b	2.66	23.93a	19.08a	15.24a
F	4.51^{**}	5.68^{**}	23.97^{**}	18.02^{ns}	13.58^{**}	40.97^{ns}	9.86^{**}	20.30^{**}	27.98^{**}
CV (%)	15.23	18.75	12.44	2.39	5.96	7.58	15.59	10.50	20.12
Stem									
Flordaguard	14.18b	29.99a	17.09a	2.51	2.38b	2.60	17.94a	11.68	12.91a
Capdeboscq	15.81b	14.99b	13.30b	3.27	3.39a	3.01	14.06b	14.37	11.22b
Okinawa Roxo	19.75a	16.57b	14.47b	3.06	3.43a	2.28	18.71a	15.58	10.35b
F	18.59^{**}	35.98^{**}	13.56^{**}	2.94^{ns}	14.74^{**}	2.17^{ns}	12.58^{**}	1.36^{ns}	25.88^{**}
CV (%)	32.65	25.66	7.56	2.58	13.23	1.55	21.65	8.78	4.12
Root									
Flordaguard	21.49b	21.43b	22.49b	4.11	5.38b	7.06	10.20b	11.68	10.89b
Capdeboscq	25.83a	24.53a	25.29a	4.76	6.69a	7.17	19.84a	14.59	14.77a
Okinawa Roxo	22.78b	21.29b	24.23ab	4.56	6.20a	6.49	10.68b	11.83	9.42b
F	42.58^{**}	15.77^{**}	1.54^{**}	2.47^{ns}	3.11^{**}	0.96^{ns}	21.25^{**}	2.98^{ns}	0.63^{**}
CV (%)	22.41	17.63	6.31	12.44	4.51	10.25	2.36	9.01	0.96

Mean values followed by different lowercase letters in the same column differ as per Tukey's test. **significant at 1% probability; ^{ns}not significant.

Plants of the 'BRS Rubimel' peach grafted onto 'Capdeboscq' significantly differed from those on the other rootstocks in terms of N accumulation in the root system for all the DAB periods that were evaluated. Notably, there were no significant differences in P accumulation in the different organs nor between the rootstock materials at 30 or 90 DAB. Nevertheless, at 60 DAB, the 'Capdeboscq' and 'Okinawa Roxo' rootstocks induced a greater accumulation of this nutrient in the stems and roots, while 'Flordaguard' promoted its greater accumulation in the leaves, without, however, significantly differing from 'Capdeboscq'.

'Flordaguard' induced a greater K accumulation in the leaves and stems than in the roots in the three evaluated periods (DAB) while 'Okinawa Roxo' induced a behavior similar to that of 'Flordaguard', except for the K content accumulated in the stems 90 DAB. 'Capdeboscq' induced a greater K accumulation in the roots 30 and 90 DAB, which is similar to what was observed with N accumulation by the same plants.

According to Guo et al. (2019), K is an essential macronutrient for several physiological processes in plants, among which the most important ones are enzyme activation, osmotic regulation, cell expansion, and pH homeostasis, in addition to playing an essential role in the absorption of other elements such as N. Moreover, the absorption rates of K^+ and NO_3^- are often positively correlated due to the need to maintain the balance between opposite charges, as well as the induced activation of K^+ in enzymes involved in nitrate assimilation (Raddatz et al., 2020). Therefore, a higher K content indirectly stimulates the absorption and assimilation of N, hence maximizing the use of this nutrient in the plant organ in which it is present in greater concentrations. This explains the response of the 'BRS Rubimel'/'Capdeboscq' plants regarding the greater accumulation of N and K in the roots, which is also associated with a greater TDM content in that organ.

Differences in the increase in stem diameter were detected between the rootstocks (F = 8.55) for the three evaluated periods, with the greatest increase (i.e., 1.64 mm) recorded for 'Capdeboscq' 30 DAB. Notably, this result is in line with the popularity of this rootstock for its greater initial vigor. Furthermore, the greatest increase was shown by 'Flordaguard' (i.e., 0.41 mm) 60 DAB and by the 'Okinawa Roxo' rootstock (i.e., 0.51 mm) 90 DAB (Table 4).

Significant differences in stem diameter below the grafting point were expected between the rootstocks in each period, since the rootstocks contain different genetic materials. However, it should be noted that in the period between the start of budding and 30 DAB, the recorded increase was considerably higher than that in the other periods, suggesting that the activity following grafting (i.e., toppling of the crown and tipping) results in a large part of the reserves accumulated in the roots being translocated to increase the diameter of the rootstock.

'Flordaguard' stood out for inducing a greater increase (i.e., 1.43 mm) in graft diameter compared with the other rootstocks from 30 to 60 DAB. However, between 60 and 90 DAB, there was no significant difference in the increase recorded in the 'BRS Rubimel' peach plants, regardless of the rootstock.

The ANOVA revealed no interaction between the rootstocks and time combination for any of the growth variables evaluated for the 'BRS Rubimel' peach plants regardless of rootstock used. However, as predicted, these same variables significantly varied with time, with differences becoming greater as the DAB progressed. In addition, the root volume, graft diameter, rootstock diameter, stem dry weight, root dry weight, and total dry weight showed significant isolated differences between the rootstocks (Table 5).

The 'Capdeboscq' rootstock had a higher mean diameter 5 cm below the grafting point, as well as greater root volume and dry matter, compared to the other rootstocks. It is worth mentioning the large amount of dry matter accumulated in the root system of this cultivar, which probably determined the higher TDM in the corresponding plants. This highlights the greater sink strength of the 'Capdeboscq' roots, which retained larger reserves and more nutrients compared to the other rootstocks under evaluation. Furthermore, the greater sink strength displayed by the 'Capdeboscq' root system can also explain the smaller graft diameter recorded in 'BRS Rubimel' on this rootstock, which preferentially allocated nutrients and phytomass to the roots, to the detriment of the scion cultivar.

The considerable sink strength of the 'Capdeboscq' roots may be the consequence of a set of metabolic and transport processes related to genetic factors that dictate and boost the flow of assimilates to be used by the root system, irrespective of the growth period. This results in a higher proportion of dry matter in this organ as opposed to increases in the GCD and stem dry matter. According to Nawaz et al. (2016), molecular and physiological aspects that are inherent to the root system of the different rootstocks can limit or facilitate the absorption and translocation of mineral ions and, consequently, influence the final concentration of nutrients that is directed to the growth of the scion cultivar.

Similarly, the greater accumulation of N and the larger increase in graft diameter in plants grafted onto 'Flordaguard' can also be explained by genetic features. Among these, the expression of genes related to N transporters, which are probably present in this genotype, have already been identified in other *Prunus* rootstocks (Gonzalo, Moreno, & Gogorcena, 2011), and whose characteristics are described as facilitating N transport to the cells, increasing the internal concentration of this nutrient, and, consequently, boosting its transport via mass flow from the root system to the shoots, favors the growth and development of grafts.

Huang et al. (2016) have highlighted the genetic divergences related to mineral nutrition in selected genetic materials to form the root system of plants. The variation in behavior between the different rootstocks in relation to nutrient absorption and translocation is due to the presence, expression, and activity of certain ion transporters, and depends on their affinity with the available nutrients, which may or may not favor the entry of certain elements to the roots (absorption) and xylem (transport), hence culminating in greater or lesser vigor in the shoots.

Table 4. Mean increase in diameter at 5 cm below and above the grafting point in 'BRS Rubimel' peach plants grafted onto three different rootstocks (i.e., 'Flordaguard', 'Capdeboscq', and 'Okinawa Roxo') in the three periods evaluated after grafting (i.e., 30, 60, and 90 days after budding – DAB).

Rootstock	Increase in stem diameter (mm) below and above the grafting point in the BRS Rubimel cultivar				
	Below			Above	
	SB-30 DAB	30-60 DAB	60-90 DAB	30-60 DAB	60-90 DAB
Flordaguard	1.44b	0.41a	0.39b	1.43a	1.03a
Capdeboscq	1.64a	0.22b	0.45b	0.97b	0.99a
Okinawa Roxo	1.36b	0.26b	0.51a	1.07b	1.04a

Mean values followed by different lowercase letters in the same column indicate a significant difference ($p < 0.05$) as per Tukey's test. SB: Start of budding, which corresponds to the moment when the rootstocks in each treatment showed a mean collar diameter (at a height of 10 cm from the ground) of 5.16 mm. The grafts in each treatment showed a mean collar diameter (5 cm above the grafting point) of 3.12 mm 30 DAB.

Table 5. Mean values for growth characteristics, namely root volume (RV), graft diameter (GD), rootstock diameter (RSD), stem dry matter (SDM), root dry matter (RDM), and total dry matter (TDM), in 'BRS Rubimel' peach plants as a function of the rootstock (i.e., 'Flordaguard', 'Capdeboscq', or 'Okinawa Roxo') used in seedling formation, evaluated 90 days after grafting.

Rootstock	RV (cm^3)	GD (mm)	RSD (mm)	SDM (g)	RDM (g)	TDM (g)
Flordaguard	39.67b	5.92a	7.96b	6.17a	7.81b	18.72b
Capdeboscq	55.22a	3.33c	8.53a	5.32b	14.19a	25.11a
Okinawa Roxo	40.22b	4.49b	8.14ab	5.40b	11.87ab	22.90a
Mean	45.04	4.58	8.21	5.63	11.29	22.24
CV (%)	17.59	12.04	4.34	21.95	28.56	28.05

Mean values followed by different lowercase letters in the same column indicate a significant difference ($p < 0.05$) as per Tukey's test. CV: coefficient of variation.

The contradictory results for greater shoot and root dry matter in plants grafted onto 'Flordaguard', and 'Capdeboscq', respectively, may also be related to the significant and simultaneous accumulation of N and K in these different parts of the plant (Table 3). According to Raddatz et al. (2020), the translocation of N from the roots to the shoots is facilitated by ideal concentrations of K^+ and NO_3^-, with K^+ acting as a counterion in the xylem sap and, hence, favoring NO_3^- loading in the shoots. Conversely, at concentrations above and below those required by the plant, the transport of both nutrients is restricted, resulting in their accumulation in the root system.

The high N use efficiency inferred for the 'Capdeboscq' plants may indicate that the dose of fertilizer used for nutritional management was greater than that required by the plants, a factor that would explain the accumulation of larger amounts of nutrients in the roots (Razaq et al., 2017; Guo et al., 2019; Raddatz et al., 2020) and, in part, the different behaviors of the 'Capdeboscq' and 'Flordaguard' rootstocks in relation to the accumulation of K and N.

The greater allocation of dry matter to the root system that occurred in the 'BRS Rubimel'/'Capdeboscq' plants is the opposite of what was expected after grafting. During this period, it was expected that budding and the development of new leaves on the grafts would act as the main sink organ, requiring a greater amount of energy both to stimulate leaf growth, hence maximizing light uptake and strengthening the production of photoassimilates, and to boost the thickening of the GCD, thus ensuring the survival and robustness of the plant in formation. This reversal of the source-sink relationship is of interest to producers, whose priority is that, after grafting, the maximum proportion of assimilates be destined to the growth and development of the plant canopy and, later, to fruiting. The present results show that 'Flordaguard' induces a greater initial vigor in the 'BRS Rubimel' peach scion by allowing the graft to act as the main sink organ, hence producing a more balanced distribution of dry matter between the organs, as well as a larger increase in graft diameter.

Comiotto et al. (2013) evaluated the vigor, production, and quality of the fruits of the Maciel cultivar grafted onto the 'Aldrighi', 'Capdeboscq', 'Flordaguard', 'Nemaguard', 'Okinawa', and 'Umezeiro' rootstocks in the south of Brazil, and concluded that the estimated production and productivity per hectare of 'Maciel' peach plants are greater when they are grafted onto 'Flordaguard' compared to the other rootstocks that were tested. Similar results were obtained by Barreto et al. (2017) for 'Maciel' cultivars grafted onto eight rootstocks, namely 'Aldrighi', 'Capdeboscq', 'Flordaguard', 'Nemaguard', 'Okinawa', 'Umezeiro', 'Tsukuba', and 'Seleção Viamão', in orchards in the south of Rio Grande do Sul during the 2014/2015 and 2015/2016 harvests, suggesting that 'Flordaguard' induces a high productivity and a higher number of fruits per plant. Moreover, the 'Flordaguard' rootstock is also strongly recommended for use in the south of Minas Gerais (Gonçalves et al., 2019), a region known for its high productivity per area (IBGE, 2017). In comparison with 23 other rootstocks, the 'BRS Libra'/'Flordaguard' combination resulted in greater yearly increase in the stem diameter of the rootstock and graft, plant survival in the field, production (kg $plant^{-1}$), and productivity (t ha^{-1}), in addition to increased fruit size and concentration of soluble solids (Gonçalves et al., 2019).

In the present study, 'Flordaguard' induced a greater accumulation of N and K in the shoots compared to 'Capdeboscq', a fact that explains not only the higher rate of dry matter accumulation in the plant canopy but also the satisfactory production in the field, as described by Guo et al. (2019) and Lemaire and Gastal (2018). In addition, the N to K ratio in the leaf is a key factor in the quality and growth of peach fruits (Dbara, Lahmar, & Mimoun, 2018), in the same way that an optimal K content has been suggested to be essential to the physiological processes of adaptation to conditions of stress (Raddatz et al., 2020).

In addition to these characteristics, which are linked to nutrition, 'Flordaguard' is an attractive material owing to its low chill requirement and its resistance to the main gall-producing nematodes (Mayer et al., 2015a). However, further studies are necessary to characterize the vigor induced by this rootstock in 'BRS Rubimel' plants under field conditions, and should cover different production cycles and management systems as well as use other scion cultivars for grafting.

The present results reinforce the importance of understanding the different patterns of nutrient absorption and translocation in the different rootstocks and of suggesting combinations that are more efficient in the use of available nutrients. In addition, they enable estimations of the subsequent effects of each combination on the vigor and productivity of the scion cultivar, even when it is still in the nursery. Such studies can provide information for the selection of suitable combinations to be used in commercial orchards, as suggested by Schmitz et al. (2014).

The production of peach plants with an adequate nutritional status and from a suitable combination of scion and rootstock can affect the start of production, production quality, and productivity. Consequently, this may affect the economic return on the capital invested by the fruit grower, as well as guide initial nutritional management, hence facilitating the optimized use of mineral nutrients. Furthermore, it can promote the reduction of waste and its impacts on the environment, in addition to reducing the costs for producing high quality seedlings.

Conclusion

The nutrient content of 'BRS Rubimel' peach plants is influenced by the rootstock used during nursery plant production.

'Capdeboscq' exhibits greater N use efficiency, as this nutrient is accumulated in larger quantity in the roots, generating greater phytomass accumulation in the root system than in the scion cultivar.

'Flordaguard' induces homogeneous nutrient accumulation and a more uniform partitioning of dry matter between the different organs during the post-graft period.

The 'Flordaguard' rootstock induces more robustness in the grafted scion of 'BRS Rubimel' and beacuse this offers great potential for use nursery plant production.

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