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Performance of clonal rootstocks for 'BRS-Kampai' peach and own-rooted trees in a mild-winter region

Desempenho de porta-enxertos clonais para pessegueiro 'BRS-Kampai' e autoenraizado em região de inverno ameno

Robson Rosa de Camargo[1], Gener Augusto Penso[1], Rafael Henrique Pertille[1], Newton Alex Mayer[2],
Carlos Eduardo Magalhães dos Santos[3], Idemir Citadin[1*]

ABSTRACT

The worldwide main peach-producing are adopting peach training systems with canopy size-controlling clonal rootstocks. However, most peach seedlings commercialised in Brazil are still on seed-propagated rootstocks, which are vigorous and heterogeneous. This study aimed to select rootstocks which induce desirable characteristics of fruit quality, yield efficiency, size control, adaptability and stability in the 'BRS-Kampai' grown in subtropical regions with mild winters. We used adaptability and stability methodology and multivariate selection index to determine yield components and fruit quality. The experiment was conducted in five cycles. The treatments consisted of 'BRS-Kampai' grafted onto 17 clonal rootstocks of *Prunus* spp. and own-rooted trees. The evaluated variables were yield per tree, yield per area, fruit mass, fruit diameter, fruit firmness, soluble solids content, titratable acidity, canopy volume and yield efficiency. The rootstocks 'Ishtara®', 'Genovesa', 'Santa Rosa' and 'Cadaman' always induced low yield and low fruit quality when used as clonal rootstocks for the 'BRS-Kampai' and showed no potential for use as rootstocks in subtropical humid regions with mild winters. The 'BRS-Kampai' own-rooted peach trees or those grafted onto 'Flordaguard', 'Okinawa' are alternatives for peach cultivation under the edaphoclimatic conditions of Pato Branco-PR, although the training and pruning systems must be adjusted due to high vigour. The clonal rootstocks 'Tsukuba-3' and 'Tsukuba-2' induced the highest production performance in the canopy cultivar BRS-Kampai, combining fruit quality, yield with higher stability, and yield efficiency making them the most suitable ones among the studied rootstocks.

Index terms: Climate adaptation, training systems, selection index, peach production, *Prunus* sp.

RESUMO

Sistemas de condução de pessegueiros com porta-enxertos clonais que reduzem vigor da copa são os mais adotados mundialmente. Entretanto, no Brasil ainda se utiliza porta-enxertos propagados por sementes, que são vigorosos e heterogêneos. Este trabalho teve como objetivo selecionar porta-enxertos que induzam qualidade de frutos, eficiência produtiva, controle de vigor, adaptabilidade e estabilidade em 'BRS-Kampai' cultivada em regiões subtropicais com invernos amenos. Foram utilizadas metodologias de adaptabilidade e estabilidade e índice de seleção multivariada para determinar os componentes de produção e qualidade dos frutos. O experimento foi conduzido em cinco ciclos. Os tratamentos consistiram de pessegueiro 'BRS-Kampai' autoenraizado ou enxertado em 17 porta-enxertos clonais de *Prunus* spp. As variáveis avaliadas foram produção por planta, produtividade por área, massa de frutos, diâmetro e firmeza de frutos, teor de sólidos solúveis, acidez titulável, volume de copa e eficiência produtiva. Em regiões subtropicais com invernos 'Ishtara®', 'Genovesa', 'Santa Rosa' e 'Cadaman' induziram baixa produtividade e baixa qualidade de frutos na 'BRS-Kampai' e não apresentam potencial para uso como porta-enxertos. 'BRS-Kampai' autoenraizadas ou enxertadas em 'Flordaguard' e 'Okinawa' são alternativas para o cultivo do pessegueiro, embora os sistemas de condução e poda devam ser ajustados devido ao alto vigor. Os porta-enxertos clonais 'Tsukuba-3' e 'Tsukuba-2' induziram o maior desempenho produtivo na 'BRS-Kampai', aliando qualidade de frutos, produtividade com maior estabilidade e eficiência produtiva tornando-os os mais indicados entre os porta-enxertos estudados.

Termos para indexação: Adaptação ao clima; sistemas de condução; índice de seleção; produção de pêssegos; *Prunus* sp.

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[1]Universidade Tecnológica Federal do Paraná, Programa de Pós-Graduação em Agronomia, Pato Branco, PR, Brasil
[2]Embrapa Clima Temperado, Pelotas, RS, Brasil
[3]Universidade Federal de Viçosa/UFV, Departamento de Agronomia, Viçosa, MG, Brasil

Corresponding author: idemir@utfpr.edu.br

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Introduction

Peach is one of the most produced temperate fruits worldwide and consumed fresh or processed. The global cultivation area has been reduced by approximately 40 thousand ha in the last decade, with a current cultivated area of 1.5 million ha. Despite this reduction, there was an increase in production in the same period of approximately 3.7 million tonnes, with a current production of more than 25 million tonnes (Food and Agriculture Organization - FAO, 2022). In this same period, the area and production of peach in Brazil have remained relatively stable production is approximately 209 thousand tons, in an area of approximately 15.6 thousand ha (Instituto Brasileiro de Geografia e Estatística - IBGE, 2022).

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In Brazil currently, the cultivar 'BRS Kampai' is one of the main cultivars planted, due to high adaptation to marginal conditions, low chill requirements, high yield, and early harvest. Furthermore, its fruits are intended for fresh consumption, with white flesh, intense red skin colour, and soluble solids content greater than 12 °Brix (Raseira et al., 2010).

The increased productivity is partly due to the more productive and adapted cultivars, in addition to significant improvements in management techniques, including the use of most suitable rootstocks (Mayer et al., 2017, 2021a; Manganaris et al., 2022) and the training systems (Iglesias & Echeverria, 2022). In the last decade, there was a considerable improvement in the rootstocks, with the optimisation of the adaptation of plants to locations with edaphoclimatic and phytosanitary conditions limiting peach production (Minas et al., 2023; Reig et al., 2020). Furthermore, the use of rootstocks increases the production efficiency and physicochemical quality of the fruits, with traits regulating the vigour of the canopy cultivar, among other relevant traits (Mayer et al., 2017; Iglesias et al., 2020; Iglesias & Echeverria, 2021, 2022; Manganaris et al., 2022).

In the last few years, new rootstocks have been obtained, mainly interspecific hybrids of *Prunus* spp. originating from crosses between domesticated and wild species of peach, almond and plum trees (Felipe, 2009; Mestre et al., 2015; Anthony & Minas, 2021; Iglesias et al., 2020; Manganaris et al., 2022). The use of clonal rootstocks is also increasing due to the use of interspecific hybrids, which sometimes makes it impossible to use seed-propagated rootstocks, avoiding the inconvenience of genetic segregation and, consequently, rootstock heterogeneity (Mayer et al., 2017, 2021b; Sobierajski et al., 2021). However, most peach seedlings commercialised in Brazil are still based on seed-propagated rootstocks, mainly due to the ease of obtaining propagative material (Mayer et al., 2017, 2021a; Oliveira et al., 2018).

The use of rootstocks by seeds is a problem in peach production because, even in advanced generations with a tendency to homozygosity, genetic segregation still occurs, leading to losses of agronomic characteristics of interest to the rootstock (Reighard & Loreti, 2008; Mayer et al., 2017). Furthermore, rootstocks of seeds origin tend to provide high vegetative growth to scion cultivars making difficult pruning, thinning, harvest and reduces yield efficiency. In vigorous trees is impossible to increase of orchard density and may prevent the use of mechanization or use of bi-dimensional cropping systems, global trend for peach tree production (Beckman, Nyczepir, & Myers, 2006; Iglesias & Echeverría, 2021; Iglesias & Echeverría, 2022; Lesmes-Vesga et al., 2022; Neri et al., 2022).

The GGE (genotype and genotype by environment) biplot analysis is one of the tools used to obtain more reliable results, allowing the observation of the interrelationship between the environment and the genotype as well as their interactions (Yan et al., 2000). The use of a selection index is also an alternative for evaluating and identifying superior genotypes, simultaneously considering different traits of interest (Cruz, Regazzi, & Carneiro, 2012; Silva & Viana, 2012). In this context, this study aimed to select rootstocks which induce desirable characteristics of fruit quality, yield efficiency, size control, adaptability and stability in the 'BRS-Kampai' scion cultivar, grown in subtropical regions with mild winters.

Material and Methods

Location and plant material

The experiment was conducted from 2016 to 2022 in Pato Branco, Paraná, Brazil, at 26°41'S, 56°07'W and an elevation of 764 m above sea level. The soil belongs to the mapping unit Inceptsoil and has a basalt origin and clayey texture. These soils of humid and subhumid regions that have altered horizons, lost bases or iron and aluminium but retain some weatherable minerals. They do not have an illuvial horizon enriched with either silicate clay or with an amorphous mixture of aluminium and organic carbon (Soil Survey Staf, 2022). The region shows a subtropical evergreen forest phase with undulating relief (Bhering et al., 2008, Natural Resources Conservation Service – USDA, Soil Survey Staff, 2022). The climate is classified as Cfa (Köppen Classification), that is, subtropical with an average temperature in the coldest month below 18 °C (mesothermal) and an average temperature in the warmest month above 22 °C, frosts in the winter and rainfall distributed in the year (Alvares et al., 2013), with an annual precipitation ranging from 2,000 to 2,500 mm (Quadros et al., 2019). The historical average is 224 chilling hours below 7.2 °C, still usually used to calculate chill accumulation in peach producing regions and chilling requirement of the peach cultivars (Raseira, Nakasu, & Barbosa, 2014).

The experiment was conducted from 2016 to 2022, but data from only 5 years of evaluation were used: 1 – 2016, 2 – 2017, 3 – 2019, 4 – 2020 and 5 – 2022. Production losses occurred in 2018 and 2021 due to frosts on August 11, 26 and 27, 2018, June 29, 2021, and July 19, 28 and 29, 2021. Minimum temperatures close to -2.0 °C were observed on all these dates, causing significant damage to fruits at the beginning of formation, making it impossible to collect ripe fruits for sampling. The blooming of the cultivar BRS-Kampai at the experimental site usually occurs from the last week of June to mid-July (Scariotto et al., 2013; Penso et al., 2018).

The experiment was conducted in randomised blocks with five replications, with one plant per replication. The treatments (Table 1) consisted of 'BRS-Kampai' peach grafted onto 17 different clonal rootstocks cultivar (all obtained via cutting propagation) of the genus *Prunus* spp. (public domain rootstock cultivars, selections, interspecific hybrids, and species of interest to be tested as rootstock) and own-rooted trees (without rootstock) of the cultivar BRS-Kampai.

Table 1: List of evaluated rootstocks in this study, description, and origin, in Pato Branco-PR, Brazil.

Treatment	Rootstock	Species	Vigour classification	Genetic Background	Origin	Nematodeos Tolerance	Waterlogging or heavy soils Tolerance	References
1	México Fila 1	*P. persica*	Vigorous	Open polinization	México	Unknown	Unknown	
2	Flordaguard	*P. persica*	Vigorous	Controlled cross (F6 - Chico 11 × *P. davidiana*)	University of Florida (USA)	Resistant to *M. javanica* and *M. incognita* races 1 and 3	Suscetible	Sherman, Lyrene and Sharp (1991); Byrne et al. (2012)
3	Tsukuba-3	*P. persica*	Vigorous	Open polinization	Japan	Resistance to *M. incognita* race 2 and *M. javanica*	Tolerant	Rossi et al. (2002); Mayer et al. (2020)
4	I-67-52-4	*P. persica*	Unknown	Open polinization	USA	Unknown	Unknown	
5	Tsukuba-1	*P. persica*	Vigorous	Open polinization	Japan	Resistance to *M. incognita* race 2 and *M. javanica*	Tolorent	Reighard (2002); Rossi et al. (2002); Mayer et al. (2020)
6	Cadaman®	*Wild peach × peach interspecific hybrid (P. davidiana × P. persica)*	Vigorous	Controlled cross	INRA (France/ Hungary)	Resistant to *Meloidogyne incognita*, M. javanica; *M. arenaria* and *M. hispanica*	Moderately tolerant	Edin and Garcin (1994); Reighard and Loreti (2008); Byrne et al. (2012); Mayer et al. (2020); Minas et al. (2023)
7	Okinawa	*P. persica*	Vigorous	Open polinization	IAC (Campinas, Brazil) from Japan	Resistance to *M. incognita (except race 3)* and *M. javanica*; tolerant to *M. floridensis*	Tolerant	Reighard (2002); Mayer et al. (2020)
8	Rigitano	*P. mume*	Semi-vigorous	Open polinization	UNESP Jaboticabal (Brazil)	Resistance to *M. javanica* and *M. incognita*	Unknown	Mayer et al. (2006); Pereira et al. 2007; Mathias et al. (2008).
9	Barrier	*P. persica* x *P. davidiana*	Vigorous	Controlled cross	Italy	Resistant to *M. incognita*, *M. javanica*, *M. arenaria*;	Tolerant	Reighard and Loreti (2008)
10	BRS-Kampai onw-rooted	*P. persica*	Vigorous	Controlled cross (Chimarrita x Flordaprince)	Embrapa (Brazil)	Unknow	Tolerant	Raseira et al. (2010)
11	G x N.9	*P. persica* x *P. dulcis*	Vigorous	Controlled cross	Zaragoza (Spain)	Resistant to *M. javanica* and *M. incognita* race 2	Tolerant	Rossi et al. (2002)
12	Clone 15	*P. mume*	Semi-vigorous	Open polinization	UNESP Jaboticabal (Brazil)	Resistance to *M. javanica* and *M. incognita*	Unknown	Mayer et al. (2006); Pereira et al. 2007; Mathias et al. (2008); Mayer et al. (2020)
13	Ishtara®	*(P. cerasifera x P. salicina) x (P. cerasifera x P. persica)*	Semi-vigorous	Controlled cross	INRA (France)	Resistant to *M. incognita*, *M. arenaria*, *M. hapla, M. hispânica and imune to M. javanica*	Moderately tolerant	Reighard and Loreti (2008); Mayer et al. (2020); Minas et al. (2023)
14	Nemared	*P. persica*	Vigorous	F3 seedlings of ‘Nemaguard’ x a red-leaf seedling	USDA (California, USA)	Resistance to *M. incógnita (except race 3) and M. javanica*	Unknown	Ramming and Tanner (1983); Layne (1987); Mayer et al. (2020)
15	Santa Rosa	*P. salicina*	Not informed	Controlled cross (P. salicina x P. simonii x P. Americana)	USA	Unknown	Tolerant	Faust and Surányi (1999)
16	Capdeboscq	*P. persica*	Vigorous	Open polinization	Embrapa (Brazil)	Unknown	Tolerant	Finardi (1998); Mayer et al. (2020)
17	Genovesa	*P. salicina*	Unknown	Unknown	CPACT, BAG-1, ameixa fila 10	Unknown	Unknown	Sobierajski et al. (2021).
18	Tsukuba-2	*P. persica*	Vigorous	Open polinization	Japan	Resistance to *M. incognita* race 2 and *M. javanica*	Tolerant	Reighard (2002); Rossi et al. (2002); Mayer et al. (2020)

The experimental orchard was set up in 2014, with a spacing of 5.5 x 2.5 m, with the rows oriented according to the contour lines. The trees were grown in a 'Y' system without irrigation, and the cultural practices and phytosanitary management were in accordance to those used in commercial orchards (Freire & Magnani, 2014; Pereira & Raseira, 2014; Reisser Jr. & Simões, 2014).

The trees were managed with two annual pruning events (green and winter pruning), and the fruits were thinned according to the vigour of the shoots at 5 weeks after full blooming (mid-August), with a distance of 8 to 10 cm between fruits on vigorous shoots and 12 to 15 cm on less vigorous ones (Costa & Botton, 2022).

Environmental data

Environmental data were collected from a weather station of the Paraná Environmental Technology and Monitoring System – SIMEPAR. Data included the sum of hours with temperatures ≤ 7.2 °C (Figure 1), the heat accumulation °GDD, considering 4.2 °C as the basal temperature, the average maximum temperature, the average minimum temperature, the average of relative humidity (RH%), and precipitation (mm) were collected for each month during the experiment (Figure 1).

Plant Variables

Vegetative variables - The variable of vegetative growth, canopy volume, was also evaluated. The canopy volume was evaluated in December of the 2016, 2017 and 2020 cycles, measuring, with the aid of a graduated ruler, the upper distance between the main trunks (Y training system), average diameter of the two main trunks, and crown height. These variables were used to calculate the canopy volume (Equation 1) in accordance with what was proposed by Rossi et al. (2004),

$$CV = \frac{\left\{\left[\left(\frac{Dt}{2}\right)\times\left(\frac{Adt}{2}\right)\times 3.1416\right]\times Hc\right\}}{3} \tag{1}$$

In which: CV - canopy volume (m^3); Dt - Maximum distance between main trunks (m); Adt - average diameter of main trunks (m); Hc - Height canopy (m). The yield efficiency (YE) calculation was carried out, dividing the yield per plant (kg of fruit per plant) by the canopy volume (m3), with values expressed in kg m^{-3}.

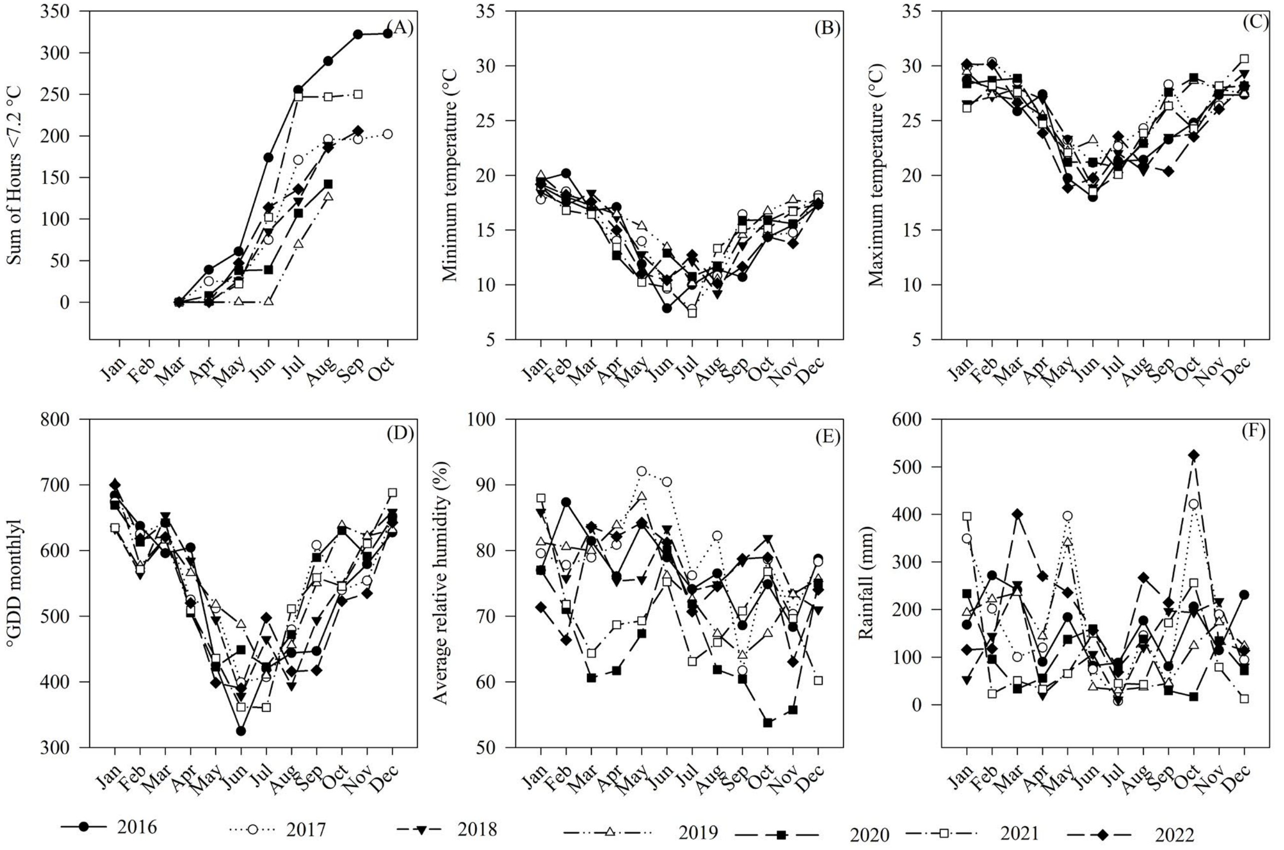

Figure 1: Environmental data from Σ hours with temperatures ≤ 7.2 °C (A), average minimum temperature (B), average maximum temperature (C), growing degree days °GDD (D), average relative humidity (E), and rainfall (F) in the years 2016 to 2022, in Pato Branco-PR, Brazil.

Yield variables - The yield component variables evaluated were yield per tree (kg tree^{-1}), yield per area (kg ha^{-1}) and fruit mass (g). Yield per tree was estimated by multiplying the total number of fruits per tree by the average fruit mass, and yield per area was obtained from the estimated production per tree multiplied by the number of trees in 1 hectare (density of 727 trees ha^{-1}).

Fruit quality variables - Quality whereas the fruit quality variables were fruit suture diameter (mm), fruit firmness (N), soluble solids contend (°Brix) and titratable acidity (mEq of malic acid). Fruit quality variables were measured at the time of fruit maturation, with a sample of 10 ripe fruits per plot. Fruit firmness was assessed individually on two sides of all subsampled fruits, using an automatic texturometer (TA.XT Express®) with a 2 mm tip. After this analysis, all punctured fruits were crushed to extract juice, from which an aliquot was removed for analysis of SS using a digital refractrometer, and the remainder for pH and AT analysis.

Statistical analysis

The data were initially subjected to normality analysis using the Lilliefors test and homogeneity analysis using the Bartlett test. Verification of the rootstock (18) x environment (5 years) interaction was conducted through analysis of variance (ANOVA) using the software Rbio (Bhering &Teodoro, 2021). The analysis of adaptability and stability was carried out using the GGE biplot methodology (Yan, 2000) and employing the same software.

The GGE biplot methodology is based on the model $Ɣ_{ij} - \ddot{y}_j = \gamma_1\varepsilon_{i1}\rho_{j1}+\gamma_2\varepsilon_{i2}\rho_{j2}+\varepsilon_{ij}$, where $Ɣ_{ij}$ represents the mean of the variable for genotype i in year j, $\ddot{Y}_j$ is the overall mean of the variable for genotypes in environment j, $Ɣ_1\varepsilon_{i1}\rho_{j1}$ represents the first principal component (PC1), $Ɣ_2\varepsilon_{i2}\rho_{j2}+\varepsilon_{ij}$ represents the second principal component (PC2), y_1 and y_2 are the eigenvalues associated with PC1 and PC2, ε_{i1} and ε_{i2} are the scores of PC1 and PC2 for genotype I, p_{j1} and ρ_{j2} are the eigenvalues associated with PC1 and PC2 for year j, and e_{ij} is the error ij associated with the model (Yan et al., 2007). Result interpretation was based on the which-won-where comparison of the GGE biplot method, described by Yan and Tinker (2006) and Yan et al. (2007).

One of the ways to observe the adaptation of a genotype to a given environment is through the angle formed between both relative to the origin. The genotype is adapted to the environment when the angle formed between them is less than 90°; in contrast, there is no adaptation of this genotype if the angle formed between them is greater than 90°. This occurs because the graphical representation of the method is the result of analysing the decomposition of the vector product values by the cosine of the angle between two vectors (Yan & Tinker, 2006; Yan et al., 2007). Regarding stability, genotypes that are closer to zero relative to PC2 are more stable. The further away they are from PC2, the more unstable they are.

The prediction of gains by the selection index was based on an ideotype. We sought to select treatments (rootstocks or own-rooted trees) that induced higher yield, fruits with higher weight and diameter, a higher concentration of soluble solids and a higher firmness of the fruit pulp to the canopy cultivar. Estimates of the prediction of gains through selection using the selection index were obtained based on the overall means of the variables from all evaluated cycles. The computational resources of the software Genes were used to carry out the statistical analyses.

The classic index of Mulamba and Mock (1978), which is based on the sum of rankings, that is, it consists of classifying or ordering the studied genotypes relative to the traits in an order favourable to the breeder's interest through the assignment of high absolute values to the best-performing genotypes, was also used. The orders of each genotype referring to each trait are added after obtaining this classification, resulting in an additional measure taken as a selection index. This method can be used by adopting different criteria or "economic weights" arbitrarily assigned to create the index (Cruz, Regazzi, & Carneiro, 2015).

The indices were applied considering three scenarios:

1 – Same economic weight (value = 1) for all variables: yield per area, yield per tree, fruit mass, fruit suture diameter, fruit firmness with skin, soluble solids content and titratable acidity.

2 – Higher economic weight (value = 3) for yield per area, followed by intermediate economic weight (value = 2) for yield per tree and fruit mass and lower economic weight (value = 1) for the variables fruit suture diameter, fruit firmness with skin, soluble solids content and titratable acidity.

3 – Higher economic weight (weight = 3) for yield per area, followed by intermediate economic weight (value = 2) for the variables fruit suture diameter, fruit firmness with skin, soluble solids content, titratable acidity, and lower weight (value = 1) for the variables fruit mass and yield per tree.

An analysis with different weight attribution scenarios was chosen to distinguish different selection objectives (choice), focusing on a global scenario and other scenarios that represented the economic viability of a genotype (yield) relative to fruit quality factors.

Results and Discussion

The Table 2 shows the overall means of the variables evaluated in the 2016, 2017, 2019, 2020 and 2022 growing cycles. These means were used for the adaptability and stability analyses and the selection index.

The variability observed among treatments of the principal components of fruit mass, yield per tree, number of fruits per tree, yield per area and canopy volume (Figures. 1A, B, C, D, and E respectively) was predominantly linked to genetic factors (PC1), that is, the effect of rootstocks, with values above 80%, whereas the environmental variations (PC2) ranged between 6% and 12% (Figure 2). This genetic variability was expected given the great variation and genetic distance among the used rootstocks, most of them with an interspecific origin (Table 1).

Table 2: General averages of the variables yield per tree (YT, kg tree^{-1}), yield per area (YA, t ha^{-1}) fruit mass (FM, g), sutural fruit diameter (SFD, mm), firmness of fruit with skin (FFWS, N), soluble solids content (SSC, °Brix), titratable acidity (TA, meq. Malic Ac.), canopy volume (CV, m^3), and yield efficiency per canopy volume (YE, kg m^{-3}) of peach 'BRS-Kampai' grafted onto 17 different clonal cultivar rootstocks and a 'BRS-Kampai' own-rooted trees, evaluated in the cycles from 2016 to 2022, in Pato Branco-PR, Brazil.

Treatment	Rootstocks and 'BRS-Kampai' own-rooted	YT	YA	FM	SFD	FFWS	SSC	TA	CV*	YE*
		kg tree^{-1}	t ha^{-1}	g	mm	N	°Brix	meq. Malic Ac.	m^3	kg m^{-3}
1	México Fila 1	20.3	14.8	122.2	58.8	83.8	12.0	0.34	4.82	2.38
2	Flordaguard	23.9	17.4	110.0	56.7	79.2	10.9	0.36	5.28	2.44
3	Tsukuba-3	26.1	18.9	110.5	56.1	79.3	10.7	0.34	3.75	3.77
4	I-67-52-4	21.5	15.6	108.2	55.4	77.1	11.5	0.36	3.70	2.96
5	Tsukuba-1	21.1	15.4	112.3	56.8	82.0	11.0	0.37	3.97	2.49
6	Cadaman®	12.9	9.4	88.1	50.8	76.4	11.6	0.37	3.23	2.80
7	Okinawa	23.4	17.0	112.1	57.4	82.7	11.3	0.34	4.09	2.83
8	Rigitano	15.3	11.1	120.8	60.2	82.3	11.5	0.35	3.47	2.19
9	Barrier	18.5	13.4	107.4	56.9	83.5	10.3	0.38	3.47	3.41
10	BRS-Kampai own-rooted	23.4	17.0	126.6	58.3	82.6	11.5	0.36	5.65	2.18
11	G *x* N.9	23.4	16.9	113.9	55.8	80.8	11.4	0.35	5.13	2.26
12	Clone 15	18.9	13.7	119.5	57.2	93.1	11.4	0.38	3.78	2.98
13	Ishtara®	6.1	4.4	71.9	47.3	80.9	12.0	0.36	1.81	2.74
14	Nemared	17.8	12.9	96.4	52.8	78.7	11.3	0.37	4.19	2.22
15	Santa Rosa	9.6	6.9	90.1	52.3	82.6	11.4	0.40	2.74	3.21
16	Capdeboscq	19.2	13.9	119.9	57.6	83.1	11.8	0.36	4.40	1.62
17	Genovesa	8.8	6.4	80.4	49.1	83.3	11.3	0.37	2.34	1.71
18	Tsukuba-2	29.2	21.3	115.9	57.4	81.3	10.7	0.36	3.95	3.03

*The canopy volume and yield efficiency data refer to the average of the 2016, 2017 and 2020 evaluation cycles.

Fruits produced on 'BRS-Kampai' own-rooted trees showed a higher mass, which was also the case for trees grafted onto 'México Fila 1', 'Okinawa', 'Capdeboscq' and 'Clone 15', with a mean fruit mass above 120 g. Fruits grown on trees grafted onto 'Ishtara®', 'Genovesa', 'Cadaman®', 'Santa Rosa' and 'Nemared' had the lowest fruit mass, below 90 g (Figure 2 A and Table 2).

Fruit mass can be strongly impacted by the canopy/rootstock combination as the rootstock regulates the partition of assimilates in the canopy, especially at the beginning of the development of the growing cycle, after dormancy release and the beginning of budbreak. During this time, the leaf area is recomposited, large amounts of reserve are mobilised to meet energy expenditure, and there is a strong competition for assimilates between vegetative and reproductive tissues within the tree.

Rootstocks that have a better capacity to distribute these trophic reserves, whether through better mobilisation or higher storage capacity, tend to have advantages from the resumption of growth until the tree becomes autotrophic (Caruso et al., 1997; Olmstead, Lang, & Lang, 2010; Weibel et al., 2011; Da Silva et al., 2014). This period is characterised by the definition of the number of fruit cells, responsible for determining the potential for the future mass gain of the formed fruits (Caruso et al., 1997).

The fruit mass variable showed stability for most rootstocks, highlighting 'Tsukuba-2', 'Okinawa', 'Flordaguard', 'Tsukuba-3', I-67-52-4 and 'Barrier', with fruit mass stability above 100 g (Figure 2A). The rootstocks 'Nemared', 'Cadaman®' and 'Genovesa' had stability but induced a lower fruit mass, that is, they always had the lowest fruit mass regardless of the environmental conditions at the cultivation site (cultivation cycles). The rootstocks 'Clone 15', 'Capdeboscq' and 'Tsukuba-1' were more unstable regarding fruit mass, although they had a mean fruit mass above 100 g (Figure 2A).

Under the evaluated conditions, the highest stability in terms of fruit mass was obtained by specific rootstocks (*P. persica*), except for 'Barrier' (*P. persica* x *P. davidiana*), with a moderate reduction in vigour as observed for the rootstocks 'Tsukuba-2' and 'Tsukuba-3', indicating a better efficiency in the partition of assimilates, with redirection to more important drains, that is, fruits (Souza et al., 2016). Rootstocks with severe growth limitation with the 'BRS-Kampai' canopy, such as plum trees (*Prunus salicina*) or wild species like *P. davidiana* tend to present increase in restriction in the supply of assimilates to fruit development, which substantially compromises the final fruit mass and, consequently, productivity (Zarrouk et al., 2005).

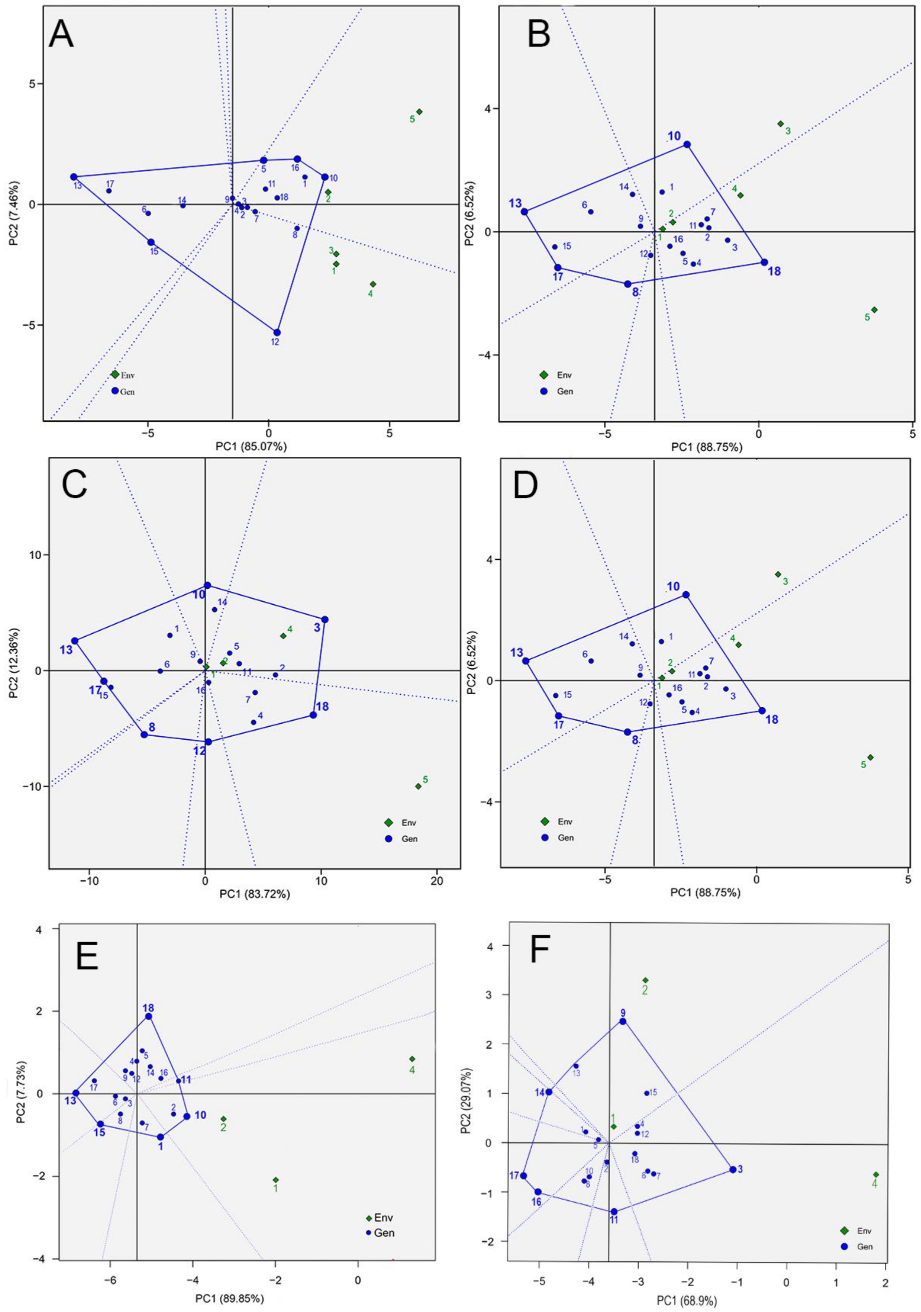

Figure 2: Principal component analysis, GGE Biplot, by the method Which-won-where, of fruit mass variable (A), fruit mass per plant (B), number of fruit (C), yield per area (D), canopy volume (E), and yield efficiency per canopy volume (F) of peach 'BRS-Kampai' grafted onto 17 different clonal cultivar rootstocks and a plants of 'BRS-Kampai' own-rooted trees, in five years of evaluation. Env. (in green) refers to evaluation cycles, in which, 1 – 2016; 2 – 2017; 3 – 2019; 4 – 2020; 5 – 2022. Gen. (in blue) refers to the rootstocks used in which, 1 – México Fila 1; 2 – Flordaguard; 3 – Tsukuba-3; 4 – I-67-52-4; 5 – Tsukuba-1; 6 – Cadaman®; 7 – Okinawa; 8 – Rigitano; 9 – Barrier; 10 – BRS-Kampai own-rooted; 11 – G x N.9; 12 – Clone 15; 13 – Ishtara®; 14 – Nemared; 15 – Santa Rosa; 16 – Capdeboscq; 17 – Genovesa; 18 – Tsukuba-2.

The rootstocks 'Capdeboscq' and 'Clone 15' showed a higher instability in fruit mass. In the first, the factor was related to the greater canopy volume, which tends to increase the number of fruits per tree, and in the latter, this can be explained by a reduction in canopy vigour and, therefore, a decrease in the number of fruits, which can lead to an increase in mean fruit mass. However, the chances of alternate bearing increase in both cases, demanding fruit thinning to regulate production (Manganaris et al., 2022).

The rootstocks 'Tsukuba-2', 'Tsukuba-3', 'Flordaguard' and 'Okinawa' and 'BRS-Kampai' own-rooted trees showed higher yields per tree, with a value higher than 23 kg tree^{-1}. Lower yields per tree were observed in trees grafted onto 'Ishtara®', 'Genovesa', 'Santa Rosa', 'Cadaman®' and 'Rigitano', with less than 15 kg tree^{-1} (Figure 2B and Table 2). This variable showed stability for most rootstocks, highlighting 'Tsukuba-3', 'Flordaguard', 'G x N.9' and 'Okinawa', with yields above 20 kg tree^{-1} (Figure 2B, Table 2). The rootstocks 'Barrier', 'Cadaman®' and 'Santa Rosa' showed stability, albeit with the lowest fruit mass. The 'BRS-Kampai' own-rooted and the rootstocks 'Tsukuba-2', 'Rigitano' and 'Genovesa' had the most unstable yields per tree (Figure 2B and Table 2).

Yield per tree is related to training systems and size control of the rootstock. Trees with high vigour may have higher yields per tree but show restrictions regarding yield per area and a reduced soil use efficiency. Density planar orchard systems with more than 1,000 trees per hectare have been recommended in modern systems, with trees in central-leader, multi-leader or double-axis (Y) training systems since the adopted rootstock induced a minor vigour of the canopy (Iglesias; Echeverria, 2022).

The number of fruits per tree showed a higher variability amongst the evaluated rootstocks (Figure 2C). The rootstocks 'Tsukuba-3', 'Tsukuba-2', 'Flordaguard', 'Okinawa', 'G x N.9' and 'Tsukuba-1' (Figure 2C) stood out for inducing the highest numbers of fruits per tree (Figure 1C), with an above average 220 fruits tree^{-1}. The trees grafted onto 'Ishtara®', 'Genovesa', 'Santa Rosa', 'Rigitano', 'Cadaman®' and 'México Fila 1' (Figure 2C) had, on average, below 96 fruits per tree.

The rootstocks 'Flordaguard', 'G x N.9' and 'Tsukuba-1' had higher stability and a high number of fruits per tree (Figure 2C). The rootstocks 'Cadaman®', 'Barrier' and 'Capdeboscq' showed stability but a low number of fruits per tree (Figure 2C). The rootstocks 'Rigitano' and 'Clone 15' had low stability and a low number of fruits per tree, whereas 'Tsukuba-2', 'Tsukuba-3', 'Nemared' and 'BRS-Kampai' own-rooted showed low stability but a higher number of fruits per tree (Figure 2C).

The rootstocks 'Tsukuba-2', 'Tsukuba-3', 'Flordaguard', 'Okinawa' and 'BRS-Kampai' own-rooted showed the highest productivity, with an average yield above 17 t ha^{-1} (Figure 2D and Table 3). The rootstocks 'Ishtara®', 'Genovesa', 'Santa Rosa', 'Cadaman®' and 'Rigitano' had the lowest productivity, with an average yield less than 12 t ha^{-1} (Figure 2D and Table 2).

The rootstocks 'Tsukuba-3', 'Flordaguard', 'Okinawa' and 'G x N.9' showed stability and higher yields per area, whereas 'Barrier', 'Santa Rosa', 'Cadaman®' and 'Ishtara®' had stability with low yields per area (Figure 2D). The rootstocks 'Mexico Fila 1' and 'I-67-52-4' and the treatment 'BRS-Kampai' own-rooted had less stability but higher productivity (Figure 2D). Furthermore, the rootstocks 'Rigitano', 'Genovesa' and 'Nemared' had low stability and low productivity (Figure 2D).

In the evaluation of canopy volume, showed high vigour, with canopy volume above 5 m^3, the rootstocks 'BRS-Kampai' own-rooted, 'Flordaguard' and G x N.9 (Figure 2E, Table 2). Whith vigour arround 3 m^3 the show the rootstocks 'México Fila 1', 'Capdeboscq', 'Nemared' e 'Okinawa' (Figure 2E, Table 2). Seven rootstocks present a significant reduction in canopy growth, with canopy volumes of around 3 m^3, which are, 'Tsukuba-1', 'Tsukuba-2', Clone 15, 'Tsukuba-3', I-67-52-4, 'Barrier', 'Rigitano' and 'Cadaman®' (Figure 2E, Table 2). With severe growth restriction, with canopy volumes of less than 3 m^3, are the rootstocks 'Santa Rosa, 'Genovesa' and 'Ishtara®' (Figure 2E, Table 2).

Regarding stability in canopy volume, most of the rootstock's present high stability, except rootstocks 'México Fila 1' and 'Tsukuba-2' which presented greater instability (Figure 2E). It stands out that they present high stability, with reduction in crown volume, but with high productivity are the rootstocks 'Tsukuba-1' and 'Tsukuba-3', with canopy volume close to 3 m^3 and yield per tree above 20 kg per tree, unlike other rootstocks such as 'Rigitano' and 'Cadaman®', despite the reduction in canopy volume close to 3 m^3, they did not result in an increase in yield per plant (Figure 2, Table 2). The rootstocks presented low adaptability to environmental conditions in relation to canopy volume 'Santa Rosa, 'Genovesa' and 'Ishtara®' (Figure 2E).

In relation to yield efficiency (Table 3, Figure 2F), it is possible to observe that there is a direct relationship between canopy volume (Table 2, Figure 2E) and fruit production (Table 2, Figure 2C), because rootstocks with high vigor have low productive efficiency, as is the case with rootstocks 'BRS-Kampai' own-rooted, and 'Capdebosc' (Figure 1F; Table 2). With greater yield efficiency are the rootstocks 'Tsukuba-3', 'Barrier', 'Santa Rosa' and 'Tsukuba-2', all with efficiency above 3 kg of fruit per m^3 canopy (Figure 2E). However, of these rootstocks, in the system evaluated with 5.5 x 2.5 m spacing, the rootstocks 'Tsukuba-3' and 'Tsukuba-2' present better performance, which maintain yield efficiency, in addition to high yield per trees, above 20 kg of fruits per plant, in addition to considerably reducing the canopy volume.

Stability and high productivity are some of the most important factors when recommending a cultivar canopy/rootstock combination. Producers always choose canopy/rootstock combinations that have greater yield, stability, and harvest predictability.

The rootstock *P. salicina* or with that species in its genealogy like 'Ishtara®', Genovesa, 'Santa Rosa' and as new selections (De Jong et al., 1994; Oldoni et al., 2019; Reig et al., 2019) has been tested in adverse soil conditions as rootstock for peach (*P. persica*), with the main objective of reducing vigour and changing the dynamics of the water potential of the canopy, aiming to increase water use efficiency and improve nutrient absorption capacity (Nasr, El-Azab, & El-Shurafa, 1977; Basile, Marsal, & De Jong, 2003; Solari, Pernice, & De Jong 2006; Zarrouk et al., 2006). The peach cultivar Suncrest demonstrated satisfactory results, with reduced tree size, without compromising fruit quality and production characteristics when grafted onto *P. salicina* in Ancina, Italy (Giorgi et al., 2005). Our results indicate that *P. salicina* rootstocks or those that have this species in their genealogy (Table 1) perform unsatisfactorily under subtropical conditions and low density of planting, with an excessive reduction in vigour and damages to the other components of yield and fruit quality, in addition to causing tree death.

It is important to highlight that the performance of the combination between *P. persica* as canopy cultivar and *P. salicina* as rootstock tends to be better under temperate climate conditions, given that, in general, *P. salicina* requires medium to high chilling (more than 400 hours ≤ 7.2 °C). Under subtropical climate conditions, where chill accumulation is limited (Figure 1) both in quantity and quality, *P. salicina* as rootstock shows low adaptation, restricting its use (Saini et al., 2020; Santana et al., 2020; Mayer et al., 2021a).

This inferior performance can be observed in all variables analyzed by the GGE Biplot methodology (Figure 2), that the rootstocks 'Cadaman®', 'Ishtara®', 'Santa Rosa' and 'Genovesa' have in their genealogy *P. salicina* or crossing with *P. davidiana* (Tabela 1) does not show adaptability to any of the environments (cycles) observed. It is noteworthy that in cycle 5 (2022), there was the greatest and best distribution of cold between the cycles, with occurrence of cold (temperatures ≤ 7.2 °C and around 10 °C) well distributed between the months of April to July (Figure 1). However, even in this condition, these rootstocks did not show adaptability to this environment.

Similar results were observed for the rootstocks 'Ishtara®', 'Barrier' and 'Cadaman®', which showed low adaptation to subtropical conditions, diverging from the results obtained in regions with a typical temperate climate with cold winters (Orazem, Stampar, & Hudina, 2011). These rootstocks are more efficient when used in areas with colder climates and high planting density systems.

The use of interspecific rootstocks is an important tool for incorporating tolerance to biotic and abiotic soil adversities, a higher efficiency in the absorption and translocation of nutrients and size control (Pinochet et al., 2002; Iglesias & Echeverria, 2022). However, the most important prerequisite is grafting compatibility with the canopy cultivar, and adaptation of plant management systems that allow high planting density (Weibel et al., 2011; Mestre et al., 2015; Anthony & Minas, 2021; Manganaris et al., 2022). In this sense, the use of interspecific rootstocks in peach, when there is a high degree of incompatibility (like *P. persica x P.salicina*), causes a significant reduction in the main yield components and in tree longevity (Mayer et al., 2017, 2021a; Sobierajski et al., 2021).

The interspecific hybrid rootstocks tested in this experiment originated from temperate regions and are indicated as rootstocks of peach cultivars with high chilling requirements (Iglesias et al., 2020). Grafting incompatibility may occur in regions with mild winters and with canopy cultivars with low chilling requirements, when involving botanically more distant genotypes, as the canopy cultivar overcomes dormancy before the rootstock. Thus, the blooming and budburst of the canopy cultivar may not be followed by an adequate supply of water and nutrients due to the dormancy condition of the rootstock, resulting in a low and delayed establishment of the photosynthetic surface, the abortion of flowers and fruits, smaller fruits, and low yields (Young & Werner, 1984; Beckman et al., 1992). Tree death was observed in extreme cases, as occurred with some trees of the rootstocks 'Santa Rosa' and 'Genovesa'.

The evaluated environment presents great variation over the years in terms of cold occurrence, in quantity, quality and duration (Figure 1). Analyzing in this context, it was observed that the environments (cycles) that occurred in 2016 (1), 2017 (2), 2019 (3) and 2020 (4) were the most commonly occurring, with a concentration of cold in the months of June and July, differing considerably from the 2022 cycle (5), in which the cold was satisfactory in quantity, quality and duration, between the months of April to July (Figure 1). With greater adaptability to cycles of greater variation, rootstocks can be considered 'Flordaguard', 'Okinawa', 'BRS-Kampai' own-rooted, G x N.9, and 'Tsukuba-3', both for fruit mass (Figure 2A), fruit mass per plant (Figure 2B), number of fruit (Figure 2C) and yield per area (Figure 2D). With greater adaptability to conditions of better cold distribution in the 2022 cycle (5), for the same variables, with the rootstocks 'Tsukuba-1', 'Tsukuba-2', 'Capedeboscq', and I-67-52-4 (Figure 2).

The same economic weight was proposed for all analysed variables in the first scenario in the ranking analysis using the Mulamba and Mock (1978) selection index, followed by two other scenarios with different economic weights for each of them (Table 3). The best-performing rootstocks 'México Fila 1', 'Okinawa', 'BRS-Kampai' own-rooted, 'Capdeboscq' and 'Tsukuba-2' showed similarity when considering the three scenarios of economic weights (Table 3). Amongst the best-ranked rootstocks, there was a higher variation relative to 'Tsukuba-2'. This rootstock showed excellent performance when considering the main yield components. However, its performance was reduced considering fruit quality variables, as shown in Scenario 3 (Table 3). The opposite occurred with the rootstock 'Rigitano', which presented a worse performance when considering the yield components (Scenario 1), but with an improvement in performance considering fruit quality variables (Table 3).

Table 3: Ranking of rootstocks and 'BRS-Kampai' own-rooted canopy cultivar in different scenarios of economic weights (EW) using the ranking sum selection index – Mulamba and Mock (1978), as a base on production variables yield per tree (kg $tree^{-1}$) (YT), yield per hectare (t ha^{-1}) (YA), fruit mass (g) (FM), Sutural fruit diameter (mm) (SFD), firmness of fruit with skin (FFWS), soluble solids contend (SS) and titratable acidity (TA) evaluated in the 2016-2022 production cycles.

Mulamba and Mock index	Variables						
	YT	YA	FM	FFWS	SFD	SSC	TA
X0	13.8	19.0	107.0	55.4	81.8	11.3	0.4
h2%	78.5	78.5	93.8	85.3	0.0	64.3	39.2
Economic weights per variable (EW)							
Scenarios	YT	YA	FM	FFWS	SFD	SSC	TA
EW - Scenario I	1	1	1	1	1	1	1
EW - Scenario II	3	2	2	1	1	1	1
EW - Scenario III	3	1	1	2	2	2	2

Ranking of rootstocks																		
Scenarios	1°	2°	3°	4°	5°	6°	7°	8°	9°	10°	11°	12°	13°	14°	15°	16°	17°	18°
Scenario I	1	10	7	16	8	18	3	11	12	5	2	4	9	13	14	15	6	17
Scenario II	18	7	10	1	3	11	16	2	8	5	12	4	9	14	6	15	13	17
Scenario III	1	7	10	16	18	8	3	11	12	2	5	4	9	13	14	15	6	17

*X0 – overall average of each variable; h2% coefficient of genetic variation; Genotypes: 1 – México Fila 1; 2 – Flordaguard; 3 – Tsukuba-3; 4 – I-67-52-4; 5 – Tsukuba-1; 6 – Cadaman®; 7 – Okinawa; 8 – Rigitano; 9 – Barrier; 10 – BRS Kampai; 11 – G x N9; 12 – Clone 15; 13 – Ishtara®; 14 – Nemared; 15 – Santa Rosa; 16 – Capdeboscq; 17 – Genovesa; 18 – Tsukuba-2.

Factors linked to yield must be observed when selecting the best rootstock as it is the main component of economic yield. However, it should not be the only factor to be observed as the yield of table fruits also depends on quality factors, which allow consumer satisfaction and facilitate commercialisation (Penso et al., 2018). Therefore, an ideal rootstock must be balanced regarding these factors.

It is important to highlight that trees grafted onto rootstocks that induce size-controlling vigor, such as 'Nemared', 'Rigitano' and 'Barrier', had lower yields per area, considering the planting density of 727 trees ha^{-1}, at a spacing of 5.5 x 2.5 m, and the training system adopted in this experiment. However, these same rootstocks could perform better in high-density orchards with another training system, such as central-leader or multi-leader systems (Anthony & Minas, 2021; Manganaris et al., 2022; Iglesias & Echeverria, 2022).

Rootstocks that induce partial size-controlling tend to present a better partitioning of assimilates amongst tree tissues, with a significant increase in photosynthetic efficiency, resulting from a better distribution of solar radiation throughout the tree canopy; this allows using the high-density orchard with respective gains in productivity per area when combined with changes in the training system (Loreti & Pisani, 1992; Minas et al., 2018; Manganaris et al., 2022; Iglesias & Echeverria, 2022). This can be seen in the rootstock 'Tsukuba-3', that under the evaluated conditions, present high yield (per area and plant), with high growth canopy reduction, which gives it high yield efficiency for the adopted production system, with adaptability and stability to the proposed environmental conditions, in addition to maintaining high fruit quality.

The rootstocks 'Genovesa', 'Cadaman®', 'Santa Rosa', 'Nemared' and 'Ishtara®' showed the lowest performance in all scenarios, with different economic weights (Table 3). There was a coincidence of interspecific rootstocks of plum (*Prunus salicina*) or interspecific hybrids with this species in the genealogy, such as for the rootstock 'Ishtara®' (Table 1).

The rootstocks 'Nemared', 'Ishtara®', 'Cadaman®' and 'Barrier' stand out regarding their use in combinations with peach and nectarine scion cultivars, such as 'Sunraycer' and 'Redhaven', as they adapt to alkaline soil conditions with iron and other soil limitations (Massai & Loreti, 2004; Orazem, Stampar, & Hudina, 2011; Minas et al., 2018; Lesmes-Vesga et al., 2022). However, these rootstocks, induced lower production under the evaluated conditions, where deep, acid, ferric and high-clay soils are predominant. The contrasting climate and soil conditions of the experimental site, combined with the conditions under which these rootstocks have been used, explain their low efficiency and adaptability.

The 'BRS-Kampai' own-rooted showed good yields and fruit quality, without rootstock (Table 3), despite its low stability and yield efficiency. In the general average yield per tree (Figure 1), the 'BRS-Kampai' own-rooted showed a similar performance when the trees were grafted onto the 'Okinawa' rootstock, considered the standard rootstock under the studied conditions and in other production areas in Brazil (Barreto et al., 2017; Shahkoomahally et al., 2020). However, when grafted onto 'Okinawa', this cultivar was considered the most adapted and stable one, as assessed by Scariotto et al. (2013) and Penso et al. (2018) in evaluations of different growing cycles under subtropical conditions.

The option of an own-rooted tree, obtained by cuttings, is usually easier, faster and cheaper compared to other methods, resulting in a reduction in the price of seedlings paid by the horticulturist.

Conclusions

In the studied conditions 'Ishtara®', 'Genovesa', 'Santa Rosa' and 'Cadaman' induced low yield and fruit quality for the 'BRS-Kampai' and showed no potential for use as rootstocks. 'BRS-Kampai' own-rooted or those grafted onto 'Flordaguard' and 'Okinawa' are alternatives for peach cultivation, however they induce high vigour. The clonal rootstocks Tsukuba-3' and 'Tsukuba-2' induced the highest production performance in the canopy cultivar BRS-Kampai, combining fruit quality, yield stability and yield efficiency, making them the most suitable ones among the studied rootstocks.

Author Contribution

Conceptual idea: Mayer, N.A.; Citadin, I.; Methodology design: Penso, G.A.; Santos, C.E.M.; Mayer, N.A.; Citadin, I. Data collection: Rosa, R.C., Pertille, R.H. Data analysis and interpretation: Rosa, R.C., Penso, G.A.; Santos, C.E.M.; Citadin, I. Writing and editing: Penso, G.A.; Citadin, I.; Santos, C.E.M.; Mayer, N.A.

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