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Rootstocks for citrus orchards in the state of Pará

Abstract – The objective of this work was to evaluate the performance of the 'Pera CNPMF-D6' orange and 'Tahiti CNPMF-02' acid lime, in combination with different rootstocks, in the state of Pará, Brazil. In the first trial, the following four rootstocks were evaluated: 'Santa Cruz Rangpur' lime, hybrid LVK × LCR-010, 'TSK Tropical' mandarin, and 'San Diego' citrandarin. In the second trial, six rootstocks were evaluated: 'Santa Cruz Rangpur' lime, hybrid LVK × LCR-010, hybrid TSKC × CTSW-033, 'Riverside' citrandarin, 'San Diego' citrandarin, and 'BRS Pompeu' citrumelandarin. Between 2019 and 2024, the following variables were evaluated: plant height; canopy volume, before and after harvest; drought tolerance; number of fruit per plant; fruit mass; productivity; and productive efficiency. Plant height was influenced by treatments only in the case of 'Pera' orange tree, which showed the highest values on the 'Santa Cruz Rangpur' and 'San Diego' rootstocks. The lowest canopy volume was found in 'Santa Cruz Rangpur' for the 'Tahiti' acid lime tree, and in TSKC × CTSW-033 for 'Pera' orange tree. All rootstocks showed drought tolerance. The greatest number of fruit per plant, and the highest values of fruit mass and productivity are observed for 'Tahiti' acid lime on the 'TSK Tropical' and 'San Diego' rootstocks and for 'Pera' orange on the 'Santa Cruz Rangpur' and 'San Diego' rootstocks.

Index terms: *Citrus ×latifolia*, *Citrus ×sinensis*, Amazon.

Porta-enxertos para pomares cítricos no estado do Pará

Resumo – O objetivo deste trabalho foi avaliar o desempenho da laranjeira 'Pera CNPMF-D6' e da limeira-ácida 'Tahiti CNPMF-02', em combinação com diferentes porta-enxertos, no estado do Pará, Brasil. No primeiro ensaio, foram avaliados os seguintes quatro porta-enxertos: limeira 'Santa Cruz Rangpur', híbrido LVK × LCR-010, tangerineira 'TSK Tropical' e citrandarin 'San Diego'. No segundo ensaio, foram avaliados seis porta-enxertos: limeira 'Santa Cruz Rangpur', híbrido LVK × LCR-010, híbrido TSKC × CTSW-033, citrandarin 'Riverside', citrandarin 'San Diego' e citrumelandarin 'BRS Pompeu'. Entre 2019 e 2024, foram avaliadas as seguintes variáveis: altura da planta; volume da copa, antes e depois da colheita; tolerância à seca; número de frutos por planta; massa de frutos; produtividade; e eficiência produtiva. A altura das plantas foi influenciada pelos tratamentos apenas no caso da laranjeira 'Pera', que apresentou valores mais elevados nos porta-enxertos 'Cravo Santa Cruz' e 'San Diego'. Os menores volumes de copa foram encontrados in 'Cravo Santa Cruz', para a limeira-ácida 'Tahiti', e em TSKC × CTSW-033 para a laranjeira 'Pera'. Todos os porta-enxertos apresentaram tolerância à seca. Os maiores números de frutos por planta, e maiores valores de massa de frutos e produtividade foram proporcionados pelos porta-enxertos 'TSK Tropical' e 'San Diego' para a limeira-ácida 'Tahiti', e pelos porta-enxertos 'Cravo Santa Cruz' e 'San Diego', para a laranjeira 'Pera'.

Termos para indexação: *Citrus ×latifolia*, *Citrus ×sinensis*, Amazônia.

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Introduction

Brazil produced 12,300,000 Mg of oranges in the season 2023/2024, ranking as the world's largest producer, followed by China and European Union (USDA, 2025). In 2023, São Paulo state was the largest producer in Brazil, accounting for 77.45% of the national production, and the state of Pará was the 7th largest producer in the country (IBGE, 2023). For the Amazon region, the citrus hub in the municipality of Capitão Poço, in the state of Pará, has a leading role as an orange producer (IBGE, 2025).

Despite the prominent position in orange production, Brazil undergoes serious incidence of phytosanitary problems. A study interviewed orange farmers, in the Brazilian citrus belt, asking them what was the major problem in citrus production, in the years 2017, 2018, and 2019 (Guerreiro Neto & Figueira, 2021). Phytosanitary problems was the major problem for 39% of the farmers. Diseases have been threatening the Brazilian global position in citrus farming (Neves & Boteon, 1998). This situation is aggravated due to the use of few rootstocks, from which 'Rangpur' lime tree (*C.* ×*limonia* Osbeck.) is the major one in the Brazilian citrus orchards. Rootstocks also affect many characteristics of the scion varieties, such as vigor, precocity, production, ripening time, fruit mass, skin and juice color, sugar and acid content in the fruit, fruit retention on the plant, fruit conservation after harvest, plant tolerance to salinity, drought, frost, diseases, among other factors (Girardi et al., 2021; Carvalho et al., 2023; Fernandes et al., 2024). Thus, studies that look for alternative rootstocks can be a good solution to face phytosanitary problems and improve fruit quality and production.

Such studies are still incipient in the Amazon region (Rodrigues et al., 2019a, 2019b; Santos et al., 2021; Capistrano et al., 2025), and they are scarce in the citrus region of Pará, especially in Capitão Poço (Gurgel et al., 2024).

The objective of this work was to evaluate the performance of the 'Pera CNPMF-D6' orange and 'Tahiti CNPMF-02' acid lime, in combination with different rootstocks, in the state of Pará, Brazil.

Materials and Methods

The experiment consisted of two trials, one for acid lime 'Tahiti CNPMF-02' (TRL1), and another one for orange 'Pera CNPMF-D6' (TRL2). Morphological and production variables were evaluated in combination with rootstock cultivars selected by the Citrus Genetic Improvement Program of Embrapa Mandioca e Fruticultura, in the municipality of Cruz das Almas, in Bahia state, Brazil.

The nursery tree production was carried out in accordance with the Normative Instruction (IN) No. 48, dated September 24, 2013, issued by the Ministry of Agriculture and Livestock (MAPA) (Brasil, 2013). In 2015, the experiment was installed at Farm Lima (01°45'S and 47°01'W), a partner of Embrapa Eastern Amazon (Belém, PA), located in the citrus hub in the state of Pará, in the municipality of Capitão Poço. The climate of the region is Am, according to the Köppen-Geiger's classification defined as rainy, with a mean annual precipitation of 2,250 mm, concentrated between January and June. The mean annual temperature is 25ºC, and the relative humidity is about 85% (Oliveira et al., 2016). The soil of the region is predominantly Latossolo Amarelo (Oxisol), medium texture (Souza et al., 2018).

A complete randomized block was the experimental design used, with two treatments: TRL1 and TRL2.

In TRL1, four rootstocks were distributed in four blocks, with four plots per block, and 10 plants per plot. The experimental unit was the mean of 10 plants in the plot (n = 16). The rootstocks were the following: 'Santa Cruz Rangpur' lime, a 'Santa Bárbara Rangpur' lime mutant clone; LVK hybrid ('Volkameriano' lemon *C.* ×*volkameriana* V. Ten. & Pasq.) × LCR-010 ('Rangpur' lime *C.* ×*limonia*); 'TSK Tropical' mandarin [*C. sunki* (Hayata) hort. ex Tanaka], a 'Sunki' mandarin mutant clone (Soares Filho et al., 2002); and 'San Diego' citrandarin (*C. sunki* x *P. trifoliata*).

TRL2 used six rootstocks, distributed in four blocks, with six plots per block, and 10 plants per plot. The experimental unit was the mean of 10 plants in the plot (n = 24). The rootstocks were: 'Santa Cruz Rangpur' lime; LVK hybrid × LCR-010; 'Riverside' citrandarin (*C. sunki* × *P. trifoliata*); 'San Diego' citrandarin; 'BRS Pompeu' citrumelandarin [*C. sunki* × (*C.* ×*paradisi* Macfad. × *P. trifoliata*)]; and the TSKC hybrid ('Sunki' mandarin *C. sunki*) × CTSW-033 (citrumelo 'Swingle' *C.* ×*paradisi* × *P. trifoliata*).

The spacing between plants was 7 m x 4 m. Morphological and agronomic variables were evaluated every six months in the growing seasons of 2019/2020,

2020/2021, 2021/2022, 2022/2023, and 2023/24. The annual season started in August and ended in July of the subsequent year. The following morphological variables were evaluated: plant height (PH, m) pre-harvest; canopy volume pre-harvest (PreCV, m^3); and canopy volume postharvest (PostCV, m^3). Plant height is the distance between ground level to the last leaf of the highest branch. Its assessment was performed using a stadiometer. The canopy volume was estimated according to Mendel (1956), using the equation below. The canopy radius was calculated as the mean between longitudinal and latitudinal diameters, divided by 2. A tape measure was used.

$$V = (2/3) \times \pi \times R^2 \times H,$$

where: V is the volume (m^3); R is the canopy radius (m); and H is the plant height (m).

The agronomic variables studied were: number of ripe fruit per plant (FN, n), fruit mass (FM, kg), productivity (PROD, Mg ha^{-1}), and productive efficiency (PE, kg m^{-3}). FM was evaluated by weighing all ripe fruit of each plant separately, using a digital scale. The FN was obtained manually by counting the ripe fruit of each plant after harvest. PROD was estimated by dividing FM by the useful area of a plant (28 m^2), converted to Mg ha^{1}, considering a planting density of 476 plants ha^{-1}. PE was estimated by dividing FN by PreCV (kg m^{-3}) (Stenzel et al., 2005).

Drought tolerance (DT) was evaluated using a 5-point scale described by Santana et al. (2015). This scale relates drought effects to the degree of leaf curling, as follows: for DT = 5, no leaf curling; DT = 4, leaves are slightly curled on some branches; DT = 3, leaves are slightly curled on all branches; DT = 2, all leaves are very curled, but few leaves have fallen; and DT = 1, all leaves are very curled, and many leaves have fallen.

The results were organized in a spreadsheet and subjected to the analysis of variance one-way. The F-test was used to verify significant differences between means ($\alpha = 0.05$), and the Scott-Knott's test was used to group the means at 5% probability. In order to carry on the analysis of variance, assumptions for normality, homoscedasticity, and independence of errors were checked, for which the tests of Shapiro-Wilk, Breusch-Pagan, and Durbin-Watson were used, respectively. All assumptions were met. The R software v.4.4.2 was used (R Core Team, 2019) in the statistical analysis. The *ExpDes* package was used (Ferreira et al., 2021) to verify the effects of the treatments.

Results and Discussion

Regarding plant height (PH), all treatments in both trials showed equal means ($p>0.05$), in each growing season. The maximum PH was 3.28 m for TRL1, and 3.04 m for TRL2. In both trials, PH was the only variable that did not express interaction with rootstocks and growing seasons. This fact was also observed by Ferreira et al. (2018).

The canopy volumes of TRL1, measured before (PreCV) and after (PostCV) harvest, showed similar patterns throughout the evaluations (Table 1). In the first two growing seasons, no significant differences were observed among the rootstocks regarding these traits. However, starting from the third growing season, a substantial increase of PreCV and PostCV values was observed, when the lime trees were grafted onto the 'San Diego' citrandarin or on the 'Tropical TSK' rootstock. These two rootstocks promoted vigorous canopy growth, with volumes more than doubling by the third growing season, and maintaining this high performance in the fourth season. In contrast, the LVK × LCR-010 hybrid exhibited the lowest canopy development, along with an irregular growth pattern. In the fourth growing season, canopy volumes were similar to those recorded in the first one, suggesting a possible susceptibility of this rootstock to climatic variations between years.

The results of PreCV for TRL2 (Table 2) showed that trees using the rootstock 'Santa Cruz Rangpur' showed the highest canopy volumes in all growing seasons except for 2019 ($p<0.05$). The canopy volume in 2019/2020 was 7.23 m^3; in 2022/2023, it reached 22.71 m^3, remaining stable (21.93 m^3) in 2023/2024. The trees with rootstock 'San Diego' showed a good PreCV performance, with values increasing from 6.67 m^3 (2019/2020) to 23.00 m^3 (2023/2024). Trees with the rootstock 'Santa Cruz Rangpur' had also a good performance in 2023/2024. However, trees using the rootstocks TSKC × CTSW-033 and 'Riverside' citrandarin showed the lowest PreCV, slowest growth, and lowest vegetative vigor in TRL2. In the last four growing seasons, the rootstocks were grouped into two categories based on the development of the scion PreCV. The high-performance group included the

'Santa Cruz Rangpur' lime and 'San Diego' citrandarin, while the remaining rootstocks formed the low-performance group for this trait (Table 2).

Contrasting results were found for 'Pera' orange grafted onto the LVK × LCR-010 hybrid, which showed a significantly greater canopy volume than the 'Santa Cruz Rangpur' lime rootstock, according to Ribeiro et al. (2021); these authors' experiments took place in a region classified as *As* according to Köppen-Geiger's climate ranking, characterized by markedly dry summers. Conversely, the present study was carried out in a region with an *Am* climate, where the dry season occurs in winter and is less severe, with approximately 4% of the annual precipitation still concentrated during that period. Therefore, it is likely that the 'Santa Cruz Rangpur' lime rootstock is better adapted to humid regions with a uniform annual rainfall distribution.

The TRL2 showed significant PostCV values between rootstocks and growing seasons (Table 2). 'San Diego' and 'Santa Cruz Rangpur' had the highest PostCV values, with 'Santa Cruz Rangpur'

Table 1. Traits of 'Tahiti' acid lime [*Citrus ×latifolia* (Yu. Tanaka) Tanaka] grafted onto four rootstocks, in four growing seasons between 2019 and 2023, and coefficients of variation (CV) of the factors 'season' (S) and 'rootstock' (R), and their interaction (S×R), for each trait.

Trait[1]	Season	Rootstock[2]				S×R
		San Diego	Santa Cruz Rangpur	LVK × LCR-010	TSK tropical	
PreCV (m^3)	2019/2020	21.82aC	18.83aC	23.91aB	24.25aC	
	2020/2021	36.62aB	29.44aB	37.63aA	38.55aB	
	2021/2022	52.02aA	39.06bA	40.86bA	54.58aA	
	2022/2023	44.35aB	20.83bC	50.31aA	51.31aA	
CV (%)	17.20		13.89			14.49
PostCV (m^3)	2019/2020	22.56aC	18.18aC	24.08aB	24.17aC	
	2020/2021	36.33aA	28.27aB	37.00aA	37.87aB	
	2021/2022	53.60aA	39.89bA	37.79bA	56.42aA	
	2022/2023	46.78ª2	22.66bC	52.02aA	54.72aA	
CV (%)	17.50		13.19			11.80
FN	2019/2020	403.14aB	401.21aC	457.29aA	488.70aA	
	2020/2021	701.53aA	553.31aA	405.48bA	635.45aA	
	2021/2022	572.24aA	468.21aB	329.78bA	580.94aA	
	2022/2023	368.00aB	90.70bD	239.59aA	410.06aA	
CV (%)	34.24		24.23			17.10
FM (kg/plant)	2019/2020	36.59aB	38.21aA	40.75aA	46.55aA	
	2020/2021	66.08aA	48.77bA	38.62bA	62.22aA	
	2021/2022	59.92aA	47.86aA	31.73bA	62.43aA	
	2022/2023	40.42aB	10.25bB	27.47aA	43.97aA	
CV (%)	34.89		25.13			19.38
PE ($kg\ m^{-3}$)	2019/2020	1.67aA	2.08aA	1.76aA	1.89aA	
	2020/2021	1.97aA	1.75aA	1.06bB	1.64aA	
	2021/2022	1.30aB	1.22aB	0.95aB	1.19aB	
	2022/2023	0.94aB	0.43aC	0.50aB	0.87aB	
CV (%)	24.40		28.32			17.75
Productivity ($Mg\ ha^{-1}$)	2019/2020	13.07aB	13.65aA	14.55aA	16.62aA	
	2020/2021	23.60aA	17.42bA	13.79bA	22.22aA	
	2021/2022	21.40aA	17.09aA	11.33bA	22.30aA	
	2022/2023	14.43aB	3.66bB	9.81aA	15.70aA	
CV (%)	34.89		25.13			19.38

[1]Traits: PreCV, preharvest canopy volume; PostCV, postharvest canopy volume; FN, number of fruit per plant; MF, mass of fruit per plant; PE, productive efficiency; and CV, coefficient of variation. [2]Means followed by equal lowercase letters, in the rows, and uppercase letters, in the columns, do not differ from each other, according to the Scott-Knott's grouping test, at 5% probability.

Table 2. Traits of 'Pera' orange [*C. ×sinensis* (L.) Osbeck] grafted onto five rootstocks, in five growing seasons between 2019 and 2024, and coefficients of variation (CV) of the factors 'season' (S) and 'rootstock' (R), and their interaction (S×R), for each trait.

Trait	Season	Rootstock						S×R
		San Diego	Sta. Cruz Rangpur	LVK x LCR-010	TSKC × CTSW-33	BRS Pompeu	Riverside	
PreCV (m^3)	19/20	6.67aD	7.23aD	3.79aD	3.89aD	3.88aD	4.52aD	
	20/21	11.51aC	13.27aC	8.13bC	7.44bC	8.00bC	8.31bC	
	21/22	14.36aB	17.13aB	11.45bB	9.69bB	11.30bB	10.98bB	
	22/23	21.68bA	22.71aA	17.03aA	14.02aA	16.53aA	16.15aA	
	23/24	23.00aA	21.93aA	16.53bA	12.56bA	16.32bA	14.75bA	
CV (%)	5.99			26,94				5.06
PostCV (m^3)	19/20	7.58aE	8.30aD	4.31bD	4.25bD	4.37bD	4.56bD	
	20/21	11.34aD	14.23aC	8.48bC	7.69bC	8.31bC	8.46bC	
	21/22	13.54aC	16.27aB	10.77bB	9.23bB	10.27bB	10.48bB	
	22/23	21.12aB	22.69aA	16.07bA	13.89bA	16.64bA	15.46bA	
	23/24	23.73aA	23.32aA	16.50bA	12.58bA	18.04bA	14.51bA	
CV (%)	2.57			22.02				4.35
FN	19/20	40.74aC	76.85aD	15.93bC	22.06bC	23.03bD	27.64bC	
	20/21	184.01aA	120.36aC	69.05bB	75.35bB	70.09bC	82.19bB	
	21/22	204.88aA	241.17aA	138.36aA	137.39aA	134.13aA	147.01aA	
	22/23	140.31aB	162.30aB	133.15aA	114.36aA	156.13aA	138.61aA	
	23/24	108.46aB	57.07aD	41.55aB	31.54aC	82.69aB	63.86aB	
CV (%)	11.51			27.47				11.91
FM (kg/plant)	19/20	8.04aC	14.87aC	3.03bD	4.23bC	3.81bC	5.26bC	
	20/21	31.51aA	22.75aB	12.55bB	11.92bB	11.01bB	13.45bB	
	21/22	43.42aA	50.11aA	28.84aA	28.65aA	26.06aA	29.85aA	
	22/23	32.24aA	36.25aA	27.40aA	24.01aA	29.90aA	28.39aA	
	23/24	18.63aB	10.24aC	6.74bC	5.41bC	12.90aB	10.52aB	
CV (%)	10.30			23.89				9.57
PE ($kg\ m^{-3}$)	19/20	1.28aB	2.04aB	0.91aB	1.20aB	1.20aB	1.53aB	
	20/21	2.61aA	1.71bB	1.52bA	1.44bB	1.13bB	1.66bB	
	21/22	2.88aA	2.99aA	2.41aA	3.15aA	2.48aA	2.88aA	
	22/23	1.52aB	1.71aB	1.98aA	1.70aB	1.97aA	1.99aA	
	23/24	0.79aC	0.45aC	0.43aC	0.45aC	0.72aB	0.74aC	
CV (%)	18.78			21.34				13.58
Productivity ($Mg\ ha^{-1}$)	19/20	2.87aC	5.31aC	1.08bD	1.51bC	1.36bC	1.88bC	
	20/21	11.25aA	8.13aB	4.48bB	4.26bB	3.93bB	4.80bB	
	21/22	15.51aA	17.89aA	10.30aA	10.23aA	9.31aA	10.66aA	
	22/23	11.52aA	12.95aA	9.78aA	8.58aA	10.68aA	10.14aA	
	23/24	6.65aB	3.66aC	2.41bC	1.93bC	4.61aB	3.76aB	
CV (%)	10.30			23.90				9.57

(1)Traits: PreCV, preharvest canopy volume; PostCV, postharvest canopy volume; FN, number of fruit per plant; MF, mass of fruit per plant; PE, productive efficiency; and CV, coefficient of variation. (2)Means followed by equal lowercase letters, in the rows, and uppercase letters, in the columns, do not differ from each other, according to the Scott-Knott's grouping test at 5% probability.

being related to a progressive increase − from 8.30 m³ (2019/2020) to 23.32 m³ (2023/2024). 'San Diego' showed PostCV values of 7.58 m³, in 2019/2020, and 23.73 m³ in 2023/2024, being statistically equal to those of 'Santa Cruz Rangpur'. However, the rootstocks LVK x LCR-010, 'BRS Pompeu', TSKC x CTSW-033, and 'Riverside' were related to lower PostCV values throughout the evaluated period. The TSKC x CTSW-033 determined statistically equal volume values to the others, with 4.25 m³ (2019/2020) and 12.58 m³ (2023/2024), indicating the slowest growth and lowest vegetative vigor.

In terms of drought tolerance (DT), TRL1 and TRL2 showed equal values for all treatments, making the analysis of variance unnecessary. Score 4 (slightly curled leaves on some branches) was attributed to the rootstocks, in the different harvests, in a massive way. This fact indicates that all rootstocks showed good tolerance to water deficit, a characteristic of utmost importance, given the harmful effects of ongoing climate change, which requires the use of drought-tolerant or water-saving rootstocks (Fernandes et al., 2024). Another study comparing scion/rootstock concluded that the citrandarin rootstock 'Indio', in the driest period, showed a greater moisture retention in the plants, which was compatible with their less stomatal opening, and greener leaves on plants of 'TSK Tropical' (Carvalho et al., 2023).

The number of fruit per plant (FN) in TRL1 was significant for the interaction between rootstocks and the evaluated growing seasons (Table 1). The LVK x LCR-010 (2020/2021 and 2021/2022) and 'Santa Cruz Rangpur' (2022/23) lime trees determined the lowest FN means, and the other treatments were statistically equal in all harvests. Rodrigues et al. (2018) analyzed the 'Tahiti' acid lime tree on the 'TSK Tropical' mandarin, 'Santa Cruz Rangpur', and 'San Diego' citrandarin lime rootstocks, obtaining means of 183.0, 265.3, and 279.8 fruit per plant, respectively, in which 'San Diego' was statistically superior. These means indicate superiority in fruit production, in which the same treatments showed 635.45, 659.27, and 725.07 fruit per plant, respectively. Ribeiro et al. (2021) evaluated the fruit number of the acid lime tree 'Tahiti' and observed that the rootstock 'Santa Cruz Rangpur' determined a mean production of 148 fruit per plant, considering the first three harvests. In their study, 76.85 to 241.17 fruit per plant were achieved for the same evaluated periods, resulting in 146.12 fruit per plant, which indicates similar results for the productive potential of the plant.

The FN in TRL2 showed significant interaction between the rootstocks and the evaluated harvests, with higher FN values observed for 'Santa Cruz Rangpur' and 'San Diego' rootstocks in the first three growing seasons, in comparison with the other treatments (Table 2).

The fruit mass (FM) in TRL1 showed a significant interaction between rootstocks and growing seasons (Table 1). In the 2020/2021, 2021/2022, and 2022/2023 growing seasons, the rootstocks 'San Diego' citrandarin and 'TSK Tropical' mandarin stood out with the highest values − 66.08 and 62.22 kg plant^{-1}, and of 59.92 and 62.43 kg plant^{-1}, in 2020/2021 and 2021/2022, respectively. For the FM of TRL2, a significant interaction between rootstocks and growing seasons was also observed (Table 2). The rootstocks 'San Diego' and 'Santa Cruz Rangpur' stood out with the highest means of FM in 2019/2020, 2020/2021, and 2023/2024 harvests. Rodrigues et al. (2018) observed that the acid lime tree 'Tahiti' grafted on 'San Diego' citrandarin and on 'TSK Tropical' mandarin showed higher FM values.

Productive efficiency (PE) in TRL1 showed significant interactions with rootstocks and growing seasons (Table 1). The LVK x LCR-010 treatment was the only one showing a low PE, differing statistically from the other treatments in the 2020/2021 harvest.

Productive efficiency in TRL2 showed statistically equal means in all rootstocks, except for the 'San Diego' citrandarin in 2020/2021 that showed the highest PE (2.61 kg m^{-3}) (Table 2). 'Santa Cruz Rangpur' was related to high PE values in the first three growing seasons: 2.04, 1.71, and 2.99 kg m^{-3}, respectively. As to TRL1, in most of the growing seasons, no significant differences were observed between treatments and PE. The highest PE was associated with a reduction of canopy volume, indicating that the rootstocks determining this behavior adjust to high-planting densities, which results in a significant increase of productivity (França et al., 2016).

Rodrigues et al. (2018) studied 'Tahiti' acid lime in the Amazon biome and found PE of 0.93 and 0.68 kg m^{-3} in six-year-old plants, for 'San Diego' and 'Cravo Santa Cruz' rootstocks, respectively. Such results are lower than the values of the present study − 1.67 and 2.08 kg m^{-3} − in the 2019/2020 growing season, for

'San Diego' and 'Santa Cruz Rangpur', respectively. However, Rodrigues et al. (2018) reported canopy volumes of 51.72 and 48.29 m³, for 'San Diego' and 'Cravo Santa Cruz', respectively, which are results close to the ones obtained in the present study. This fact indicates that the discrepancy between the studies may be related to the higher FM obtained in the current research, 66.08 and 48.77 kg per plant, in the growing season 2020/2021, for 'San Diego' and 'Santa Cruz Rangpur', respectively. Rodrigues et al. (2018) reported 19.41 and 21.30 kg per plant in 2015, for 'San Diego' and 'Cravo Santa Cruz', respectively, which are lower values than the ones of the present study.

TRL2 showed reduced PE due to the larger canopy volume for 'Santa Cruz Rangpur' rootstock, for which one of the treatments showed best production performance. Ribeiro et al. (2021) reported PE of 5.53 kg m^{-3} and a canopy volume of 4.62 m³ for 'Santa Cruz Rangpur' rootstock, while in the present study the finding was PE of 2.99 kg m^{-3} and PreCV of 17.13 m³, in the growing season 2021/2022, for the same rootstock. This fact can also be verified by the lower amount of fruit observed by the Ribeiro et al. (2012) (148) in relation to that verified in the present work (241).

Conclusions

1. The rootstocks 'TSK Tropical' mandarin and 'San Diego' citrandarin determined a greater productive performance of the 'Tahiti CNPMF-02' acid lime tree.

2. The rootstocks 'Santa Cruz Rangpur' lime and 'San Diego' citrandarin determined a greater productive performance of the 'Pera CNPMF-D6' orange tree.

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Data availability statement

The data supporting the findings of this study are available in the article. Should any raw data be needed, they will be provided by the corresponding author upon reasonable request.

Declaration of use of AI technologies

No generative artificial intelligence (AI) was used in this study.

Conflict of interest statement

The authors declare no conflicts of interest.

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