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Propagation

Evaluation of multiple rootstocks for ‘Montenegrina’ mandarin in Londrina, Paraná, Brazil

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Abstract- Most commercial orchards of mandarins in Paraná grow ‘Ponkan’ trees predominantly grafted on ‘Rangpur’ lime. The limited genetic diversity of citrus orchards for both scion and rootstock may promote pest and disease outbreaks. The late season ‘Montenegrina’ willowleaf mandarin has high potential for orchard diversification because of its higher productivity and better fruit quality. Therefore, this study assessed the agronomic performance of ‘Montenegrina’ mandarin trees grafted on multiple rootstocks under the edaphoclimatic conditions of Londrina, Paraná, Brazil. The trial was set in a randomized block design using the rootstocks of ‘Rangpur’ lime, ‘Cleopatra’ mandarin, ‘Sunki’ mandarin, ‘Swingle’ citrumelo, and ‘Fepagro C-13’ citrange replicated six times. The ‘Montenegrina’ mandarin trees were assessed for vegetative growth, yield, and fruit quality. The trees had similar size and yield, regardless of the rootstock, and low alternate bearing indices. The fruit quality parameters varied among the rootstocks between the four cropping seasons. Fruits from trees on ‘Rangpur’ and ‘Cleopatra’ exhibited the highest maturation indices, whereas those from ‘Swingle’ and ‘Fepagro C-13’ produced larger fruits with low number of seeds. In general, ‘Montenegrina’ trees can be grown on all evaluated rootstocks without incompatibility and loses in Londrina, Northern Paraná, Brazil.

Index terms: *Citrus deliciosa* Tenore, scion-rootstock combinations, physicochemical quality, tree growth, fruit yield.

Avaliação de múltiplos porta-enxertos para tangerina ‘Montenegrina’ em Londrina Paraná, Brasil

Resumo - A maioria dos pomares comerciais de tangerineiras no Paraná cultiva ‘Ponka’ enxertada predominantemente no limão ‘Cravo’. A estreita diversidade genética dos pomares de citros, tanto para copa quanto para porta-enxerto, pode promover o surgimento de pragas e de doenças. A tangerina ‘Montenegrina’ tem alto potencial para diversificação de pomares, pois é produtiva e tem frutos de boa qualidade. Portanto, este trabalho teve como objetivo avaliar o desempenho agronômico da tangerineira ‘Montenegrina’ enxertada em múltiplos porta-enxertos nas condições edafoclimáticas de Londrina, Paraná, Brasil. O experimento foi realizado em blocos ao acaso, utilizando os porta-enxertos limão ‘Cravo’, tangerina ‘Cleópatra’, tangerina ‘Sunki’, citrumelo ‘Swingle’ e citrange ‘Fepagro C-13’ repetidos seis vezes. A tangerineira ‘Montenegrina’ foi avaliada quanto ao crescimento vegetativo, à produção e à qualidade dos frutos. As plantas obtiveram tamanho e produtividade semelhantes, independentemente do porta-enxerto, e baixos índices de alternância de produção. Diferenças foram observadas entre os porta-enxertos para os parâmetros de qualidade dos frutos, com base em quatro safras. Frutos de plantas sobre o ‘Cravo’ e ‘Cleópatra’ exibiram os maiores índices de maturação, enquanto ‘Swingle’ e ‘Fepagro C-13’ produziram frutos maiores, com baixo número de sementes. Em geral, a tangerineira ‘Montenegrina’ pode ser cultivada sobre todos os porta-enxertos avaliados, sem incompatibilidade e perdas em Londrina, Norte do Paraná, Brasil.

Termos para indexação: *Citrus deliciosa* Tenore, combinações copa-porta-enxerto, qualidade físico-química, crescimento vegetativo, produção de frutos.

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Introduction

Mandarins are the second largest group of Citrus spp. produced worldwide, though nearly three-quarters of the global mandarin production happens in Asia (WON; MIN, 2018; FAO, 2019). China is the largest producer of mandarins, followed by Spain, Turkey, Morocco, Egypt, United States, and Brazil (FAO, 2019). The Brazilian production of mandarins is close to one million tons produced in an area of 49,281 ha (FAO, 2019; IBGE, 2019). The most important mandarin-growing areas in Brazil are in São Paulo, Minas Gerais, Rio Grande do Sul, and Paraná (IBGE, 2019). Among the commercial cultivars of mandarins grown in Paraná, 'Ponkan' (*Citrus reticulata* Blanco) grafted on 'Rangpur' lime (*C. limonia* Osbeck) is the most used scion-rootstock combination (TAZIMA et al., 2014).

The Brazilian citrus industry has been exposed to several diseases caused by fungi, bacterium, and viruses that can affect tree longevity, yield, and fruit quality. Some of these diseases may become epidemic due to the narrow genetic basis of citrus scions and rootstocks (CARVALHO et al., 2019). Therefore, genetic diversification of citrus orchards is important to reduce the risks of insect pests and disease outbreaks (EMMANOUILIDOU; KYRIACOU, 2017; CARVALHO et al., 2019). Rootstocks may play an important role in several characteristics of citrus trees, such as vegetative growth, yield, fruit quality, earliness of harvest, and resistance or tolerance to biotic and abiotic stresses (CASTLE, 2010).

Rangpur' lime (*Citrus limonia* Osbeck) is widely used as rootstock in Brazil (CARVALHO et al., 2019). This rootstock is compatible with almost all citrus cultivars, has adapted to a wide range of soil conditions, and is tolerant to drought and citrus tristeza virus (CTV) (IAPAR, 1992). Trees grafted on 'Rangpur' are precocious and productive, yielding fruits of good quality. However, it is susceptible to citrus blight, citrus sudden death (CSD), and gummosis, caused by the *Phytophthora* spp. (POMPEU JUNIOR; BLUMER, 2014). Several other rootstocks have been assessed for scion cultivars. Trees grafted on 'Cleopatra' mandarin (*C. reshni* Hort. ex Tanaka) and 'Sunki' mandarin (*C. sunki* Hort. ex Tanaka) (SIVIERO et al., 2002) produce fruits of high quality (CASTLE; BALDWIN, 2011). 'Swingle' citrumelo [*C. paradisi* Macf. × *Poncirus trifoliata* (L.) Raf.] also induces good yield to the scion, producing fruits of very good quality (CASTLE et al., 2010). 'Fepagro C-13' citrange [*C. sinensis* (L.) Osb. × *P. trifoliata* (L.) Raf.] is a promising rootstock in Brazil (STENZEL et al., 2005; POMPEU JUNIOR; BLUMER, 2014; BACAR et al., 2017; CARVALHO et al., 2021) and has been used in Southern Brazil due to its cold tolerance (IAPAR, 1992). However, studies assessing 'Montenegrina' (*C. deliciosa* Tenore) performance on multiple rootstocks are scarce (SCHÄFER et al., 2001).

'Montenegrina', a late-season mandarin, originated in South Brazil by spontaneous mutation of the 'Comum' mandarin (OLIVEIRA et al., 2016). This cultivar is a typical willowleaf or Mediterranean mandarin which is very popular in Brazil and is moderately tolerant to citrus canker caused by the bacterium *Xanthomonas citri* subsp. *citri* (PAVAN et al., 2007; OLIVEIRA et al., 2016). Fruits are small to medium in size, seedy, easy to peel, and transport resistant, showing excellent quality with a unique flavor (PANZENHAGEN et al., 1999; PAVAN et al., 2007; KOLLER, 2009; BRACKMANN et al., 2008; ROSA et al., 2012; NEVES et al., 2018). Therefore, this study evaluated the horticultural performance of 'Montenegrina' mandarin trees grafted on multiple rootstocks in Londrina, Paraná, Brazil.

Materials and Methods

Field location and experimental trial

The study was conducted in Londrina, Paraná, Southern Brazil, from 2005 through 2012. The experimental orchard was established in December 2005 at a latitude of 23º21'34'' S, longitude of 51º09'53'' W, and altitude of 585 m, on a red-yellow Latosol soil with clay texture (USDA, 1999). The climate of the region is Cfa-humid subtropical, according to the Köppen classification. The annual minimum and maximum mean temperatures are 16.1 °C and 27.3 °C, respectively (IAPAR, 2021). The annual rainfall is 1,641 mm, which mainly occurs during the spring and summer seasons (Figure 1), and relative humidity is 70.5% (IAPAR, 2021).

The rootstock seedlings were grown from seeds obtained from the Citrus Active Germplasm Bank of the Instituto de Desenvolvimento Rural do Paraná - IAPAR/Emater (IDR - Paraná), which also provided the 'Montenegrina' mandarin budwoods for grafting. The rootstocks included in our trial were 'Rangpur' lime (*C. limonia* Osb.), 'Cleopatra' mandarin (*C. reshni* Hort. ex Tanaka), 'Sunki' mandarin (*C. sunki* Hort. ex Tanaka), 'Swingle' citrumelo [*C. paradisi* Macf. cv. Duncan × *Poncirus trifoliata* (L.) Raf.], and 'Fepagro C-13' citrange [*C. sinensis* (L.) Osb. × *P. trifoliata* (L.) Raf.]. The orchard was established with trees spaced at 7.0 × 4.0 m between and within rows, respectively, comprising 357 trees ha^{-1}. The experimental design included a randomized block with five treatments (rootstocks), six replicates, and two trees per plot.

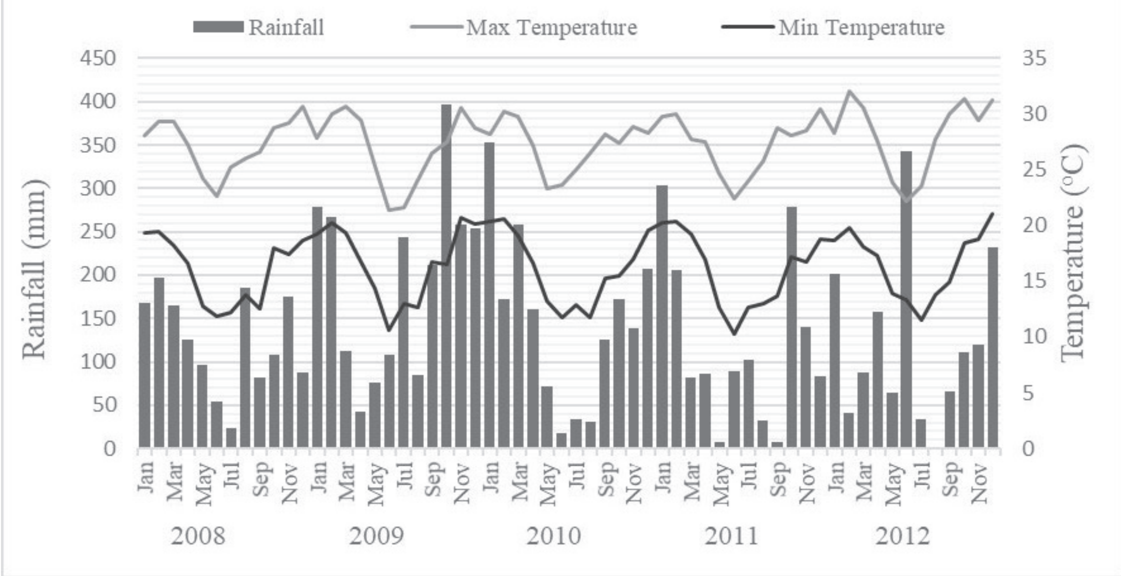

Figure 1. Rainfall and maximum and minimum temperatures from 2008 through 2012 in Londrina, Paraná, Brazil. Source: IDR - Paraná (2021)

Orchard management

The management was based on the recommendations established for Paraná (IAPAR, 1992), which include preventive spraying of copper-based chemicals to control citrus canker (*Xanthomonas citri* subsp. *citri*) and, as needed, insecticide and fungicide applications to prevent insect pests and other diseases. Fertilizers were applied based on soil analyses. Weed control was conducted by periodic mowing on the middle rows and by herbicide application in the rows. Trees were not irrigated. Tree pruning and fruit thinning were not performed.

Tree growth

The vegetative growth was evaluated annually in August from 2007 through 2011, just after harvest. Tree height (TH) and canopy diameter (CD) were measured, and the canopy volume (CV) was calculated according to Mendel (1956).

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

where CV = canopy volume, CR = canopy radius (m), and TH = tree height (m). CV was expressed in m^3.

The trunk circumference of the trees was measured at 10 cm above and 10 cm below the graft union and converted to diameter to determine the trunk diameter. The results were expressed in cm. Trunk ratios were calculated based on trunk diameters above and below the graft union.

Fruit yield

Annual yield was determined in August of each year during the harvest, and the cumulative yield (CY) was established based on five harvests, from 2008 through 2012. Cumulative yield of the trees on 'Rangpur' lime was used as the basis to calculate the relative yield of the 'Montenegrina' mandarin trees grafted on all other rootstocks, as as 'Rangpur' has been the most used rootstock in Brazil for several decades yield efficiency (YE) of the trees was determined based on the ratio between average fruit yield for 2008 through 2011 harvests and CV assessed in 2011. The fluctuation in yield was expressed in terms of alternate bearing index (ABI), following Pearce and Doberšek-Urbanc (1967).

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

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

Fruit quality

Fruit quality was evaluated based on 10 fruit samples per plot, randomly collected from the trees in August from 2008 through 2011, just before harvest. Fruits were immediately packaged in polypropylene bags (25 × 40 cm) and transported to the laboratory for analyses. Fruits were measured (height and diameter) using a digital Vernier caliper (ABS Mitutoyo, Kawasaki, Japan), weighed (FW), and classified according to the standards established for fresh fruits (OECD, 2010; CEAGESP, 2011). The shape of the fruits was also determined based on the ratio between fruit height (FH) and fruit diameter (FD). Number of seeds (NS) was also obtained by counting. Fruit samples were juiced using a Croydon extractor (Croydon, Duque de Caxias, Brazil). The juice content (JC) was determined according to the following equation:

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

where JC = juice content, JW = juice weight (g), and FW = fruit weight (g). JC was expressed in %.

Total soluble solid (TSS) content was determined in a digital refractometer (Atago Co., Ltd, Tokyo, Japan) using 0.3 mL of undiluted juice, and the values were corrected to 20 °C and expressed in °Brix. Titratable acidity (TA) was determined using 25 mL of juice and 0.1 N NaOH in the automatic titrator TitroLine easy (Schott Instruments GmbH, Mainz, Germany), and expressed in percentage of citric acid (AOAC, 2010). The ratio between TSSs and TA was calculated (TSS TA^{-1}) in order to determine fruit maturation index. Additionally, the technological index (TI) was calculated according to Di Giorgi et al. (1990).

$$TI = \frac{TSS \times JC \times 40.8}{10000}$$

where TI = technological index, TSS = total soluble solids (°Brix), and JC = juice content (%).

Statistical Analysis

The data were tested for normal distribution and homogeneity at $p \leq 0.05$, and then submitted to analysis of variance (ANOVA) followed by the comparison of means using Tukey's post-hoc test at $p \leq 0.05$. All data were assessed in a randomized block design and complemented with a factorial arrangement (five treatments × four crop seasons) for the fruit quality parameters. The statistical analyses were conducted in *R* version 3.4.1 (The R Foundation for Statistical Computing, Vienna, Austria) using the ExpDes package (Husson et al., 2017).

Results and Discussion

Tree growth

Differences among six-year-old 'Montenegrina' trees grafted on different rootstocks were observed for trunk diameter above (TDA) and below (TDB) the graft union as well as for trunk index (Table 1). In contrast, no differences were observed among such trees for height (TH), canopy diameter (CD), and volume (CV). TH ranged from as low as 2.13 m for the ones grafted on 'Fepagro C-13' to 2.28 m for the ones on 'Rangpur', while CD fluctuated from 2.98 m for trees on 'Rangpur' to 3.09 m for those grafted on 'Cleopatra'. The CV of all mandarin trees was larger than 10 m^3, independent of the rootstocks.

Table 1. Growth of six-year-old 'Montenegrina' mandarin trees grafted on different rootstocks in Londrina, Paraná, Brazil (mean value ± standard deviation).

Rootstock	Tree height TH (m)	Canopy diameter CD (m)	Canopy volume CV (m^3)	Trunk diameter above graft union TDA[1] (cm)	Trunk diameter bellow graft union TDB[1] (cm)	Trunk index TI (TDA TDB^{-1})
'Rangpur' lime	2.28 ± 0.22 a[2]	2.98 ± 0.43 a	11.0 ± 3.46 a	8.30 ± 0.58 a	11.41 ± 1.42 b	0.73 ± 0.06 a
'Cleopatra' mandarin	2.27 ± 0.14 a	3.09 ± 0.35 a	11.6 ± 2.87 a	7.74 ± 0.42 ab	11.30 ± 0.62 b	0.70 ± 0.04 a
'Sunki' mandarin	2.21 ± 0.23 a	3.03 ± 0.18 a	10.7 ± 1.85 a	8.06 ± 0.29 ab	11.30 ± 0.74 b	0.72 ± 0.03 a
'Swingle' citrumelo	2.26 ± 0.23 a	3.02 ± 0.46 a	11.3 ± 3.90 a	7.21 ± 0.38 b	13.90 ± 1.11 a	0.52 ± 0.02 b
'Fepagro C-13' citrange	2.13 ± 0.10 a	3.00 ± 0.17 a	10.1 ± 1.54 a	7.77 ± 0.74 ab	13.40 ± 1.01 a	0.58 ± 0.06 b
CV (%)	6.76	10.03	21.22	6.73	7.80	7.85
F-value	1.08 ns	0.11 ns	0.35 ns	3.60*	10.73***	19.70***

[1]Trunk diameter was calculated based on trunk circumference measurements 10 cm above and 10 cm below the graft union;
[2]Means followed by the same letter in the column did not differ significantly according to the Tukey's test ($p \leq 0.05$);
Significance levels: ns, non-significant; *, $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$.

Though there were no differences among rootstocks for TH measurements at six years of age, the initial growth of the ‘Montenegrina’ mandarin were faster for trees grafted on ‘Cleopatra’ and ‘Sunki’ than those on all other rootstocks based on the first five years of tree development (Figure 2). Trees grafted on these two rootstocks had an average height of 2.00 m at four years and did not show differences in CV. On the other hand, trees had slow growth when grafted on ‘Swingle’ an ‘Fepagro C-13’ and scored the lowest trunk indices (<0.6), significantly different ($p \leq 0.05$) from trees grafted on all other rootstocks.

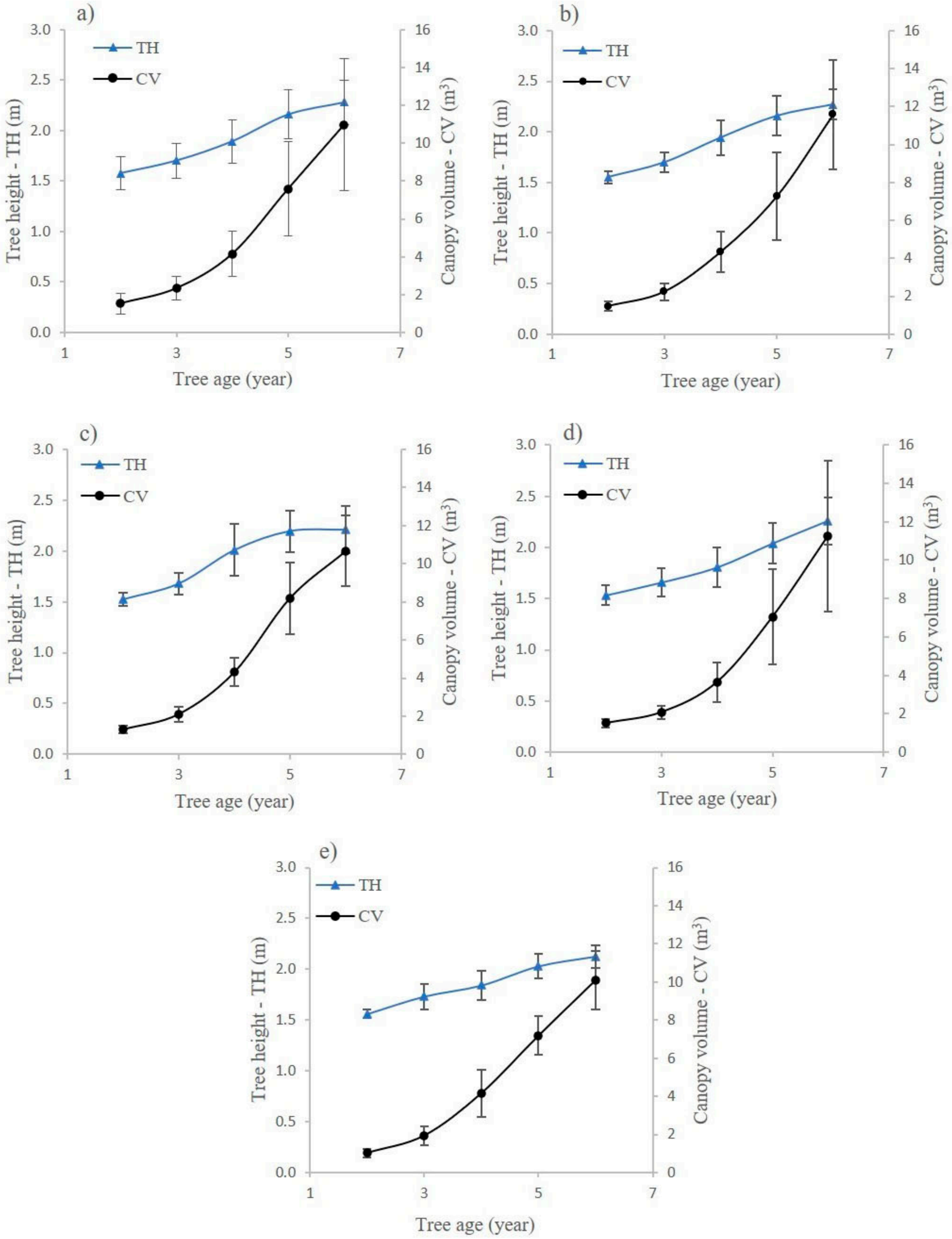

Figure 2. Height (TH) and canopy volume (CV) development of ‘Montenegrina’ mandarin trees grafted on ‘Rangpur’ lime (a), ‘Cleopatra’ mandarin (b), ‘Sunki’ mandarin (c), ‘Swingle’ citrumelo (d), and ‘Fepagro C-13’ citrange (e) in Londrina, Paraná, Brazil.

The growth of six-year-old 'Montenegrina' mandarin trees assessed here aligned with those reported for the same scion in another trial with eight-year-old trees grafted on three different rootstocks in Southern Brazil (SCHÄFER et al., 2001). This scion, grafted on 'Swingle' citrumelo and 'Troyer' citrange, was larger (2.65 and 2.61 m respectively) than trees on 'Trifoliate' orange, which were only 2.29 m in height. It is worth mentioning that these authors did not observe differences in CV among the rootstocks, and the volumes ranged between 11 and 14 m^3. Other studies conducted in Brazil for different mandarin cultivars, such as those for 'Span Americana', 'Fallglo', 'Sunburst', 'Fairchild', and 'Swatow' mandarins have shown similar results (MOURÃO FILHO et al., 2007; ESPINOZA-NÚÑEZ et al., 2008; STUCHI et al., 2008; SILVA et al., 2013).

The trunk indices recorded for 'Swingle' and 'Fepagro C-13' were low as the trunk diameter of these rootstocks was larger than the scion. This parameter may indicate the degree of scion and rootstock compatibility. According to Bassal (2009), trunk indices close to 1 indicate high level of compatibility between scion and rootstock. We observed indices larger than 0.7 for trunks of trees grafted on 'Rangpur', 'Cleopatra', and 'Sunki', indicating good compatibility between scion and rootstock. The cross-sectional area of the trunk above the graft union (41 cm^2) was 73% smaller than the area below the graft union (153 cm^2) in trees grafted on 'Swingle' citrumelo, indicating an overgrowth. However, the 'Montenegrina' trees grafted on all evaluated rootstocks did not show any symptom of incompatibility or a decline effect six years after planting. The cross-sectional area of the scion trunk in trees grafted on 'Swingle' (59 cm^2) resembled that of the same scion of eight-year-old trees (SCHÄFER et al., 2001). Large differences between the trunk section area above and below the graft union were also reported for other mandarin scions grafted on 'Swingle', which resulted in low trunk indices. This rootstock induced trunk index of 0.65 for the 'Nova' tangelo (GEORGIOU, 2000), similar to the ones for the 'Clementine' (0.63) and 'Oktisu' satsuma mandarins (0.69) (GEORGIOU, 2002; TAZIMA et al., 2013).

Fruit yield

Differences in fruit yield were observed in the first two harvests when trees were three and four years old (Table 2). Trees grafted on 'Rangpur' and 'Swingle' had the highest fruit yields than those on all other rootstocks in the first harvest, indicating precocity of fruit production. However, trees on 'Rangpur' showed the lowest fruit yield in the second harvest, differing from those on 'Swingle' that ranked the highest fruit yield in this season at 63 kg $tree^{-1}$. 'Rangpur' and 'Swingle' have also induced early fruiting for many other mandarin cultivars grown in different citrus-growing areas and conditions, such as 'Clementine' (GEORGIOU, 2002), 'Fallglo', 'Sunburst' (MOURÃO FILHO et al., 2007), 'Fairchild' (ESPINOZA-NÚÑEZ et al., 2008), 'Swatow' (STUCHI et al., 2008), and 'Span Americana' (SILVA et al., 2013). From 2010 through 2012, we did not observe differences in fruit yield among the 'Montenegrina' trees grafted on multiple rootstocks. These yields were close to those obtained by Gonzatto et al. (2016) for nineteen-year-old 'Montenegrina' mandarin trees grafted on 'Trifoliate' orange, in which the yield ranged from 36 to 68 kg $tree^{-1}$ for trees with variable fruit thinning. On the other hand, lower yields were observed in another trial for the same scion-rootstock combination (PANZENHAGEN et al., 1999).

Table 2. Fruit yield of 'Montenegrina' mandarin trees grafted on different rootstocks in Londrina, Paraná, Brazil (mean value ± standard deviation).

Rootstock	Fruit yield (kg tree^{-1})					Cumulative yield (2008–12) CY (kg tree^{-1})	Yield efficiency (2008–11) YE[1] (kg m^{-3})	Alternate bearing index ABI
	2008	2009	2010	2011	2012			
'Rangpur' lime	23.2 ± 3.45 a[2]	29.5 ± 5.08 b	67.4 ± 14.0 a	24.8 ± 3.82 a	37.3 ± 4.93 a	182.3 ± 35.9 a		0.31 ± 0.09 a
'Cleopatra' mandarin	17.6 ± 3.02 ab	33.6 ± 8.49 ab	55.7 ± 12.4 a	28.5 ± 8.39 a	28.8 ± 7.40 a	164.2 ± 38.5 a	3.05 ± 0.62 a	0.22 ± 0.06 a
'Sunki' mandarin	17.9 ± 3.99 ab	39.8 ± 8.38 ab	41.6 ± 13.1 a	24.1 ± 6.18 a	29.3 ± 9.57 a	152.6 ± 38.0 a	2.94 ± 0.60 a	0.27 ± 0.12 a
'Swingle' citrumelo	24.4 ± 5.33 a	62.6 ± 12.1 a	39.8 ± 13.4 a	34.2 ± 11.6 a	28.1 ± 9.07 a	189.1 ± 37.4 a	4.06 ± 0.56 a	0.32 ± 0.09 a
'Fepagro C-13' citrange	14.2 ± 5.91 b	49.1 ± 9.3 ab	62.2 ± 4.59 a	38.8 ± 7.51 a	29.2 ± 8.10 a	193.5 ± 35.3 a	4.13 ± 0.81 a	0.32 ± 0.06 a
CV (%)	24.47	39.63	33.93	39.25	31.77	14.15	15.89	34.26
F-value	4.73**	3.64*	2.76 ns	1.71 ns	0.93 ns	2.89 ns	1.37 ns	1.02 ns

[1]YE was based on the average yield from 2008 through 2011 and the CV assessed in 2011.
[2]Means followed by the same letter in the column did not differ significantly according to the Tukey's test ($p \leq 0.05$);
Significance levels: ns, non-significant; *, $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$.

The cumulative yields across five consecutive harvests ranged from 153 kg tree^{-1} for trees grafted on 'Cleopatra' mandarin to 194 kg tree^{-1} for those on 'Fepagro C-13' citrange (Table 2). In general, trees grafted on 'Swingle' and 'Fepagro C-13' were more productive. In contrast, 'Cleopatra' and 'Sunki' induced the lowest yields to 'Montenegrina' across five harvests. The cumulative yields of 'Montenegrina' were higher than those reported by Schäfer et al. (2001) for three to eight-year-old trees grafted on 'Troyer' citrange, 'Trifoliate' orange, and 'Swingle' citrumelo. Three to nine-year-old 'Fallglo' and 'Fairchild' mandarin trees (MOURÃO FILHO et al., 2007; ESPINOZA-NÚÑEZ et al., 2008) had cumulative yields similar to the ones recorded in this study for 'Montenegrina' mandarin after seven harvests. These yields are higher than those for 'Sunburst' mandarin trees grafted on 'Cleopatra', 'Swingle', and 'Rangpur' after seven harvests (MOURÃO FILHO et al., 2007).

'Swingle' and 'Fepagro C-13' provided the highest YE to the scion, confirming their potential as rootstock for 'Montenegrina' as observed for other citrus scions (STENZEL et al., 2003; BACAR et al., 2017; CRUZ et al., 2019; CARVALHO et al., 2021). The alternate bearing of 'Montenegrina' mandarin was not influenced by the rootstocks during the early years of fruit yield (Table 2). These indices were between 0.22 and 0.32, similar to those reported in previous studies for other mandarin cultivars (STENZEL et al., 2003; MOURÃO FILHO et al., 2007; ESPINOZA-NÚÑEZ et al., 2008).

Fruit quality

All measured parameters showed a significant interaction between rootstock and season (Table 3 and 4). Fruits produced by trees on 'Fepagro C-13' and 'Swingle' had the same height and diameter across the evaluated period (Table 3). On the other hand, a variation in size was observed in fruits from 'Rangpur', 'Cleopatra', and 'Sunki'. These rootstocks produced larger fruits in the first two cropping seasons, after which the fruits decreased in size. The lowest number of fruits produced in the early years of yield may have promoted larger fruit sizes (Table 2 and 3). However, regardless of the rootstock and cropping season, 'Montenegrina' fruits showed a commercially acceptable size (OECD, 2010; CEAGESP, 2011). Fruit height and diameter ratios of fruits were below 0.90 for those produced in trees on 'Rangpur' and 'Cleopatra' and became moderately oblate (Table 3). In general, fruits produced in all scion-rootstock combinations were round in shape, similar to 'Okitsu' satsuma (TAZIMA et al., 2013), 'Michal', 'Tami', and 'Fairchild' (GOLDENBERG et al., 2014). These mandarins exhibited shape index larger than 0.84, as was also observed for fruits of 'Montenegrina' on some rootstocks. However, other mandarins, such as 'Sigal' and 'Yusuf-Efendi', were rather oblate in shape and showed a shape index of approximately 0.65, indicating that mandarins may vary in shape (GOLDENBERG et al., 2014, 2018).

Table 3. Physical quality of fruits from ‘Montenegrina’ mandarin trees grafted on different rootstocks in Londrina, Paraná, Brazil (mean value ± standard deviation).

Source of variance	Fruit height FH (mm)				Fruit diameter FD (mm)			
Rootstock	2008	2009	2010	2011	2008	2009	2010	2011
‘Rangpur’ lime	58 ± 0.80 abAB[1]	61 ± 2.65 abA	54 ± 3.10 abC	55 ± 1.57 acBC	66 ± 2.58 aAB	69 ± 1.40 aA	63 ± 1.27 aBC	62 ± 1.89 abC
‘Cleopatra’ mandarin	59 ± 2.65 abA	60 ± 1.66 bA	51 ± 3.11 bcB	52 ± 1.08 cB	66 ± 1.32 aA	69 ± 1.91 aA	60 ± 1.90 bcB	60 ± 1.69 abB
‘Sunki’ mandarin	62 ± 2.16 aA	65 ± 2.29 aA	49 ± 1.39 cC	54 ± 1.70 bcB	65 ± 3.65 aB	71 ± 1.89 aA	58 ± 2.06 cC	59 ± 2.37 bC
‘Swingle’ citrumelo	57 ± 2.73 bA	58 ± 2.28 bA	56 ± 1.71 aA	57 ± 1.75 abA	64 ± 2.73 aA	63 ± 1.28 bA	61 ± 1.71 abA	63 ± 1.75 aA
‘Fepagro C-13’ citrange	61 ± 2.31 abA	59 ± 2.46 bAB	57 ± 3.57 aB	58 ± 2.02 aAB	66 ± 2.40 aA	65 ± 1.09 bA	61 ± 2.00 abB	61 ± 2.18 abB
CV (%)	4.03				3.22			
Block	0.61 ns				0.94 ns			
Rootstocks	6.69***				5.79***			
Year	61.94***				73.76***			
Rootstock × Year	8.09***				6.70***			
	Fruit shape index FSI (FH FD^{-1})				Fruit weight FW (g)			
	2008	2009	2010	2011	2008	2009	2010	2011
‘Rangpur’ lime	0.88 ± 0.03 bA	0.89 ± 0.03 abA	0.85 ± 0.03 bA	0.88 ± 0.01 bcA	133 ± 5.13 abB	145 ± 4.17 bA	118 ± 7.11 aC	121 ± 8.26 aC
‘Cleopatra’ mandarin	0.89 ± 0.03 abA	0.86 ± 0.03 bA	0.85 ± 0.02 bA	0.86 ± 0.02 cA	133 ± 7.31 abA	140 ± 7.39 bcA	106 ± 7.21 bB	108 ± 6.82 bB
‘Sunki’ mandarin	0.93 ± 0.02 aA	0.91 ± 0.03 abA	0.84 ± 0.03 bB	0.91 ± 0.01 abA	127 ± 5.40 bB	163 ± 9.46 aA	95 ± 8.25 bD	108 ± 7.40 bC
‘Swingle’ citrumelo	0.91 ± 0.01 abA	0.92 ± 0.02 aA	0.91 ± 0.04 aA	0.90 ± 0.02 abA	129 ± 6.15 abA	126 ± 2.70 cA	120 ± 6.47 aA	124 ± 8.18 aA
‘Fepagro C-13’ citrange	0.92 ± 0.03 abA	0.88 ± 0.01 abB	0.94 ± 0.04 aA	0.95 ± 0.03 aA	139 ± 7.69 aA	129 ± 7.93 cdAB	122 ± 6.94 aBC	117 ± 7.08 abC
CV (%)	3.39				5.67			
Block	0.75 ns				1.60 ns			
Rootstocks	13.75***				3.85**			
Year	4.83**				108.20***			
Rootstock × Year	3.42***				15.93***			
	Number of seeds NS				Juice content JC (%)			
	2008	2009	2010	2011	2008	2009	2010	2011
‘Rangpur’ lime	11 ± 0.86 aA	7 ± 0.65 cB	11 ± 0.77 aA	5 ± 1.20 abC	41 ± 1.48 bC	33 ± 2.51 bD	51 ± 0.87 aA	45 ±1.98 aB
‘Cleopatra’ mandarin	11 ± 0.92 aA	9 ± 1.91 aA	10 ± 1.08 abA	5 ± 1.24 abB	43 ± 0.94 aC	33 ± 2.25 bD	53 ± 1.13 aA	46 ± 1.43 aB
‘Sunki’ mandarin	8 ± 0.97 bB	7 ± 0.62 bcB	12 ± 0.63 aA	3 ± 1.30 bC	43 ± 1.83 aB	31 ± 1.50 bC	53 ± 1.21 aA	45 ± 1.86 aB
‘Swingle’ citrumelo	10 ± 1.73 abA	8 ± 0.85 acBC	9 ± 1.68 bAB	6 ± 1.17 aC	43 ± 0.98 aC	46 ± 1.20 aAB	47 ± 1.87 bA	44 ± 0.67 aBC
‘Fepagro C-13’ citrange	9 ± 1.43 abA	9 ± 1.18 abA	5 ± 1.29 cB	4 ± 1.12 abB	41 ± 1.62 bB	36 ± 1.57 bC	47 ± 0.70 bA	41 ± 1.88 aB
CV (%)	14.28				3.51			
Block	2.07 ns				2.28 ns			
Rootstocks	9.67***				23.33***			
Year	122.86***				46.72***			
Rootstock × Year	12.72***				37.56***			

[1]Means followed by the same letter, lowercase in the column and capital case in the row, did not significantly differ according to Tukey’s test ($p \leq 0.05$); Significance levels: ns, non-significant; *, $p \leq 0.05$;

** $p \leq 0.01$; *** $p \leq 0.001$.

Table 4. Chemical quality of the ‘Montenegrina’ mandarin fruits from trees grafted on different rootstocks in Londrina, Paraná, Brazil (mean value ± standard deviation).

Source of variance	Total soluble solids TSS (°Brix)				Titratable acidity TA (g 100 mL^{-1})			
Rootstock	2008	2009	2010	2011	2008	2009	2010	2011
‘Rangpur’ lime	9.5 ± 0.48 aC[1]	10.0 ± 0.36 cBC	11.3 ± 0.41 abA	10.3 ± 0.54 aB	0.80 ± 0.05 bC	0.83 ± 0.05 bC	0.98 ± 0.09 aA	0.92 ± 0.07 bAB
‘Cleopatra’ mandarin	9.6 ± 0.22 aB	11.3 ± 0.33 aA	11.5 ± 0.50 abA	10.1 ± 0.55 aB	0.91 ± 0.09 abAB	0.88 ± 0.08 abB	1.03 ± 0.08 aA	0.87 ± 0.03 bB
‘Sunki’ mandarin	9.6 ± 0.12 aC	10.5 ± 0.37 bcB	11.6 ± 0.60 aA	10.1 ± 0.15 aBC	0.93 ± 0.07 aB	0.82 ± 0.06 bB	1.10 ± 0.16 aA	1.13 ± 0.04 aA
‘Swingle’ citrumelo	10.0 ± 0.35 aB	10.1 ± 0.15 cAB	10.5 ± 0.57 cAB	10.7 ± 0.28 aA	1.01 ± 0.03 aA	0.97 ± 0.03 aA	1.02 ± 0.07 aA	1.08 ± 0.08 aA
‘Fepagro C-13’ citrange	9.9 ± 0.17 aB	10.9 ± 0.43 abA	10.8 ± 0.48 bcA	10.5 ± 0.31 aAB	1.02 ± 0.06 aAB	0.98 ± 0.07 aB	1.01 ± 0.05 aB	1.13 ± 0.09 aA
CV (%)	1.94				8.26			
Block	0.58 ns				0.16 ns			
Rootstocks	2.87*				17.0***			
Year	60.58***				20.98***			
Rootstock × Year	6.40***				4.40***			
	Ratio (TSS TA^{-1})				Technological index TI (kg TSS box^{-1})			
	2008	2009	2010	2011	2008	2009	2010	2011
‘Rangpur’ lime	12.1 ± 1.09 aA	12.1 ± 0.65 abA	11.3 ± 0.74 aA	11.2 ± 0.86 aA	1.58 ± 0.12 bC	1.34 ± 0.08 cD	2.37 ± 0.09 aA	1.90 ± 0.16 aB
‘Cleopatra’ mandarin	10.6 ± 0.96 bB	12.5 ± 1.00 abA	11.1 ± 0.57 aB	11.5 ± 0.54 aAB	1.70 ± 0.07 abC	1.54 ± 0.11 bD	2.48 ± 0.11 aA	1.88 ± 0.08 aB
‘Sunki’ mandarin	10.4 ± 0.78 bB	13.0 ± 0.73 aA	10.3 ± 0.70 aB	9.0 ± 0.50 bC	1.70 ± 0.07 abC	1.33 ± 0.07 cD	2.52 ± 0.15 aA	1.86 ± 0.10 aB
‘Swingle’ citrumelo	9.9 ± 0.33 bA	10.6 ± 0.27 cA	10.2 ± 0.42 aA	10.0 ± 0.58 bA	1.78 ± 0.06 aB	1.90 ± 0.06 aAB	2.01 ± 0.18 bA	1.91 ± 0.05 aAB
‘Fepagro C-13’ citrange	9.7 ± 0.61 bB	11.4 ± 0.41 bcA	10.8 ± 0.86 aA	9.3 ± 0.73 bB	1.64 ± 0.08 abBC	1.60 ± 0.08 bC	2.05 ± 0.09 bA	1.76 ± 0.12 aB
CV (%)	3.30				2.88			
Block	0.29 ns				1.38 ns			
Rootstocks	21.46***				8.01***			
Year	33.06***				27.07***			
Rootstock × Year	5.67***				18.85***			

[1]Means followed by the same letter, lowercase in the column and capital case in the row, did not significantly differ according to Tukey’s test ($p \leq 0.05$);
Significance levels: ns, non-significant; *, $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$.

Similar to fruit size, FW varied between the first two seasons when values ranged from 126 g for fruits produced in 'Swingle' to 163 g for the ones in 'Cleopatra' (Table 3). In contrast, FW varied from 95 to 124 g in the following seasons, when trees grafted on 'Sunki' and 'Cleopatra' produced the smallest fruits. However, fruits produced in trees grafted on all evaluated rootstocks were heavier than those reported in another study under different levels of thinning and pruning (ROSA et al., 2012). Nevertheless, 'Montenegrina' fruits had acceptable commercial weight without thinning and pruning (OLIVEIRA et al., 2016). This is very important for saving the production cost. These findings agree with those observed by Tazima et al. (2013, 2014) for fruit quality of 'Oktisu' satsuma mandarin grafted on nine rootstocks at two locations in the Northern region of Paraná, Brazil. These authors reported adequate FW in both experiments, similar to the study of Fallahi and Rodney (1992) on fruits of 'Fairchild' mandarin trees grafted on six rootstocks, and that of Pacheco et al. (2017) on fruits of 'Fremont' mandarin trees grafted on 'Rangpur' lime.

Another important aspect considered by the consumers is the number of seeds in mandarin fruits. Seedless fruits or fruits with low number of seeds are preferred during purchase. The number of seeds ranged from three to twelve seeds per fruit (Table 3). 'Fepagro C-13' imparted the lowest number of seeds across the evaluated period. These findings were confirmed by Oliveira et al. (2016), who observed an average of eight seeds per fruit in trees grown on 'Trifoliate' orange.

The juice content in fruits was affected by both cropping season and rootstock (Table 3). This qualitative parameter was above the minimal standards of the OECD (2010) and CEAGESP (2011) for mandarins in almost all cropping seasons, which are 33% and 35% respectively. It should be noted that fruits from 'Rangpur', 'Cleopatra', and 'Sunki' had juice contents below these standards only in 2009. Climatic conditions may have affected the juice content of 'Montenegrina' mandarin fruits from this cropping season (Figure 1). In general, the juice contents of the fruits from trees grafted on all rootstocks were close to those reported for the same cultivars in another trial (OLIVEIRA et al., 2016).

Although physical characteristics may play an important role in consumer decision, chemical parameters such as TSS, TA, and the TSS TA^{-1} ratio are important determinants in establishing fruit maturity. Non-climacteric fruits, including citrus, display a progressive reduction in the respiration rate during maturation while the ethylene production remains at basal levels (CAO et al., 2019). Thus, citrus must be harvested at an appropriate maturity stage when the active biochemical reactions are at their peaks (LADANIYA, 2008; ROKAYA et al., 2016; ALFEREZ et al., 2021).

The TSS content in juice varied among the tested factors (Table 4). The TSS contents reported in the first season were 9.5 and 10.0 °Brix for 'Rangpur' and 'Swingle', respectively. In the following seasons, almost all fruit samples had TSS content above 10.0 °Brix. The lowest TSS measured at the first year of fruit yield (2008) may be related to the tree age, as TSS contents are generally lower in fruits of young trees (BOWMAN et al., 2016). However, the sugar contents were adequate when compared to the CEAGESP (2011) standards of 9.0 °Brix. These results are consistent with those reported in other studies assessing the same scion grafted on 'Trifoliate' orange (ROSA et al., 2012; OLIVEIRA et al., 2016).

Similarly, the citric acid contents were within the amount reported for this scion in previous studies (BRACKMANN et al., 2008; OLIVEIRA et al., 2016). The percentage of citric acid ranged from 0.80% to 1.13%, depending on the cropping season and rootstock (Table 4). The lowest TA was recorded in fruits produced by 'Rangpur'. The acidity range recorded in the 'Montenegrina' fruit was appropriate and acceptable for fresh consumption (OECD, 2010). Acidity levels are also important for the processing industry (LADANIYA, 2008), as acidity ~1.0% provides flexibility to meet each specific consumer need and may prevent juice decay by microorganisms.

The brix-acidity ratio (TSS TA^{-1}) exceeded the baseline value of 8.5 established for fresh mandarin (Table 4; CEAGESP, 2011). Moreover, these ratios (9.0–13.0) were higher than those reported by Rosa et al. (2012) in Southern Paraná for this cultivar. This parameter can be affected by environmental conditions, as differences in the daily thermal amplitude usually result in a fluctuation of fruit acidity (ROSA et al., 2012). Similar brix-acidity ratios have been reported for other mandarin cultivars such as 'Fairchild' and 'Okitsu' satsuma (ESPINOZA-NÚÑEZ et al., 2008; CANTUARIAS-AVILÉS et al., 2010; TAZIMA et al., 2014).

The TIs, which indicate the amount of TSS in a box of 40.8 kg, were variable (Table 4). Fruits produced in all scion-rootstock combinations had low TIs in the first two harvest seasons when trees were three to four years old, as they also had low values for TSS and juice contents (Tables 3 and 4). On the other hand, fruits produced in the last two harvests had high TIs, which were up to 2.5 for those from 'Sunki' mandarin. These findings are consistent with those recorded for fruits of 'Okitsu' satsuma mandarin trees grafted on different rootstocks (TAZIMA et al., 2014). Further, they were higher than the ones obtained in fruits of 'Span Americana' mandarin trees grafted on 'Rangpur' lime (SILVA et al., 2013).

Conclusions

The growth and yield performances of 'Montenegrina' mandarin trees were not affected by the tested rootstocks under the edaphoclimatic conditions of Londrina, Paraná, Southern Brazil. Though there were differences among rootstocks and cropping seasons for the physicochemical quality parameters of fruits, all five tested rootstocks induced commercially acceptable fruit quality. Therefore, 'Montenegrina' trees can be grown on all evaluated citrus rootstocks without incompatibility and loses in the Northern Paraná. With these findings, the citrus growers can select the best scion-rootstock combination based on their region and requirements, promoting the diversification of citrus orchards.

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