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Research article

Rootstock selection for 'Swatow' Mandarin trees grown at different locations throughout the Brazilian subtropics

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ABSTRACT

Evaluating citrus rootstocks is of paramount importance in determining their suitability for a certain region and promoting resilience in orchards by increasing the genetic pool, thereby potentially contributing to a more strategic establishment of new plantings. This long-term field study (2000–2013) aimed to evaluate different rootstocks for 'Swatow' mandarin grown at two locations (Paranavaí and Londrina) in the Brazilian subtropics. Nine rootstocks were evaluated, including 'Rangpur' lime, 'Swingle' citrumelo, 'Volkamer' lemon, 'Caipira DAC' sweet orange, 'Cleopatra' and 'Sunki' mandarins, 'Trifoliate' orange, 'Carrizo', and 'Fepagro C-13' citranges. Trees were assessed for vegetative growth, yield, fruit quality, density, and yield estimates. The experimental design was a randomized block arranged in a 9 × 2 setting (rootstock × location) with 6 replicates and 4 trees per plot. 'Swatow' trees grew more vigorously in Londrina than Paranavaí, particularly for 'Cleopatra' and 'Sunki' pairings. Tree vigor was reduced with 'Trifoliate', resulting in higher tree density estimates and yield efficiency. This rootstock, along with 'Rangpur', 'Swingle', and 'Carrizo' provided superior yield to the scion. All tested rootstocks conferred good fruit quality. Fruits were larger and heavier in 'Sunki' pairings, showing higher soluble solids (SS) content, along with 'Caipira DAC', 'Trifoliate', 'Swingle', and 'Carrizo' at both locations. Our findings confirm the suitability of 'Trifoliate' orange, 'Carrizo' citrange, or 'Caipira DAC' orange rootstocks as promising candidates for 'Swatow' mandarin cultivation in humid subtropical and analogous regions. Further investigations are invoked to improve the horticultural performance of 'Swatow' mandarin trees grafted onto these rootstocks.

1. Introduction

Sweet orange [*Citrus* ×*sinensis* (L.) Osb.] dominates the Brazilian citrus industry, contributing to an average annual production of

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16 million tons [1]. Brazil has expanded its citrus cultivation area, incorporating other citrus varieties, such as mandarins and their hybrids, which collectively produce around 1.0 million tons each year [1]. Nonetheless, these regions face a shortage of mandarin varieties.

In the past few decades, the combinations of 'Ponkan' mandarin (*C. reticulata* Blanc.) and 'Murcott' tangor [*C. reticulata* Blanc. × *C.* ×*sinensis* (L.) Osb.] grafted onto 'Rangpur' lime (*C.* ×*limonia* Osb.) rootstock have been the most prevalent throughout Brazil, constituting 80 % of the total acreage for mandarin and mandarin-like production [2–4]. This narrow genetic pool, for both scion and rootstock varieties, made the Brazilian citrus industry vulnerable to biotic and abiotic influences. Introducing new genotypes through genetic diversification is one of the most effective measures to improve citrus protection in orchards. In this way, 'Swatow' mandarin (*C. reticulata* Blanc.) may be a potential alternative in new plantings. This mid-season mandarin has shown desirable characteristics for *in natura* consumption [4,5], along with resistance to alternaria brown spot (ABS) caused by the fungus *Alternaria alternata* (Fr.) Keissl [6] and citrus canker caused by the bacterium *Xanthomonas citri* subsp. *citri* [7], two detrimental diseases for mandarin production. These characteristics support its suitability for cultivation in Paraná, since the state presents high favorability for the ABS occurrence, particularly during May and September [8]. Moreover, huanglongbing (HLB, a.k.a. citrus greening) disease has threatened the citrus industry worldwide in the last two decades, drastically affecting tree physiology, fruit quality, and yield potential [9,10]. These detrimental impacts have resulted in an increasing demand for rootstock liners in replanting and resetting HLB-affected orchards, as no resistant *Citrus* spp. genotypes have been reported to date [11].

The environment also plays a key role in citrus production, particularly under climate change, which has altered the air temperatures and rainfall distribution over the years, resulting in long periods of drought and crop losses [12]. Given these circumstances, the implementation of irrigation systems in citrus orchards increased from 25 % to 39 % from 2015 to 2022 in the Brazilian citrus belt [2]. However, access to irrigation technology remains hindered in certain areas [12]. Thus, selecting a variety that is better adapted, for both scion and rootstock, is imperative to promote resilience in new orchards.

Several citrus rootstocks have been tested to identify genotypes compatible with a particular mandarin variety that is better adapted to a certain region [4,13–20]. Among them, 'Rangpur' lime has shown compatibility with most commercial scion varieties and adaptability to a wide range of environmental conditions [21]. This rootstock poses tolerance to drought, calcareous soils, and citrus tristeza virus (CTV) [22,23]. All of these traits were effective in making 'Rangpur' the most important citrus rootstock in Brazil for several decades. Currently, 'Swingle' citrumelo [*C. paradisi* Macfad. cv. Duncan × *Poncirus trifoliata* (L.) Raf.] has been increasingly used in new citrus-growing areas in Brazil. In 2020, 56 % of the licensed nurseries produced in São Paulo were grafted on 'Swingle', while only 27 % were from 'Rangpur' [24].

A previous study has investigated the influence of rootstocks for 'Swatow' mandarin cultivation in the Brazilian tropical region [4], which included 'Rangpur' lime, 'Swingle' citrumelo, 'Orlando' tangelo (*C. reticulata* Blanc. 'Dancy' × *C. paradisi* Macfad. cv. Duncan), and 'Cleopatra' mandarin (*C. reshni* hort. ex Tanaka). However, the authors reported no discernible variances among these rootstocks concerning yield performance and fruit quality under tropical conditions after seven years of data collection. These results underscore the importance of further exploration into new rootstock options for 'Swatow' mandarin as a potential alternative for 'Rangpur' and 'Swingle' in the humid subtropical and similar regions.

Considering the need for rootstock and scion diversification, undertaking evaluations of different combinations is of the utmost

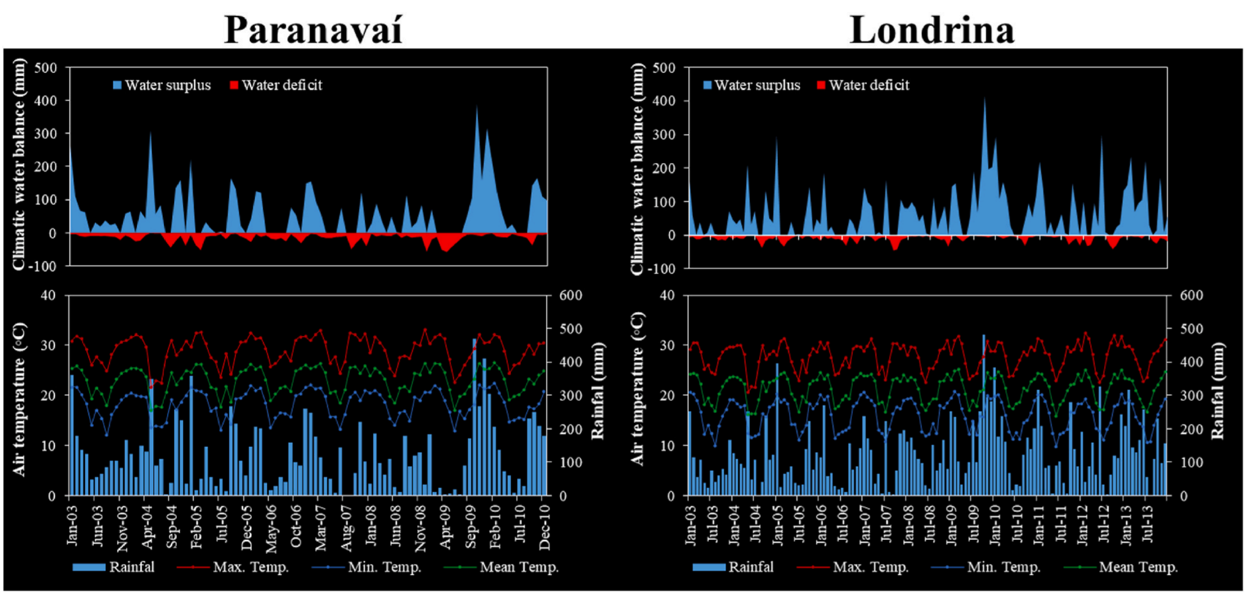

Fig. 1. Climatic water balance (mm), monthly air temperature (°C; Max. Temp., maximum temperature; Min. Temp., minimum temperature; Mean Temp., mean temperature) and rainfall (mm). Data are from the 2003–2010 period in Paranavaí and from 2003 to 2013 in Londrina. (Source: IDR–Paraná, 2023).

importance in determining their suitability for new citrus plantings. Therefore, we report here the evaluation of nine rootstocks for 'Swatow' mandarin trees grown at two different locations in the Brazilian humid subtropical, where tree vigor, yield, fruit quality, and estimates of tree density and yield were used as selection markers in a long-term study.

2. Materials and methods

2.1. Experimental location

Trees were planted in two experimental areas located in the municipalities of Paranavaí (23° 05′ S; 52° 26′ W, and 480 m a.s.l.) and Londrina (23°21′34″ S, 51°09′53″ W, and 585 m a.s.l.) in the northwest and north regions of the state of Paraná, Brazil, respectively. The experimental areas were ~175 km apart from each other. These regions incorporate the main citrus-producing area in the state of Paraná but are composed of a scarcity of citrus varieties, which is based mainly on sweet oranges ('IAPAR 73', 'Pera', 'Valencia' and 'Folha Murcha' varieties) using the 'Rangpur' lime and 'Swingle' citrumelo as the dominant rootstocks.

The climate of both regions is humid subtropical (Cfa) according to the Köppen-Geiger climate classification. The type of soil is Typic Hapludox with sand texture (11 % clay, 2 % silt, and 87 % sand in the 0–40 cm layer) in Paranavaí and clay texture (70 % clay, 13 % silt, and 17 % sand in the 0–40 cm layer) in Londrina (Supplement 1), with slightly wavy to flat relief [25]. Meteorological conditions were monitored daily for the entire experimental period by meteorological stations located within ~1.0 km from the experimental plots (Fig. 1). Climatic water balance was calculated for the experimental period according to the Thornthwaite and Mather [26] method using an available water capacity of 100 mm (Fig. 1).

2.2. Plant material

All propagative materials were provided by the Active Germplasm Bank of Citrus (AGB–Citrus) of the IDR-Paraná established in Londrina, state of Paraná, Brazil. Rootstocks were propagated by seeds, in which nucellar plants were selected to be grafted based on commercial nursery practices. All rootstock liners were grafted with budwoods from certified 'Swatow' mandarin (*C. reticulata* Blanc.) plants (accession: I-348). All nursery plants were cultivated in a screen house under controlled conditions. Nine rootstock genotypes were evaluated in this study: 'Rangpur lime' (*C.* ×*limonia* Osb.), 'Cleopatra' mandarin (*C. reshni* hort. ex Tanaka), 'Fepagro C-13' citrange [*C.* ×*sinensis* × *P. trifoliata* (L.) Raf.], 'Volkamer' lemon [*C. volkameriana* (Risso) V. Ten. & Pasq.], 'Carrizo' citrange [*C.* ×*sinensis* × *P. trifoliata* (L.) Raf.], 'Sunki' mandarin [*C. sunki* (Hayata) hort. ex Tanaka], 'Trifoliate' orange [*P. trifoliata* (L.) Raf.], 'Swingle' citrumelo [*C. paradisi* Macfad. cv. Duncan × *P. trifoliata* (L.) Raf.], and 'Caipira DAC' sweet orange [*C.* ×*sinensis* (L.) Osb.]. Nursery plants (~14 months of age) were planted in July 2000 in Londrina and January 2001 in Paranavaí at tree spacing of 6.0 m × 6.5 m, corresponding to 256 trees per hectare. The experiments were carried out in randomized complete block design with six biological replicates, with each replicate consisting of four trees (two trees were used as a border). In total, 108 trees per experiment were evaluated for this study.

2.3. Orchard management

Each experimental area was managed according to the recommended nutritional, pest, and disease control management programs for citrus cultivation in the state of Paraná [27]. Fertilizers were applied four times a year on average, based on soil chemical analysis, from August through March to supply the maintenance requirements for nitrogen (N), potassium (K), phosphorus (P), boron (B), and zinc (Zn). The doses applied of each fertilizer were based on tree age. Weeds were managed with periodic mowing (five times a year on average) using an ecological mower between rows and herbicide sprays in rows when required, according to the commercial recommendation [27]. Trees were not irrigated or neither pruned/thinned over the experimental period.

2.4. Tree size measurements

Tree growth measurements were carried out in July 2010, just after the annual harvests, when trees were around nine years old. Tree height and canopy diameter were used to calculate the canopy volume as previously described by Mendel [28]:

$$CV = \frac{2}{3} \times \pi \times CR^2 \times TH,$$

where CV = canopy volume (m^3); CR = canopy radius (m) and TH = tree height (m).

In addition, the trunk circumference was measured with a cloth measuring tape 10 cm above and below the graft union, and then, converted to diameter. The trunk index was calculated based on the ratio between the scion and rootstock trunk diameters.

2.5. Fruit yield

Annual yields were determined in July from 2003 through 2010 in Paranavaí and from 2003 through 2013 in Londrina, comprising seven and ten harvest seasons, respectively. Cumulative yields were determined after the annual harvests and the average of each harvest period was calculated. Yield efficiency was calculated based on the relationship between fruit yield ($kg{\cdot}tree^{-1}$) and canopy volume (m^3) determined in 2010. The results were expressed in $kg \cdot m^{-3}$. The alternate bearing index was also calculated according to Pearce and Doberšek-Urbanc [29]:

$$ABI = \frac{1}{n-1} \times \left\{ \frac{|a_2 - a_1|}{a_2 + a_1} + \frac{|a_3 - a_2|}{a_3 + a_2} + \ldots + \frac{|a_n - a_{n-1}|}{a_n + a_{n-1}} \right\},$$

where ABI = alternate bearing index, n = number of years, and a_1, a_2, …, $a_{(n-1)}$, $a_{(n)}$ = yields of the corresponding years.

2.6. Fruit quality

Fruit quality was determined based on 10-fruit samples harvested per plot. Samples were randomly collected at tree height of 1–2 m from the two innermost trees per block, usually in May from 2007 through 2009, before annual harvests. The evaluated parameters were based on the average for the assessed period. Fruit length and diameter were measured with a digital Vernier caliper (ABS, Mitutoyo, Kawasaki, Japan). Fruit was weighed and classified according to the fresh citrus and industrial standards [30–32]. The fruit shape index was also calculated, assessing the relationship between fruit length and diameter. Fruit samples were juiced using an extractor (Croydon, Duque de Caxias, Brazil). Juice content was determined based on the juice and fruit weight ratio:

$$JC = \frac{JW}{FW} \times 100,$$

where JC = juice content (%); JW = juice weight (g) and FW = fruit weight (g).

The soluble solids (SS) content was measured with a digital refractometer (PAL-3, Atago Co., Ltd, Tokyo, Japan) in a 0.3 mL aliquot of undiluted juice. The temperature was corrected to 20 °C, and the results were expressed in °Brix. Titratable acidity (TA) was determined by titration of a standard 0.1 N NaOH solution in 25 mL of diluted juice using an automatic titrator (TitroLine® easy, Schott Instruments GmbH, Mainz, Germany) and phenolphthalein as a visual end-point indicator. The acidy level was expressed in grams of citric acid per 100 mL of juice ($g \cdot 100\ mL^{-1}$) [33]. The SS/TA ratio was also determined for all fruit samples. The technological index, which indicates the amount of SS content per standard citrus box (40.8 kg of maximum capacity), was calculated according to the method proposed by Di Giorgi et al. [34]:

$$TI = \frac{SS \times JC \times 40.8}{10000},$$

where TI = technological index ($kg\ TSS \cdot box^{-1}$); SS = soluble solids (°Brix) and JC = juice content (%).

2.7. Plant density and yield estimates for new plantings

The number of trees per hectare (tree density), tree, and row spacing were estimated for new plantings of 'Swatow' trees based on the variations of rootstock selections and growing location. The estimates study assumed a free spacing of 2.5 m between rows (canopy diameter + 2.5 m), for better equipment movement and field operations within the orchard, and 15 % tree overlap in rows (canopy diameter × 0.85) [35]. Fruit yield was estimated according to the theoretical number of trees per hectare and the average fruit yield per tree was determined for the 2008–2010 period when trees stabilized their vegetative growth and were in full production in both locations. The SS yield was determined according to the estimated yield and expressed in tons of SS per hectare ($t\ SS \cdot ha^{-1}$):

$$SS\ Yield = \frac{SS \times JC \times EY}{10000},$$

where SS Yield = soluble solids yield ($t\ SS \cdot ha^{-1}$); SS = soluble solids (°Brix); JC = juice content (%); and EY = estimate yield. Adapted from Di Giorgi et al. [34].

2.8. Data analyses

The data were analyzed according to the experimental design and tested for normal distribution and homogeneity at $p \leq 0.05$. All statistical analyses were processed in R v. 4.3.1 (The R Foundation for Statistical Computing, Vienna, Austria) within the RStudio interface. The horticultural data were submitted to analysis of variance (ANOVA), and means were grouped by the Scott-Knott's test at $p \leq 0.05$ using the ExpDes package. Significant variables were taken together and submitted to the multivariate analysis using a mean value for each rootstock at each location. A principal component analysis (PCA) and a UPGMA (unweighted pair-group method with arithmetic mean) hierarchical clustering were deployed based on the standardized Euclidean distance using the FactoMineR package.

3. Results

3.1. Tree size

Tree size was determined for each rootstock combination at both locations when trees were nine years old (Table 1). Highly significant interactions ($p \leq 0.001$) were found among the tested rootstocks and locations regarding vegetative growth parameters, except for the trunk diameter index. In Paranavaí, the most vigorous combination was found for 'Carrizo', 'Cleopatra', 'Sunki', 'Volkamer', and 'Caipira DAC' rootstocks, which resulted in an average tree height of 4.00 m and a canopy volume larger than 25.0 m^3. On the other hand, the 'Trifoliate', 'Swingle', 'Fepagro C-13', and 'Rangpur' (Fig. 2) imparted the lowest vigor to the grafted trees, with a height between 3.50 and 3.77 m and a canopy volume of 19.6–25.6 m^3. These 'Trifoliate'-related rootstocks also had the lowest scion trunk diameters with means between 11.5 and 11.9 cm, differing significantly from those reported for all other rootstocks, from 14.9 to 16.9 cm. Differences were also observed between the tested genotypes for the rootstock trunk diameters, in which 'Trifoliate' and 'Fepagro C-13' had the lowest diameter, equivalent to 'Rangpur' and 'Volkamer'. In any case, the ratio between the scion and rootstock trunk diameters was significantly lower for the 'Trifoliate'-related rootstocks, from 0.577 to 0.740. These values indicate a large amplitude between the rootstock and scion trunk diameters, resulting in differences in vegetative growth at the bud union. These trunk diameter indices were significantly higher for all other rootstock combinations, which resulted in an average of 0.828.

In Londrina, 'Cleopatra' and 'Sunki' were also the most vigorous rootstocks for 'Swatow' mandarin, showing a tree height average of 4.70 m and a canopy volume of 56.0 m^3 after nine years of planting. In contrast, 'Rangpur' and 'Volkamer' imparted the lowest vigor to the grafted trees with a tree height range between 3.72 and 4.01 m and canopy volume of 24.4–31.6 m^3, similar to 'Trifoliate' and 'Carrizo'. As opposed to the results reported in Paranavaí, 'Swingle' was very vigorous in Londrina compared to all other tested rootstocks. This vigor was also confirmed for the rootstock trunk diameter, in which 'Swingle' showed an average of 23.6 cm, significantly different from those reported for 'Rangpur' and 'Volkamer', 16.2 and 16.9 cm. The scion trunk diameters were higher for

Table 1

Tree size of 'Swatow' mandarin trees grafted on nine rootstocks at two locations (Paranavaí and Londrina) in the state of Paraná, Brazil. Measurements were assessed in 2010 in both locations, when trees were nine-year-old.

Source of variation	Tree height (m)	Canopy diameter (m)	Canopy volume (m^3)	Rootstock trunk diameter[a] (cm)	Scion trunk diameter[a] (cm)	Trunk diameter index[b]
Paranavaí						
Rangpur lime	3.77 b[c]	3.58 a	25.6 a	18.49 b	14.92 b	0.807 b
Volkamer lemon	4.00 a	3.46 b	25.3 a	18.32 b	15.54 b	0.847 a
Cleopatra mandarin	4.12 a	3.71 a	30.7 a	19.81 a	16.68 a	0.839 a
Sunki mandarin	4.12 a	3.66 a	29.5 a	19.97 a	16.66 a	0.833 a
Caipira DAC orange	3.94 a	3.51 a	25.8 a	19.07 a	15.57 b	0.816 b
Trifoliate orange	3.50 b	3.26 b	19.6 b	17.24 b	11.46 c	0.665 d
Swingle citrumelo	3.53 b	3.28 b	20.2 b	20.00 a	11.54 c	0.577 e
Fepagro C-13 citrange	3.66 b	3.21 b	19.9 b	18.30 b	11.88 c	0.650 d
Carrizo citrange	4.15 a	3.85 a	32.9 a	20.08 a	14.90 b	0.740 c
Mean	3.87 B	3.50 B	25.5 B	19.03 A	14.35 B	0.753 B
Londrina						
Rangpur lime	3.72 d	3.53 c	24.4 d	16.26 d	13.63 c	0.839 a
Volkamer lemon	4.01 d	3.87 c	31.6 d	16.90 d	14.59 b	0.865 a
Cleopatra mandarin	4.77 a	4.72 a	55.7 a	20.81 b	17.31 a	0.832 a
Sunki mandarin	4.78 a	4.72 a	56.2 a	21.15 b	17.52 a	0.828 a
Caipira DAC orange	4.26 c	4.24 b	40.2 c	18.79 c	15.46 b	0.825 a
Trifoliate orange	3.90 d	4.12 b	34.9 c	18.95 c	12.92 c	0.683 c
Swingle citrumelo	4.44 b	4.75 a	52.8 a	23.59 a	14.87 b	0.630 d
Fepagro C-13 citrange	4.13 c	4.58 a	45.2 b	21.30 b	14.43 b	0.677 c
Carrizo citrange	3.99 d	4.09 b	39.7 c	17.78 c	13.33 c	0.751 b
Mean	4.22 A	4.29 A	42.3 A	19.50 A	14.90 A	0.770 A
CV (%)	6.39	8.17	18.39	7.44	8.47	3.84
F value						
Block	1.55ns	0.52ns	2.08ns	0.42ns	1.24ns	1.89ns
Rootstock	12.68[f]	6.32[f]	12.95[f]	12.67[f]	22.68[f]	121.1[f]
Location	51.33[f]	166.4[f]	195.6[f]	2.89ns	5.24[d]	9.45[e]
Rootstock × Location	5.89[f]	7.69[f]	9.84[f]	6.87[f]	5.67[f]	1.27ns

[a] Trunk diameters were based on trunk circumference measurements 10 cm above and 10 cm below the graft union.
[b] Trunk diameter index was expressed as the ratio between scion and rootstock trunk diameters.
[c] Means followed by the same lowercase and capital letters in the column, respectively for rootstock means within the same location and with the location means, belong to the same group according to Scott-Knott's test. Significance level: ns, non-significant.
[d] , $p \leq 0.05$.
[e] , $p \leq 0.01$.
[f] , $p \leq 0.001$.

Fig. 2. Five-year old 'Swatow' mandarin trees grafted on 'Rangpur' lime in Paranavaí, state of Paraná, Brazil.

'Cleopatra' and 'Sunki' (17.3 and 17.5 cm) and lower for 'Trifoliate', 'Carrizo', and 'Rangpur' (12.9, 13.3, and 13.6 cm). Despite these divergences, the trunk diameter indices were close to those reported in Paranavaí, where all 'Trifoliate'-related rootstocks exhibited the lowest scores (range: 0.630–0.751). All other rootstocks had scores between 0.825 and 0.865.

3.2. Fruit yield

Variations in fruit yield were observed within the tested rootstocks and locations (Fig. 3). Trees start bearing fruit three years after planting at both locations. However, the production stabilized with a significant load when trees were five to six years old. In Paranavaí, yield was evaluated from 2003 to 2010, except for the 2006 harvest due to technical issues. At this location, 'Rangpur' and 'Volkamer' were precocious, bearing significant yields in the first years of production, which resulted in the highest cumulative yields (623 and 583 kg, respectively) after seven years of data collection, along with 'Carrizo', 'Cleopatra', and 'Sunki' (623, 596 and 538 kg respectively). On the other hand, trees grafted on 'Fepagro C-13', 'Swingle', 'Trifoliate', and 'Caipira DAC' had the lowest yield performance over time, with a cumulative yield of 344, 450, 484, and 500 kg, respectively. Despite showing a low cumulative yield, 'Trifoliate' reached the highest yield efficiency (5.52 kg·m^{-3}), calculated by the ratio between yield and canopy volume (Table 2).

In Londrina, yield was evaluated from 2003 to 2013 except for the 2007 harvest season, which was not performed due to technical issues. At this location, trees showed significant yields after six years from planting. Trees grafted on 'Swingle' were precocious, bearing significant yields in the first year of production, which resulted in the highest cumulative yield (1206 kg) after ten years of data collection. As opposed to the results reported in Paranavaí, 'Volkamer' and 'Rangpur' had the lowest cumulative yields for 'Swatow' trees in Londrina, 614 and 626 kg respectively. All other rootstocks scored intermediate cumulative yields for this scion, ranging from 855 kg for 'Trifoliate' to 1058 for 'Sunki'. Furthermore, the 'Volkamer', 'Cleopatra', 'Sunki', and 'Caipira DAC' pairings resulted in lower yield efficiency (2.56–2.91 kg·m^{-3}) compared to all other combinations (2.99–3.63 kg·m^{-3}; Table 2). In both locations, the alternate bearing indices were low ($\leq$0.50), and no variations were detected between the tested rootstocks for this parameter.

3.3. Plant density and yield estimates for new plantings

The plant density and yield estimates were calculated for new plantings based on the horticultural performance of 'Swatow' trees on different rootstocks and locations. Significant interactions ($p \leq 0.001$) were detected among the tested factors for most parameters (Table 3). In Paranavaí, the largest spacing between rows (6.35–6.00 m) and trees (2.63–2.89 m) was recorded for 'Carrizo', 'Cleopatra', 'Sunki', 'Rangur', and 'Caipira DAC', while the other rootstocks ensured the smallest spacing between rows (<6.00 m) and trees (<2.60 m). The smallest row and tree distances estimated for 'Fepagro C-13', 'Trifoliate', and 'Swingle' resulted in the highest tree densities (712–734 trees·ha^{-1}), which were significantly higher than those averages recorded for the other rootstocks (558–656 trees·ha^{-1}). Moreover, the 'Rangpur', 'Volkamer', 'Cleopatra', 'Trifoliate', and 'Carrizo' pairings exhibited higher estimate yields (72–74 t·ha^{-1}) than 'Sunki', 'Swingle', 'Caipira DAC' and 'Fepagro C-13' (49–63 t·ha^{-1}). 'Fepagro C-13' also showed the poorest SS yield (1.66 t SS·ha^{-1}) under the Paranavaí soil-climate conditions, differing from all other rootstocks (2.25–2.74 t SS·ha^{-1}).

In Londrina, the largest spacing between rows and trees was estimated for 'Swingle' (7.25 and 3.57 m respectively), 'Cleopatra' (7.22 and 3.54 m respectively), 'Sunki' (7.22 and 3.54 m respectively) and 'Fepagro C-13' (7.08 and 3.44 m respectively; Table 3). In contrast, 'Rangpur' ensured the smallest distances between rows (6.03 m) and trees (2.65 m), which resulted in the highest number of trees estimated per area (629 trees·ha^{-1}) differing from all other rootstock pairings (388–544 trees·ha^{-1}). Regarding the yield potential, all tested rootstocks had equivalent estimated yield. Further, 'Volkamer' showed the lowest SS yield estimation (1.37 t SS·ha^{-1}) differing from those recorded for all other rootstock pairings (1.69–194 t SS·ha^{-1}).

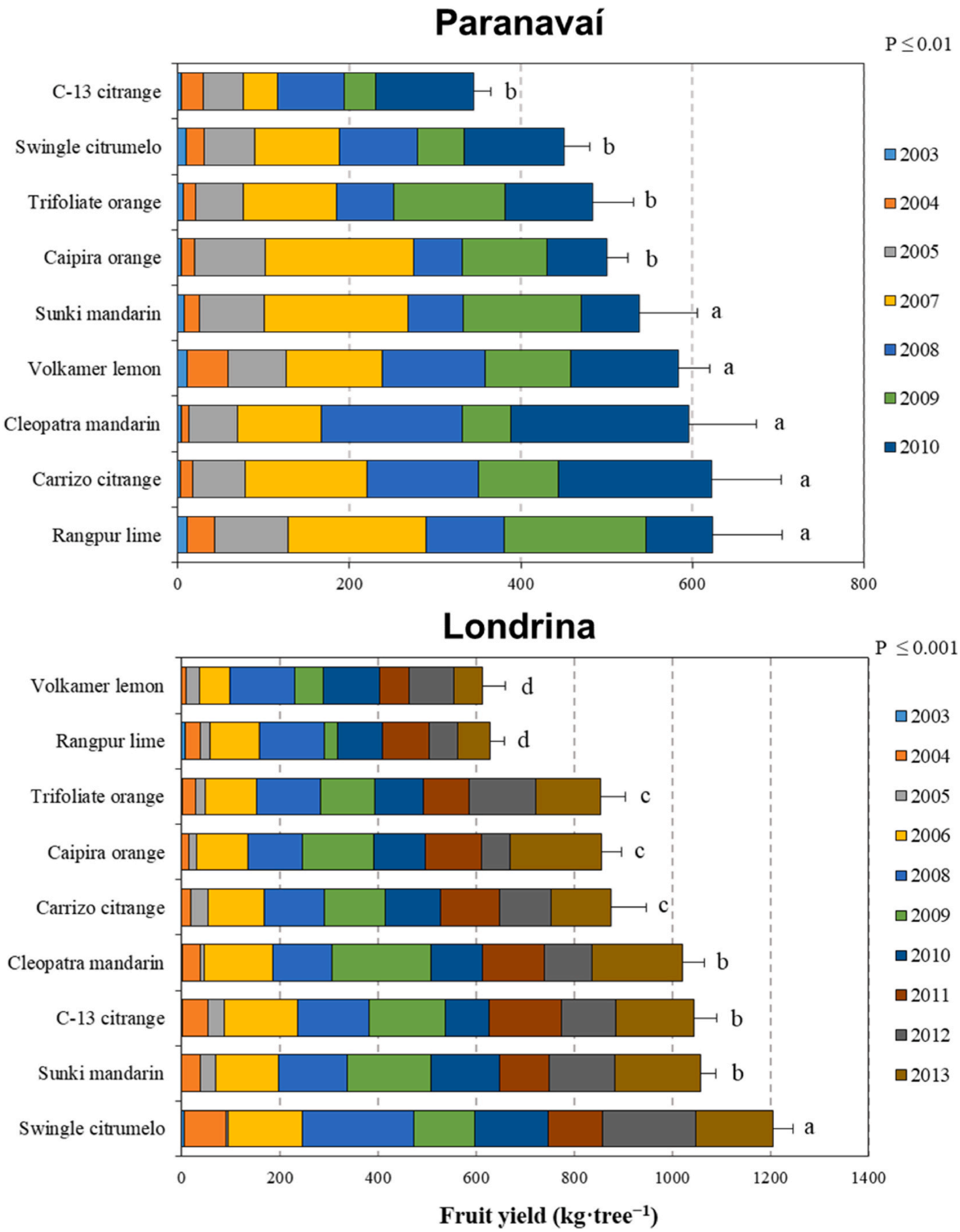

Fig. 3. Annual and cumulative yields of 'Swatow' mandarin trees grown on nine rootstocks in Paranavaí and Londrina, state of Paraná, Brazil, from 2003 up to 2013.

3.4. Fruit quality evaluation

Fruit quality was evaluated from 2007 to 2009 within the scion–rootstock combination and location. The average of this period was used for the statistical analysis (Table 4). The rootstock × location interactions were significant for most of the evaluated parameters. In Paranavaí, fruits harvested from 'Sunki' were larger, showing the highest fruit length (72.6 mm) and diameter (76.8 mm), differing from those fruits from 'Rangpur', 'Fepagro C-13' and 'Cleopatra', 69.0 and 73.0 mm on average, respectively. The shape index recorded for 'Cleopatra', 'Sunki', and 'Fepagro C-13' were significantly higher (~0.95) than those found in fruits from the other rootstock combinations (~0.92), which indicates a more oblate shape. 'Volkamer', 'Cleopatra', 'Fepagro C-13', and 'Carrizo' produced

Table 2
Yield mean, yield efficiency and alternate bearing index of 'Swatow' mandarin trees grafted on nine rootstocks at two locations (Londrina and Paranavaí) in the state of Paraná, Brazil.

Source of variation	Yield mean (2003–2010)	Yield efficiency ($kg \cdot m^{-3}$)[a]	Alternate bearing index (ABI)
Paranavaí			
Rangpur lime	89.05 a[b]	4.54 b	0.384 a
Volkamer lemon	83.32 a	4.55 b	0.362 a
Cleopatra mandarin	85.16 a	4.26 c	0.472 a
Sunki mandarin	76.82 a	3.70 c	0.454 a
Caipira DAC orange	71.42 b	3.94 c	0.430 a
Trifoliate orange	69.08 b	5.52 a	0.392 a
Swingle citrumelo	64.31 b	4.56 b	0.352 a
Fepagro C-13 citrange	49.21 b	3.42 c	0.444 a
Carrizo citrange	89.00 a	4.09 c	0.409 a
Mean	75.26 A	4.29 A	0.411 A
Londrina			
Rangpur lime	58.53 b	3.63 a	0.442 a
Volkamer lemon	57.70 b	2.90 b	0.504 a
Cleopatra mandarin	87.74 a	2.56 b	0.493 a
Sunki mandarin	92.60 a	2.67 b	0.397 a
Caipira DAC orange	70.97 b	2.91 b	0.417 a
Trifoliate orange	70.42 b	3.25 a	0.365 a
Swingle citrumelo	106.77 a	3.16 a	0.452 a
Fepagro C-13 citrange	89.66 a	2.99 a	0.439 a
Carrizo citrange	75.40 b	3.28 a	0.406 a
Mean	78.87 A	3.04 B	0.435 A
CV (%)	20.69	17.25	24.26
F value			
Block	2.00ns	1.94ns	0.54ns
Rootstock	2.62[c]	4.69[d]	0.96ns
Location	1.38ns	103.0[d]	1.46ns
Rootstock × Location	7.89[d]	2.25[c]	1.16ns

[a] Yield efficiency was based on the 2008–2010 average yield and the vegetative growth parameters measured in 2010.
[b] Means followed by the same lowercase and capital letters in the column, respectively for rootstock means within the same location and with the location means, belong to the same group according to Scott-Knott's test. Significance level: ns, non-significant.
[c] , $p \leq 0.05$.
[d] , $p \leq 0.001$.

the heaviest fruits (193 g on average) differing from the other rootstocks (182 g on average). No significant differences were detected between rootstocks for the number of seeds (11 seeds on average) nor juice content (34.2 % on average) at this location. 'Trifoliate', 'Sunki', and 'Caipira DAC' presented equivalent and high SS concentrations in the juice of 'Swatow' mandarin (~10.8 °Brix) while 'Volkamer' scored low for this parameter (9.9 °Brix). Regarding the TA, the concentration of citric acid in fruits from 'Sunki' and 'Cleopatra' was significantly higher (0.78 $g \cdot 100\ mL^{-1}$ on average) than those measured in juice samples from all other rootstocks (0.68 $g \cdot 100\ mL^{-1}$ on average). The SS/TA ratio also fluctuated between the rootstocks. 'Rangpur', 'Cleopatra', and 'Sunki' ranked low for this parameter (13.9 on average), differing from the other rootstocks (15.6 on average). Regarding the technological index, fruits produced in the 'Volkamer' and 'Fepagro C-13' exhibited the poorest performance with an average of 1.35 kg $SS \cdot box^{-1}$.

In Londrina, the 'Swatow' trees produced larger fruits on 'Volkamer' (Fig. 4), 'Carrizo', 'Sunki', and 'Fepagro C-13' with a length of 69.4 mm and diameter of 73.9 mm on average (Table 4). These rootstocks also exhibited the highest fruit shape indices (~0.95). No significant differences were detected between the rootstock for fruit weight (173 g on average). Trees on 'Cleopatra' and 'Swingle' imparted the highest number of seeds per fruit (~14 seeds). Regarding the juice content, fruits from 'Cleopatra' and 'Caipira DAC' were juicier (33.5 and 33.2 % respectively) than the other rootstocks (30.2 % on average). All rootstocks imparted high SS content to the fruits, in which the concentration recorded for 'Rangpur', 'Cleopatra', 'Sunki', 'Caipira DAC', 'Trifoliate', and 'Carrizo' were equivalent (~10.6 °Brix), but higher than those found in fruits from 'Fepagro C-13', 'Volkamer', and 'Swingle' (~10.2 °Brix). The citric acid levels recorded in the juice of 'Swatow' fruits were relatively low and similar between the assessed materials (0.64 $g \cdot 100\ mL^{-1}$ on average). This was also observed for the SS/TA ratios showing equivalent values (~16.4). 'Cleopatra', 'Caipira DAC', and 'Rangpur' were more efficient in accumulating SS, represented by the TI (kg $SS \cdot box^{-1}$). These rootstocks ranked high for this parameter with an average of 1.42 kg $SS \cdot box^{-1}$, superior to those recorded by the other rootstocks (1.27 kg $SS \cdot box^{-1}$ on average).

3.5. Multivariate analysis

The principal component analysis (PCA) was conducted to investigate the impact of each significant parameter on the horticultural performance of 'Swatow' mandarin trees, which were cultivated in two distinct environments based on vegetative growth, yield, fruit quality, planting, and yield estimates (Fig. 5). The first two PCs represented 62.4 % of the data variation (PC1 = 43.30 %; PC2 = 19.10 %). Four distinct clusters were identified based on the resemblances observed among the rootstocks, as exemplified by the projection of

Table 3
Estimates[a] of minimum row and tree spacing, maximum tree density, fruit yield, and soluble solids (SS) yield for new plantings of 'Swatow' mandarin trees grafted on nine rootstocks at two locations (Paranavaí and Londrina) in the state of Paraná, Brazil. Means were based on the scion-rootstock performance from 2007 to 2010 in both locations.

Source of variation	Row spacing (m)	Tree spacing (m)	Tree density (trees·ha^{-1})	Estimate yield (t·ha^{-1})	SS yield (t SS·ha^{-1})
Paranavaí					
Rangpur lime	6.08 a[b]	2.68 a	622.1 b	74.4 a	2.59 a
Volkamer lemon	5.96 b	2.59 b	656.3 b	73.5 a	2.35 a
Cleopatra mandarin	6.22 a	2.79 a	592.3 b	73.5 a	2.69 a
Sunki mandarin	6.16 a	2.74 a	557.7 b	63.2 b	2.31 a
Caipira DAC orange	6.00 a	2.63 a	643.8 b	62.7 b	2.25 a
Trifoliate orange	5.76 b	2.44 b	719.5 a	72.3 a	2.68 a
Swingle citrumelo	5.78 b	2.46 b	712.8 a	63.2 b	2.38 a
Fepagro C-13 citrange	5.71 b	2.41 b	734.1 a	48.7 c	1.66 b
Carrizo citrange	6.35 a	2.89 a	602.9 b	72.3 a	2.74 a
Mean	6.00 B	2.63 B	649.1 A	67.1 A	2.35A
Londrina					
Rangpur lime	6.03 c	2.65 c	629.1 a	55.0 a	1.83 a
Volkamer lemon	6.37 c	2.90 c	543.8 b	49.3 a	1.53 b
Cleopatra mandarin	7.22 a	3.54 a	392.4 c	55.6 a	1.98 a
Sunki mandarin	7.22 a	3.54 a	394.5 c	57.4 a	1.86 a
Caipira DAC orange	6.74 b	3.18 b	467.3 c	54.4 a	1.92 a
Trifoliate orange	6.62 b	3.09 b	491.8 b	54.7 a	1.69 a
Swingle citrumelo	7.25 a	3.57 a	388.3 c	63.1 a	1.93 a
Fepagro C-13 citrange	7.08 a	3.44 a	412.0 c	55.8 a	1.67 a
Carrizo citrange	6.59 b	3.07 b	508.0 b	57.9 a	1.82 a
Mean	6.79 A	3.21 A	469.7 B	55.9 B	1.80 B
CV (%)	4.98	8.17	14.97	16.95	20.60
F value					
Block	0.52ns	0.52ns	0.40ns	1.94ns	1.53ns
Rootstock	6.32[e]	6.32[e]	3.70[e]	1.86ns	2.72[c]
Location	166.4[e]	166.4[e]	123.8[e]	31.0[e]	44.7[e]
Rootstock × Location	7.69[e]	7.69[e]	5.40[e]	2.83[d]	1.34ns

[a] Estimates study was based on vegetative growth, yield, and fruit quality data of 'Swatow' mandarin trees grafted onto different rootstocks; tree density and row/tree spacing projections were calculated according to De Negri and Blasco [34] and used to estimate fruit yield and SS yield.
[b] Means followed by the same lowercase and capital letters in the column, respectively for rootstock means within the same location and with the location means, belong to the same group according to Scott-Knott's test. Significance level: ns, non-significant.
[c] , $p \le 0.05$.
[d] , $p \le 0.01$.
[e] , $p \le 0.001$.

the first two PCs. Trees grafted on 'Sunki' in Paranavaí were categorized into a single group primarily associated with heavy fruit weight, but also had low yield efficiency and SS content. Furthermore, similarities were detected between 'Sunki' in Londrina and 'Cleopatra' in Paranavaí. These rootstocks promoted a higher SS/TA ratio within heavier fruits. The highest yield efficiency and tree height were observed for the pairings formed with 'Swingle' and 'Fepagro C-13' in Paranavaí and 'Swingle', 'Caipira DAC' and 'Rangpur' in Londrina, which resulted in the lowest tree vigor, besides of ensuring the smallest tree and row spacing estimates. All other combinations behaved equally according to the location, where they exhibited improved yields and fruit quality but, in some cases, imparted greater vegetative vigor to the scion.

4. Discussion

The performance of 'Swatow' mandarin trees grafted on nine rootstocks was evaluated at two different locations under the humid subtropical conditions in southern Brazil. Significant interactions ($p \le 0.05$) were found among the accessed rootstocks and locations for almost all variables. Trees grew vigorously in Londrina compared to Paranavaí (Table 1). These differences are probably related to the soil-climate conditions, as trees received the same management program at both locations. The soil in Paranavaí is characterized as Typic Hapludox with sand texture (Supplement 1), implying a lower water-storage capacity compared to Londrina's clay-laden soil (Supplement 1). This is important, as trees were not irrigated over the experimental duration.

Air temperature and rainfall also played a vital role in tree growth. In Paranavaí, the average air temperature and water deficit were notably higher (23.0 °C and −181.5 mm, respectively) compared to the averages recorded in Londrina (21.4 °C and −124.2 mm) from 2003 to 2010 (Fig. 1). These environmental conditions led to significant constraints on tree development, with limited water availability and elevated temperatures that may have favored drought and heat stress [36]. On the other hand, trees grafted onto 'Rangpur' and 'Volkamer' showed consistent results in terms of vigor in both locations. These findings could be attributed to the drought tolerance conferred by these two rootstocks to the grafted tree [22,37,38].

The most vigorous combinations were observed for 'Sunki' and 'Cleopatra' across both locations (Table 1). Previous research has

Table 4
Three-season average fruit quality of 'Swatow' mandarin trees grafted on nine rootstocks at two locations (Paranavaí and Londrina) in the state of Paraná, Brazil. Means were based on the average of fruit quality parameter from 2007 to 2009.

Source of variation	Fruit length FL (mm)	Fruit diameter FD (mm)	Fruit shape (FL/FD)	Fruit weight (g)	Number of seeds	Juice content (%)	Soluble solids SS (°Brix)	Titratable acidity TA ($g{\cdot}100\ mL^{-1}$)	Ratio ($SS{\cdot}TA^{-1}$)	Technological index (kg $SS{\cdot}box^{-1}$)
Paranavaí										
Rangpur lime	67.3 b[a]	72.3 b	0.93 b	179.4 b	11.0 a	34.7 a	10.2 c	0.73 b	14.1 b	1.44 a
Volkamer lemon	69.0 b	75.3 a	0.92 b	194.6 a	10.7 a	32.2 a	9.9 d	0.61 d	16.2 a	1.30 b
Cleopatra mandarin	69.4 b	73.4 b	0.95 a	192.3 a	11.8 a	35.2 a	10.4 c	0.76 a	13.8 b	1.49 a
Sunki mandarin	72.6 a	76.8 a	0.95 a	181.5 b	11.3 a	34.1 a	10.8 a	0.79 a	13.8 b	1.50 a
Caipira DAC orange	70.4 b	76.4 a	0.92 b	181.7 b	12.0 a	33.4 a	10.8 a	0.68 c	15.7 a	1.46 a
Trifoliate orange	69.7 b	75.0 a	0.93 b	182.4 b	10.9 a	32.9 a	10.9 a	0.69 c	15.9 a	1.46 a
Swingle citrumelo	69.4 b	76.1 a	0.91 b	185.5 b	10.5 a	35.4 a	10.7 b	0.72 b	14.9 a	1.54 a
Fepagro C-13 citrange	69.9 b	73.2 b	0.96 a	192.5 a	10.9 a	33.3 a	10.3 c	0.67 c	15.6 a	1.40 b
Carrizo citrange	69.9 b	76.9 a	0.91 b	191.1 a	10.8 a	36.2 a	10.5 b	0.71 b	15.0 a	1.48 a
Mean	69.7 A	75.1 B	0.92 B	186.8 A	11.1B	34.2 A	10.5 A	0.71 A	15.0 B	1.45 A
Londrina										
Rangpur lime	67.8 b	73.9 a	0.93 b	175.8 a	12.3 b	31.4 b	10.6 a	0.66 a	16.1 a	1.36 a
Volkamer lemon	69.8 a	76.7 a	0.95 a	182.1 a	11.5 b	30.3 b	10.2 b	0.58 a	17.7 a	1.26 b
Cleopatra mandarin	66.9 b	72.2 a	0.93 b	167.9 a	13.7 a	33.5 a	10.6 a	0.65 a	16.4 a	1.45 a
Sunki mandarin	69.0 a	73.3 a	0.94 a	174.4 a	12.2 b	30.8 b	10.5 a	0.66 a	15.9 a	1.32 b
Caipira DAC orange	67.5 b	72.7 a	0.93 b	170.3 a	12.0 b	33.2 a	10.6 a	0.63 a	17.0 a	1.44 a
Trifoliate orange	67.0 b	72.0 a	0.93 b	163.7 a	12.6 b	29.2 b	10.6 a	0.65 a	16.4 a	1.26 b
Swingle citrumelo	67.9 b	73.3 a	0.93 b	174.7 a	12.9 a	29.9 b	10.3 b	0.63 a	16.2 a	1.25 b
Fepagro C-13 citrange	68.9 a	72.1 a	0.96 a	168.6 a	12.0 b	29.7 b	10.1 b	0.65 a	15.5 a	1.22 b
Carrizo citrange	69.7 a	73.4 a	0.95 a	178.3 a	12.1 b	30.0 b	10.5 a	0.65 a	16.3 a	1.29 b
Mean	68.3 B	73.0 B	0.94 A	172.8 B	12.4 A	30.9 B	10.4 A	0.64 B	16.4 A	1.32 B
CV (%)	2.58	1.98	2.19	5.84	7.96	7.16	2.13	7.57	7.09	
F value										
Block	0.18ns	0.22ns	0.40ns	0.80ns	0.29ns	0.20ns	1.09ns	1.96ns	1.53ns	0.46ns
Rootstock	3.50[c]	5.45[d]	3.20[c]	2.24[b]	2.87[c]	2.48[a]	12.3[d]	6.33[d]	4.34[d]	4.83[d]
Location	18.0[d]	55.6[d]	4.26[b]	47.4[d]	51.0[d]	52.9[d]	0.84ns	47.4[d]	41.3[d]	53.9[d]
Rootstock × Location	2.33[a]	4.16[d]	2.39[b]	1.37ns	1.64ns	1.85ns	6.14[d]	1.54ns	1.56ns	2.75[c]

[a] Means followed by the same lowercase and capital letters in the column, respectively for rootstock means within the same location and with the location means, belong to the same group according to Scott-Knott's test. Significance level: ns, non-significant.
[b] , $p \leq 0.05$.
[c] , $p \leq 0.01$.
[d] , $p \leq 0.001$.

consistently shown that these rootstocks tend to induce significant vigor to the scion compared to other commercially used rootstocks in the same geographical region. These studies encompassed such citrus varieties as 'Oktisu' satsuma [15], 'Emperor' mandarin [18], and 'Salustiana' sweet orange [39]. Equivalent results were reported for 'Cleopatra' paired with 'Navelina' and 'Navelate' under Mediterranean climate conditions, confirming the robust performance of this rootstock genotype across diverse growing environments [40,41]. 'Sunki' also induced large tree size to various sweet orange selections under tropical conditions [42], where the canopy

Fig. 4. Fruits from seven-year-old 'Swatow' mandarin trees grafted on 'Volkamer' lemon in Londrina, state of Paraná, Brazil.

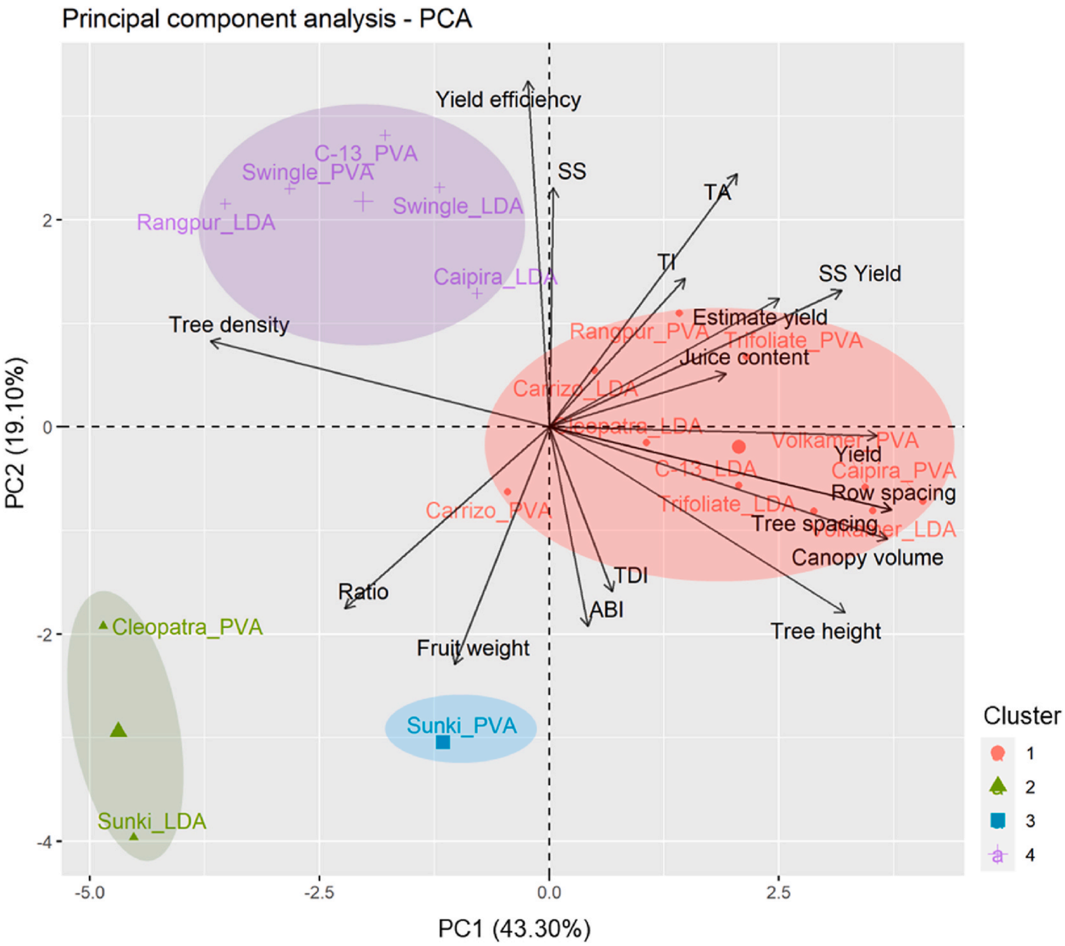

Fig. 5. Principal component analysis (PCA) for the evaluated variables (vegetative growth, yield, fruit quality and estimates for planting and yield) of 'Swatow' mandarin trees grafted on nine rootstocks at two locations (Paranavaí and Londrina) in the state of Paraná, Brazil. The variables used in the PCA were arranged based on their PC scores and the individuals (rootstock) into each environment (PVA, Paranavaí; LDA, Londrina) and were grouped into four distinct clusters: 1, 2, 3 and 4. Variables: TDI, trunk diameter index; tree height (m); canopy volume (m^3); tree spacing (m); row spacing (m), tree density ($tree{\cdot}ha^{-1}$); estimates yield ($t{\cdot}ha^{-1}$); SS yield, soluble solids yield ($t\ SS{\cdot}ha^{-1}$); yield ($kg{\cdot}tree^{-1}$); yield efficiency ($kg{\cdot}m^{-3}$); ABI, alternate bearing index; fruit weight (g); juice content (%); SS, soluble solids (°Brix); TA, titratable acidity ($g{\cdot}100\ mL^{-1}$); ratio ($SS{\cdot}TA^{-1}$); TI, technological index ($kg\ SS{\cdot}box^{-1}$).

volume was 38 % larger than the ones on 'Swingle'. Conversely, 'Trifoliate', 'Rangpur', and 'Volkamer' rootstocks displayed the lowest vigor in 'Swatow' trees across both locations, resulting in tree heights ranging from 3.5 to 4.0 m and canopy volumes between 19.6 and 34.2 m^3. Notably, the lowest vigor of the grafted trees conferred by 'Trifoliate' resulted in higher tree density estimates for new orchards (~607 trees·ha^{-1}). This density estimate aligns closely with the average tree density currently employed in sweet orange-producing areas of the Brazilian citrus belt (~567 trees·ha^{-1}) [2]. All other rootstock combinations induced varying levels of tree vigor depending on the experimental site (Table 1).

Tree size is a critical factor to consider when establishing new citrus orchards. Smaller trees with high yield efficiency offer advantages for maximizing spraying and other field operations, as compact trees provide better spray coverage to the canopy [43,44], lower spray volume, and faster scouting [45]. This aspect is particularly important in the management of HLB, as inadequate insecticide coverage to inner canopy areas may limit the effectiveness of insecticides in controlling the Asian citrus psyllid (ACP; *Diaphorina citri*), the vector of the phloem-limited bacteria '*Candidatus* Liberibacter spp.' associated with HLB disease [44]. Additionally, shorter trees have the potential to reduce pruning and harvest labor costs, besides being more suitable for high-density planting and mechanization [43].

The rootstock and scion trunk diameters were also measured to elucidate the scion–rootstock affinity level, which was based on the growth rates of the trunk diameters at the bud union. The 'Trifoliate', 'Swingle', 'Fepagro C-13', and 'Carrizo' rootstocks induced the lowest trunk diameter indices for the scion (≤0.75) in both locations (Table 1), indicating significant disparities in trunk growth between the scion and rootstock. These 'Trifoliate'-relative rootstocks are recognized to impart trunk overgrowth or benching at the bud union for most commercial citrus varieties [46]. In severe instances, this overgrowth can lead to weakened bud union or physiological disorders [22], potentially resulting in stunted growth and decline of the grafted tree [47]. However, a moderate overgrowth of the rootstock trunk, as observed in our study, does not appear to cause any deleterious effect on trunk strength or tree physiology [22].

The yield of 'Swatow' trees was outperformed on 'Rangpur', 'Carrizo', 'Cleopatra', 'Volkamer', and 'Sunki' in Paranavaí, and 'Swingle' in Londrina over time. These findings align with previous reports for 'Afourer' mandarin grown in Murcia, Spain, where 'Carrizo' citrange yielded up to 77 kg more per tree than *Citrus macrophylla* Wester [20]. The yield efficiency observed in our study for 'Swingle', 'Trifoliate', and 'Rangpur' rootstocks was notably higher and consistent in both locations, strongly endorsing their commercial suitability for 'Swatow' production in humid subtropical regions and/or areas with similar soil-climate conditions. Our prior investigations have consistently highlighted the superior yield potential of these rootstocks for various citrus varieties cultivated in the same geographical area, including 'Emperor' and 'Montenegrina' mandarins [18,48], 'Okitsu' satsuma [15], and 'Salustiana' sweet orange [39]. By choosing these rootstocks, fruit yield can potentially be enhanced through adjustments in tree density during new plantings (Table 3), as evidenced by significant yield estimations for 'Swatow' trees. Previous studies have also validated the exceptional yield predictions associated with 'Trifoliate' rootstock for 'Okitsu' satsuma mandarin [15,16] cultivated in Londrina (89.3 t·ha^{-1}) and Paranavaí (113.4 t·ha^{-1}).

Additionally, trees grafted onto 'Volkamer', 'Rangpur', 'Fepagro C-13', and 'Swingle' rootstocks were the most precocious in Paranavaí. Similarly, 'Swingle' and 'Fepagro C-13' highlighted this aspect in Londrina. This is a positive aspect of rootstock selection, particularly considering the reduced economic lifespan of orchards in the presence of HLB. In such scenarios, a precocious combination of scion and rootstock ensures a swift return on investment [45].

The rootstock effect on fruit quality of 'Swatow' mandarin was moderate in both locations. Trees grafted on 'Sunki' and 'Volkamer' produced larger and heavier fruits compared to those produced by the other rootstocks. However, the fruit diameters recorded in all combinations were categorized as medium size based on the commercial standards for mandarins (B category: 70–82 mm) established by the Brazilian fresh fruit market [30]. Regarding fruit shape, 'Swatow' trees produced typically flat-type fruits irrespective of the rootstock.

'Swatow' fruits were seedy and commercially classified as low-seeded fruit (~12 seeds) according to Albrigo et al. [49]. These seed counts are comparable to or even lower than those reported in previous studies for various mandarins and mandarins-like varieties, including 'Cravo', 'Nules', 'Emperor', 'Montenegrina', and 'Murcott' [18,48,50,51]. This characteristic holds significant importance when selecting a citrus scion-rootstock combination, as consumer preference for seedless or low-seeded fruits, coupled with larger size and easy peeling traits, has increased [31,49,51].

Mandarins are mature when they meet specific criteria regarding juice content, soluble solids (SS), acidity (TA), and SS/TA ratio [31,52,53]. These parameters are crucial for determining the optimal harvest time, especially considering that citrus is classified as a non-climacteric fruit [53]. Harvesting citrus at the appropriate maturity level is vital because no further change in maturation occurs after harvest. In the case of 'Swatow' mandarins, the juice content across all combinations was relatively low (≤36 %) in both locations (Table 4). The minimum juice content required for the commercial trade of mandarins and mandarin-like fruits is 33 %, as established by international standards [31,32]. Based on this criterion, only 'Swatow' trees grafted onto 'Cleopatra' and 'Caipira DAC' rootstocks produced fruits meeting this baseline in both locations. The influence of rootstocks on juice content is contingent upon annual climate variation and soil conditions [36]. Lower juice content is typically associated with a lower juice osmotic potential, as evidenced by 'Rough' lemon rootstock in a previous study [54]. Nevertheless, our findings underscore the importance of adopting improved management practices to enhance the fruit quality of 'Swatow' mandarins. This may involve adjustments in irrigation, nutritional programs, thinning, pruning, and other horticultural practices [49].

As citrus fruit matures, SS accumulates while organic acids decrease in the flesh [53]. Across all rootstock pairings, fruit exhibited high SS content in both locations (9.9–10.9 °Brix), meeting the minimum standard grade required by the fresh market [30–32]. The level of citric acid recorded for all rootstock treatments was between 0.58 and 0.79 g·100 mL^{-1}, which falls within the range established for the fresh fruit market, between 0.50 and 1.00 % [55].

The SS/TA ratio is a widely used indicator of citrus fruit internal quality and varies according to local standards [53]. Generally, SS/TA ratios of at least 7 to 9:1 are considered acceptable for commercial marketability according to international maturity standards [49]. In any case, fruits from all rootstock combinations met this criterion in our study. While mandarins are primarily marketed in the fresh fruit sector due to their rich color and quality, the juice processing industry may incorporate mandarin juice at a maximum ratio of 1:10 to orange juices to enhance color, odor/aroma, or to market it as a single-strength juice [49,56]. In this regard, the TIs estimated for 'Swatow' mandarin fruits during the evaluation period were notably lower in Londrina compared to Paranavaí, primarily due to the lower juice content of the fruits produced at this location. Regarding rootstocks, 'Cleopatra' and 'Caipira DAC' emerged as the most efficient selections for achieving higher TIs in both locations.

In general, all tested rootstocks had positive impacts on the quality of 'Swatow' fruits in the studied environments. Fruits from trees grafted onto 'Sunki' rootstock were larger and heavier, having higher SS concentrations like those from 'Caipira DAC', 'Trifoliate', 'Swingle', and 'Carrizo' at both locations. However, the juice content was relatively low across most rootstock treatments.

Another crucial consideration is the resistance of 'Swatow' mandarin against ABS, which allows growers to foster genetic diversification along with citrus protection in orchards. This is particularly significant as the primary mandarin and mandarin-like varieties cultivated in Brazil, i.e., 'Ponkan' and 'Murcott', are highly susceptible to this disease [3]. 'Swatow' also exhibits good resistance to citrus canker [7], an essential trait given that only genotypes resistant to this bacterial disease are authorized for citrus cultivation in the state of Paraná [27]. Furthermore, the alternative rootstocks examined in our study as substitutes for 'Rangpur' and 'Swingle' exhibit tolerance to a wide range of biotic and abiotic factors. Among them, 'Cleopatra', 'Trifoliate', 'Fepagro C-13', and 'Carrizo' confer resilience against some species of *Phytophthora* and resistance to CTV along with 'Sunki' [21,22,57]. Tree drought and salinity tolerance may be acquired using 'Cleopatra', 'Sunki', and 'Volkamer' as rootstock [22], thus instigating their use in areas with erratic rainfall patterns or limited irrigation infrastructure. Hence, when selecting a rootstock for a certain region, it is crucial to consider multiple horticultural traits and their resistance/tolerance against biotic and abiotic factors.

5. Conclusion

'Swatow' mandarin trees exhibited robust performance under rainfed conditions in the Brazilian subtropics, albeit displaying variation in horticultural traits contingent upon rootstock and location. The compact nature of trees induced by 'Trifoliate' orange rootstock, coupled with its exceptional yield efficiency and excelled fruit quality with high soluble solids (SS) content and low acidity level, positions this genotype as a promising and attractive option for establishing new 'Swatow' orchards in regions with a humid subtropical climate or similar conditions. Additionally, the lower vigor induced by this rootstock may enhance orchard operations, potentially reducing the production cost of 'Swatow' mandarin cultivation, making it a more appealing option for citrus growers.

'Carrizo' citrange and 'Caipira DAC' orange also emerge as interesting rootstock candidates for this variety, as these genotypes ensured solid results on annual yields and good fruit quality, equivalent to those observed for 'Swingle' and 'Rangpur', Brazil's most prevalent rootstocks. 'Sunki' and 'Cleopatra' mandarins conferred consistent yields and good fruit quality to 'Swatow' trees but showed the inconvenience of vigorous growth. On the other hand, 'Fepagro C-13' citrange and 'Volkamer' lemon failed to meet initial expectations, leading to inconsistent yields across the locations.

Considering the demands of modern citrus production, 'Swatow' mandarin on 'Trifoliate' orange and 'Carrizo' citrange on 'Caipira DAC' orange rootstocks are the best combinations to increase genetic diversification in new mandarin plantings in subtropical and analogous regions.

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Data availability statement

Data will be made available on request from the corresponding author.

Ethics statements

Informed consent was not required for this study.

CRediT authorship contribution statement

Deived Uilian de Carvalho: Writing – original draft, Methodology, Formal analysis, Data curation. **Maria Aparecida da Cruz:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Thaís Cristina Morais Vidal:** Investigation, Formal analysis. **Ronan Carlos Colombo:** Writing – review & editing, Investigation, Formal analysis. **Inês Fumiko Ubukata Yada:** Formal analysis, Data curation. **Carmen Silvia Vieira Janeiro Neves:** Writing – review & editing, Supervision, Methodology. **Rui Pereira Leite Junior:** Writing – review & editing, Supervision, Resources, Methodology. **Zuleide Hissano Tazima:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

[1] Food and Agriculture Organization of the United Nations – FAO, FAOSTAT: production crops, Available online at: http://www.fao.org/faostat/en/#data/QC/visualize, 2022. (Accessed 19 December 2023).
[2] Fund for Citrus Protection – Fundecitrus, Tree Inventory and Orange Crop Forecast for the São Paulo and West-Southwest Minas Gerais Citrus Belt, Fundecitrus, 2023, p. 148p.
[3] M. Bastianel, R. Martinelli, F.T. Devite, M. Cristofani-Yaly, R.V. Ferreira, E.S. Stuchi, F.A. Azevedo, Reaction of mandarins to the alternaria brown spot and huanglongbing: identification of potential varieties for these diseases to be managed in the field, Horticulturae 9 (2023) 641, https://doi.org/10.3390/horticulturae9060641.
[4] E.S. Stuchi, E. Espinoza-Núñez, F.A.A. Mourão Filho, E.M.M. Ortega, Vigor, produtividade e qualidade de frutos de quatro tangerineiras e híbridos sobre quatro porta-enxertos, Rev. Bras. Frutic. 30 (2008) 741–747, https://doi.org/10.1590/S0100-29452008000300030.
[5] C.G. Neves, D.O.J. Amaral, M.F.B. de Paula, L.S. de Nascimento, G. Costantino, O.S. Passos, M.A. Santos, P. Ollitrault, A.S. Gesteira, F. Luro, F. Micheli, Characterization of tropical Mandarin collection: implications for breeding related to fruit quality, Sci. Hortic. (Canterb.) 239 (2018) 289–299, https://doi.org/10.1016/j.scienta.2018.05.022.
[6] M.M. Porcino, L.C. Nascimento, J. O Souza, B.O. Souza, M.C. Nunes, Caracterização morfogenética e reação de resistência de genótipos de tangerineira a *Alternaria alternata* f. sp. *citri*, Summa Phytopathol. 43 (2017) 118–123, https://doi.org/10.1590/0100-5405/171161.
[7] A.M. Amaral, S.A. Carvalho, L.F.C. Silva, M.A. Machado, Reaction of genotypes of citrus species and varieties to *Xanthomonas citri* subsp. *citri* under greenhouse conditions, J. Plant Pathol. 92 (2010) 519–524.
[8] L.E.O. Aparecido, G.B. Torsoni, R.F. Lima, A.C.C. Baratti, M.F.M. Rossi, A.F. Santos, P.M. Peche, Climate zoning: identifying suitable regions for the occurrence of Alternaria Brown spot in tangerine trees in Brazil, Pest Manag. Sci. 80 (2024) 1615–1631, https://doi.org/10.1002/ps.7894.
[9] B. Alquezar, L. Carmona, S. Bennici, M.P. Miranda, R.B. Bassanezi, L. Peña, Cultural management of Huanglongbing: current status and ongoing research, Phytopathology 112 (2022) 11–25, https://doi.org/10.1094/PHYTO-08-21-0358-IA.
[10] Q. Cai, C. Liu, M. Yuan, L. Pan, Q. Yang, L. Zhou, HLB induce changes in the tree physiology of citron (*Citrus medica* L. var. *sarcodactylis* Swingle), Physiol. Mol. Biol. Plants 28 (2022) 517–531, https://doi.org/10.1007/s12298-022-01129-z.
[11] M.N. Alves, S.A. Lopes, L.L. Raiol-Junior, N.A. Wulff, E.A. Girardi, P. Ollitrault, L. Peña, Resistance to '*Candidatus* liberibacter asiaticus,'the huanglongbing associated bacterium, in sexually and/or graft-compatible citrus relatives, Front. Plant Sci. 11 (2021) 617664, https://doi.org/10.3389/fpls.2020.617664.
[12] V. Gitz, A. Meybeck, L. Lipper, C.D. Young, S. Braatz, Climate change and food security: risks and responses, FAO Report 110 (2016) 3–36. http://www.fao.org/3/a-i5188e.pdf.
[13] A. Georgiou, Evaluation of rootstocks for 'Clementine'Mandarin in Cyprus, Sci. Hortic. 93 (2001) 29–38, https://doi.org/10.1016/S0304-4238(01)00311-9.
[14] T. Cantuarias-Avilés, F.A.A. Mourão Filho, E.S. Stuchi, S.R. Silva, E. Espinoza-Núñez, Tree performance and fruit yield and quality of 'Okitsu'Satsuma Mandarin grafted on 12 rootstocks, Sci. Hortic. 123 (2010) 318–322, https://doi.org/10.1016/j.scienta.2009.09.020.
[15] Z.H. Tazima, C.S.V.J. Neves, I.F.U. Yada, R.P. Leite Junior, Performance of "okitsu" satsuma Mandarin on nine rootstocks, Sci. Agric. 70 (2013) 422–427, https://doi.org/10.1590/S0103-90162013000600007.
[16] Z.H. Tazima, C.S.V.J. Neves, I.F.U. Yada, R.P. Leite Junior, Performance of 'Okitsu' satsuma Mandarin trees on different rootstocks in Northwestern Parana State, Semina Ciências Agrárias 35 (2014) 2297, https://doi.org/10.5433/1679-0359.2014v35n5p2297.
[17] M. Caruso, A. Continella, G. Modica, C. Pannitteri, R. Russo, F. Salonia, C. Arlotta, A. Gentile, G. Russo, Rootstocks influence yield precocity, productivity, and pre-harvest fruit drop of mandared pigmented Mandarin, Agronomy 10 (2020) 1305, https://doi.org/10.3390/agronomy10091305.
[18] M.A. Cruz, C.S.V.J. Neves, D.U. Carvalho, R.C. Colombo, J. Bai, I.F.U. Yada, R.P. Leite Junior, Z.H. Tazima, Five rootstocks for "Emperor" Mandarin under subtropical climate in Southern Brazil, Front. Plant Sci. 12 (2021) 777871, https://doi.org/10.3389/fpls.2021.777871.
[19] F. Hayat, J. Li, S. Iqbal, Y. Peng, L. Hong, R.M. Balal, M.N. Khan, M.A. Nawaz, U. Khan, M.A. Farhan, C. Li, W. Song, P. Tu, J. Chen, A mini review of citrus rootstocks and their role in high-density orchards, Plants 11 (2022) 2876, https://doi.org/10.3390/plants11212876.
[20] A.A. Maciá-Vázquez, J.J. Martínez-Nicolás, D. Núñez-Gómez, P. Melgarejo, P. Legua, Influence of rootstock on yield, morphological, biochemical and sensory characteristics of 'Afourer' variety mandarins, Sci. Hortic. 325 (2024) 112644, https://doi.org/10.1016/j.scienta.2023.112644.
[21] J. Pompeu Junior, Citros, Porta-Enxertos, Instituto Agronômico/FAPESP, 2005, pp. 63–94.
[22] K.D. Bowman, J. Joubert, The Genus Citrus, Citrus Rootstocks, Elsevier, 2020, pp. 105–127, https://doi.org/10.1016/B978-0-12-812163-4.00006-1.
[23] J. Pompeu Junior, S. Blumer, Híbridos de trifoliata como porta-enxertos para laranjeira Pêra, Pesqui. Agropecuária Trop. 44 (2014) 9–14, https://doi.org/10.1590/S1983-40632014000100007.
[24] E.A. Girardi, J. Pompeu Junior, J. Teofilo Sobrinho, W.S. Soares Filho, O.S. Passos, M. Cristofani-Yaly, O.R. Sempionato, E.S. Stuchi, L.C. Donadio, D. Mattos Junior, Guia de Reconhecimento dos Citros em Campo: Um Guia Prático Para o Reconhecimento em Campo de Variedades de Laranjeira-Doce e Outras Espécies de Citros Cultivadas no Estado de São Paulo e Triângulo Mineiro, Fundecitrus, 2021, p. 158p.
[25] J.O.I. Larach, A. Cardoso, A.P. Carvalho, D.P. HochmüLler, J.S. Martins, M.D.J. Rauen, P.J. Fasolo, R.O. Potter, Levantamento de Reconhecimento dos Solos do Estado do Paraná, Embrapa Solos, 1984.
[26] C.W. Thornthwaite, J.R. Mather, The Water Balance, Drexel Institute of Technology, Publications in Climatology, 1955, p. 86p.
[27] Instituto Agronômico do Paraná – IAPAR, A Citricultura No Paraná, IAPAR, 1992.
[28] K. Mendel, Rootstock-scion relationships in Shamouti trees on light soil, Ktavim 6 (1956) 35–60.

[29] S.C. Pearce, S. Dobersek-Urbanc, The measurement of irregularity in growth and cropping, J. Hortic. Sci. 42 (1967) 295–305, https://doi.org/10.1080/00221589.1967.11514216.
[30] Companhia de Entrepostos e Armazéns Gerais de São Paulo – CEAGESP, Normas de Classificação de Citros de Mesa, CEAGESP, 2010.
[31] M. Ladaniya, Citrus Fruit: Biology, Technology and Evaluation, Elsevier Academic Press, 2022, p. 833p, https://doi.org/10.1016/C2012-0-06022-X.
[32] Organization for Economic Co-operation and Development – OECD, Citrus Fruits, International Standards for Fruit and Vegetables, OECD Publishing, 2010.
[33] Association of official agricultural chemists – AOAC, official methods of analysis, Agric. Rev. 21 (1990) 1–15.
[34] F. Di Giorgi, B.Y. Ide, K. Dib, R.J. Marchi, H.R. Triboni, R.L. Wagner, Contribuição ao estudo do comportamento de algumas variedades de citros e suas implicações agroindustriais, Citrus Res. Tech. 11 (1990) 567–612.
[35] J.D. De Negri, E.E.A. Blasco, Citricultura Brasileira, Planejamento e implantação de um pomar cítrico. Fundação Cargill, 1991, pp. 318–332.
[36] J. Morales Alfaro, A. Bermejo, P. Navarro, A. Quinones, A. Salvador, Effect of rootstock on citrus fruit quality: a review, Food Rev. Int. 39 (2023) 2835–2853, https://doi.org/10.1080/87559129.2021.1978093.
[37] M. Şahin-Çevik, B. Çevik, A. Coşkan, Identification and expression analysis of salinity-induced genes in Rangpur lime (*Citrus limonia*), Hortic, Plant J. 6 (2020) 267–276, https://doi.org/10.1016/j.hpj.2020.07.005.
[38] S.F. Silva, M.T. Miranda, C.P. Cunha, A.P. Domingues-Junior, J.A. Aricetti, C. Caldana, E.C. Machado, R.V. Ribeiro, Metabolic profiling of drought tolerance: revealing how citrus rootstocks modulate plant metabolism under varying water availability, Environ. Exp. Bot. 206 (2023) 105169, https://doi.org/10.1016/j.envexpbot.2022.105169.
[39] D.U. Carvalho, C.S.V.J. Neves, M.A. Cruz, R.C. Colombo, I.F.U. Yada, R.P. Leite Junior, Z.H. Tazima, Performance of 'Salustiana' sweet orange on different rootstocks under Brazilian subtropical conditions, Sci. Hortic. 287 (2021) 110226, https://doi.org/10.1016/j.scienta.2021.110226.
[40] M.A. Forner-Giner, J.J. Hueso, J.M. Agüera, P. Legua, J.B. Forner, Effects of citrus rootstocks on growth, yield and fruit quality of Navelate orange, J. Food Agric. Environ. 9 (2011) 400–403.
[41] M.A. Forner-Giner, A. Alcaide, E. Primo-Millo, J.B. Forner, Performance of "navelina" orange on 14 rootstocks in northern valencia (Spain), Sci. Hortic. 98 (2003) 223–232, https://doi.org/10.1016/S0304-4238(02)00227-3.
[42] E.A. Girardi, T.S. Cerqueira, T.E. Cantuarias-Avilés, S.R. Silva, E.S. Stuchi, Sunki Mandarin and swingle citrumelo as rootstocks for rain-fed cultivation of late-season sweet orange selections in northern São Paulo state, Brazil, Bragantia 76 (2017) 501–511, https://doi.org/10.1590/1678-4499.2016.350.
[43] E.A. Girardi, J.G.P. Sola, M.S. Scapin, A.S. Moreira, R.B. Bassanezi, A.J. Ayres, L. Peña, The perfect match: adjusting high tree density to rootstock vigor for improving cropping and land use efficiency of sweet orange, Agronomy 11 (2021) 2569, https://doi.org/10.3390/agronomy11122569.
[44] R.A. Rehberg, P. Trivedi, W. Bahureksa, J.L. Sharp, S.C. Stokes, R.F. Menger, T. Borch, Quantification of insecticide spatial distribution within individual citrus trees and efficacy through Asian citrus psyllid reductions under different application methods, Pest Manag. Sci. 77 (2021) 1748–1756, https://doi.org/10.1002/ps.6195.
[45] E.S. Stuchi, E.A. Girardi, Utilização de práticas culturais na citricultura frente ao Huanglongbing, Embrapa Mandioca e Fruticultura, 2010, p. 75p.
[46] K.D. Bowman, G. McCollum, Five new citrus rootstocks with improved tolerance to Huanglongbing, Hortscience 50 (2015) 1731–1734, https://doi.org/10.21273/HORTSCI.50.11.1731.
[47] S.M. Garnsey, W.S. Castle, D.P.H. Tucker, R.E. Rouse, H.K. Wutscher, M.C. Kesinger, Budunion incompatibilities and associated declines observed in Florida among trees on Swingle citrumelo and other trifoliate orange-related rootstocks. Proceedings of the Florida State Horticultural Society114, 2001, pp. 121–127.
[48] D.U. Carvalho, C.S.V.J. Neves, M.A. Cruz, I.F.U. Yada, R.P. Leite Junior, Z.H. Tazima, Evaluation of multiple rootstocks for 'montenegrina' Mandarin in Londrina, Paraná, Brazil, Rev. Bras. Frutic. 44 (2022) e–817, https://doi.org/10.1590/0100-29452022817.
[49] L.G. Albrigo, L.W. Timmer, L.L. Stelinski, Citrus, CABI, 2019, p. 314p, https://doi.org/10.1079/9781845938154.0000.
[50] C.A. Pacheco, F.A. Azevedo, V.N.P.B. Barros, M. Cristofani-Yaly, M.R. Verruma-Bernardi, Fremont - iac 543: tangerine with potential for the Brazilian market, Rev. Bras. Frutic. 39 (2017) e–436, https://doi.org/10.1590/0100-29452017436.
[51] R.M. Pio, J.O. Figueiredo, E.S. Stuchi, S.A.B. Cardoso, Citros, Variedades Copas, Instituto Agronômico/FAPESP, 2005, pp. 39–57.
[52] L. Goldenberg, Y. Yaniv, R. Porat, N. Carmi, Mandarin fruit quality: a review, J. Sci. Food Agric. 98 (2018) 18–26, https://doi.org/10.1002/jsfa.8495.
[53] J. Lado, M.J. Rodrigo, L. Zacarías, Maturity indicators and citrus fruit quality, Stewart Postharvest Rev. 10 (2014) 1–6.
[54] L.M. Carvalho, H.W. Carvalho, I. Barros, C.R. Martins, W.D.S. Soares Filho, E.A. Girardi, O.S. Passos, New scion-rootstock combinations for diversification of sweet orange orchards in tropical hardsetting soils, Sci. Hortic. 243 (2019) 169–176, https://doi.org/10.1016/j.scienta.2018.07.032.
[55] M.E.C. Pereira, F.F. Cantillano, A.S.D. Gutierez, G.V.B. Almeida, Post Harvest Procedures in Integrated Production of Citrus, Embrapa Mandioca e Fruticultura, 2006.
[56] A.J. Pérez-López, D. Saura, J. Lorente, A.A. Carbonell-Barrachina, Limonene, linalool, α-terpineol, and terpinen-4-ol as quality control parameters in Mandarin juice processing, Eur. Food Res. Technol. 222 (2006) 281–285, https://doi.org/10.1007/s00217-005-0055-5.
[57] W.S. Castle, Rootstocks for Fruit Crops, Citrus Rootstocks, John Wiley and Sons, 1987, pp. 361–369.