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The Perfect Match: Adjusting High Tree Density to Rootstock Vigor for Improving Cropping and Land Use Efficiency of Sweet Orange

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Abstract: The rise in the productivity of sweet orange in Brazil has been related to the use of superior rootstocks and higher tree density, among other factors. In order to investigate whether the cropping system and the land use efficiency would benefit from more intensive cultivation, the performance of Valencia sweet orange was evaluated over nine years on four rootstocks, which induced contrasting vigor, at 513, 696 and 1000 trees·ha^{-1}. Agronomic Institute of Campinas (IAC) 1697 and IAC 1710 citrandarins, and diploid and allotetraploid (4×) Swingle citrumelos were classified as semi-dwarfing, super-standard, standard, and dwarfing rootstocks, respectively. The fruit yield per tree was decreased at higher tree densities, notably for more vigorous rootstocks. Conversely, the cumulative productivity was increased over the evaluation period by 27% at 1000 trees·ha^{-1}, irrespective of the rootstock, and the most vigorous rootstock resulted in 2.5 times higher production than the dwarfing one on average. Most fruit quality parameters were seldom influenced by the tree density, while the rootstock was a decisive factor in improving the quality and the soluble solids content. Dwarfing rootstocks allowed for harvesting 17% more fruit per minute by manual pickers. Because the tree row volume per area is lower with such rootstocks, even at higher tree density, spray volume can be reduced, although appropriate equipment should be developed for better spray coverage on smaller trees. Nine years after planting under strict vector control, the cumulative incidence of huanglongbing-symptomatic trees on IAC 1710 was double that on Swingle 4×. Taken together, the results suggested that the land use efficiency in the citrus industry can be further improved by planting vigorous rootstocks at moderate to high tree densities. Nevertheless, obtaining highly productive semi-dwarfing and dwarfing rootstocks is the sine qua non for making high-density pedestrian sweet orange orchards more profitable.

Keywords: *Citrus* spp.; dwarfing; fruit yield and quality; huanglongbing; sustainable production systems; tree spacing

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1. Introduction

Sweet oranges [*Citrus* × *sinensis* (L.) Osbeck] are the most cultivated and consumed citrus fruits for both juice processing and fresh fruit in the world. Brazil, China, India, USA, Mexico, and Spain are the largest producers, accounting for 63.5% of the global production of 78.7 million of tons in 2019 [1]. However, from 2000 to 2019, the harvested areas significantly increased in most producing countries, whereas they decreased by 31% and 37% in Brazil and USA, respectively, the major sweet orange juice producers with

589,610 and 206,350 ha, respectively. Moreover, in the USA, the decrease in area was accompanied by a 1.53-fold reduction of fruit yield (FY), mainly due to the devastating spread of huanglongbing (HLB) in the state of Florida [2], resulting in a 59% decline of the total production. On the other hand, Brazil maintained similar production, irrespective of the decrease in the harvested area, because the average productivity increased by 1.16-fold in the same period to 28.95 t·ha^{-1} or a 1.53-fold increase in production compared with that in 1980 [1].

This remarkable improvement of sweet orange yield, despite the presence of HLB since 2004, is associated to several practices that have been extensively implemented in Brazil, such as the use of healthy citrus nursery trees grown in screen houses [3,4]; the adoption of improved rootstock varieties, with the replacement of the Rangpur lime (*C.* × *limonia* Osbeck) rootstock with Swingle citrumelo [*C.* × *paradisi* Macfad. × *Poncirus trifoliata* (L.) Raf.] and Sunki mandarin [*C. sunki* (Hayata) hort. ex Tanaka] rootstocks [5,6]; better soil and nutrition management and use of cover crops [7,8]; improvements in pest and disease management that decrease spread rates and crop losses [9–13]; the expansion in the use of drip irrigation on about one third of the harvested area [14,15]; and the profile of the citrus farms, with those cultivating more than 200,000 trees responding for most production, which have been migrating to southern areas with milder climate and lower HLB incidence in the citrus belt of São Paulo, Paraná and Minas Gerais States [14,16,17]. In addition, the average tree density in the citrus belt increased from 370 to 564 trees per hectare in the 2000–2020 period [14]. Tree densities up to 1000 trees per hectare have been demonstrated to increase FYs, especially at the initial harvests, contributing to the economic feasibility of the sweet orange crop [18], and have gained more importance as an HLB management strategy [19–21].

Regardless of its potential to boost early productivity, high-tree-density plantings require greater investment and may lead to the reduction of yield due to excessive tree crowding and difficulties in operations [22]. To address such limitations, the tree size control has been evaluated in high-density citrus orchards, including the use of pruning [23], training systems [24], irrigation [25], and dwarfing rootstocks [26]. This last method is considered the most suitable to ensure that trees will be permanently trained to the allocated space, besides facilitating several practices including harvesting, scouting, and spraying [27]. In other woody fruit crops, high tree density associated with adapted varieties, either scions or rootstocks, allows for high-efficiency production systems [28–30].

In citrus, the Flying Dragon trifoliate orange [*P. trifoliata* (L.) Raf. var. *monstrosa* (T. Itô) Swingle] has long been considered the only true dwarfing rootstock, and its use was demonstrated as commercially feasible under tropical conditions specially for more vigorous scion varieties such as lemons [*C.* × *limon* (L.) Burm. f.] and Persian lime [*C.* × *latifolia* (Yu. Tanaka) Tanaka] [26,31]. However, the extensive use in combination with sweet orange has not attained commercial relevance in the main producing regions to date, with growers generally preferring more vigorous rootstocks. This has encouraged the development of new, alternative dwarfing rootstocks in most citrus-breeding programs, and some promising genotypes have been obtained by conventional cross [32–34], tetraploidization [35,36], and genetic transformation [37].

There is a consensus that one of the strategies to assure the long-term sustainability of agriculture and food security relies on a more efficient use of land [38–41]. By considering this, it is more likely to meet the rising food demand of the increasing population while liberating land for other non-agricultural uses as well as conservation [42,43]. In the Brazilian citrus industry, the productivity increases in the 2000–2020 period have allowed substantiating land-sparing, about 267,000 hectares [1], and it is estimated that for each 2.52 hectares of cultivated sweet orange within the farms in São Paulo State, there is another hectare of preserved native vegetation [44]. In order to elucidate whether citrus production in subtropical conditions may benefit from an even more intensive land use, in this work, we evaluated the association of high-tree-density orchards with rootstocks that induce contrasting vigor, including diploid and allotetraploid selections of the Swingle citrumelo, on the performance of Valencia sweet orange for juice processing over nine years. Moreover, the cumulative HLB incidence and the spraying efficacy were assessed to further investigate the possible role of tree size and spacing on disease management.

2. Materials and Methods

2.1. Plant Materials

Valencia sweet orange [*C.* × *sinensis* (L.) Osbeck] was evaluated as a standard processing scion variety. Four rootstock genotypes were evaluated: IAC (Agronomic Institute of Campinas) 1710 (*C. reticulata* Blanco cv. Changsha × *P. trifoliata* cv. English Small) and IAC 1697 [*C. sunki* (Hayata) hort. ex Tanaka × *P. trifoliata* cv. Benecke] citrandarins, which correspond to US-801 and US-812 in the United States, respectively [45,46]; the industry standard rootstock, namely the 4475 selection of Swingle citrumelo (*C.* × *paradisi* cv. Duncan × *P. trifoliata*); and an allotetraploid selection of Swingle citrumelo. In São Paulo State conditions, IAC 1710 citrandarin induces a larger tree size and a higher production of Valencia sweet orange compared to Swingle citrumelo, whereas both IAC 1697 and Swingle citrumelo show intermediate tree vigor with a high productivity [5,45,47]. The allotetraploid Swingle citrumelo (Swingle 4×) merges two divergent genomes from two genera (*Citrus* and *Poncirus*) presenting preferential disomic segregation classical for allotetraploids [48]. It has dwarfing potential [49] and corresponded to allotetraploid individuals that were visually selected from a seedbed of diploid Swingle citrumelo, based on morphological traits of leaves, stems, and roots compared with diploid individuals [50]. Later, their tetraploidy resulting from chromosome doubling was confirmed by the flow cytometry analysis of pooled samples of leaf and bark pieces as previously described [51]. All nursery stocks were grown in a screenhouse using citrus pots and plant materials collected from certified mother plants, including budwood of Valencia sweet orange. Rootstock were propagated by seed, and nucellar plants were selected for use in the experiment only by visual inspection, which is consistent with commercial nursery practices.

2.2. Tree Density and Experimental Design

The tree spacing was evaluated at three densities: 5.00 m × 2.00 m, 5.75 m × 2.50 m, and 6.50 m × 3.00 m (between-rows × in-rows), which corresponded to 1000, 697, and 513 trees·ha^{-1}, respectively. In 2020, the average tree density in the Brazilian citrus belt was of 564 trees·ha^{-1} [14]. A completely randomized split-plot design was used, with the tree density as the plot (main treatment) and the rootstock variety as the sub-plot (secondary treatment). Twelve treatments with seven replications were evaluated (three planting densities per plot × four rootstock varieties per sub-plot). The experimental unit comprised 24 trees, with four parallel planting lines of six trees in each line. The planting lines were arranged in the NE direction at an azimuth angle of 54.5°.

2.3. Experimental Area and Tree Care Conditions

The experiment was planted in February 2012 in a commercial farm in the municipality of Gavião Peixoto, in the center region of the state of São Paulo (21°43′38″ S, 48°23′25″ W, 608 m). The local climate is Cwa type (mountain subtropical) according to the Köppen–Geiger classification [52]. Meteorological variables at the site were recorded throughout the evaluation period (Figure A1). Soil was classified as a dystrophic red to red-yellow oxisol with loamy to clayey texture, slightly wavy relief [53], with the following chemical characteristics in February 2021 (0–20 cm depth): pH ($CaCl_2$) = 5.6; cation exchange capacity (CEC) = 63.6 cmol$_c$·dm^{-3}; Ca = 26 cmol$_c$·dm^{-3}; Mg = 13 cmol$_c$·dm^{-3}; K = 2 cmol$_c$·dm^{-3}; (H + Al) = 23 cmol$_c$·dm^{-3}, V = 64%; P = 58 mg·dm^{-3}; S = 10 mg·dm^{-3}; B = 0.44 mg·dm^{-3}; Fe = 32 mg·dm^{-3}; Mn = 4.8 mg·dm^{-3}; Cu = 6.3 mg·dm^{-3}; Zn = 2.9 mg·dm^{-3}; and organic matter (O.M.) = 19 g·kg^{-1}.

Cultivation practices followed standard recommendations for sweet orange trees in Brazil [54]. Trees were rainfed from 2012 to 2018, and after harvesting in October, a supplementary drip irrigation was installed (2 mm·d^{-1} with a single row of 1.6 L·h^{-1}

emitters at a 0.8 m spacing). Soil was prepared by the following consecutive practices: subsoiling; harrowing; leveling; furrowing at the planting line; limestone, phosphate and gypsum application at the furrow bottom; and three-rod subsoiling to close the furrow for planting. NPK fertilizers were applied three times a year during the rainy season (September to March), to supply an annual average of 172.4 kg of N, 52.5 kg of P_2O_5, and 108.3 kg of K_2O per hectare from 2012 to 2020. Foliar micronutrients (B, Mn, and Zn) sprays were carried out three times a year during the rainy season. Until October 2020, trees were allowed to grow naturally. After the harvesting in 2020, trees were pruned by hedging (15° inclination) and topping (30° inclination) with a rear pendant trimmer (HLC-6, Hidrautec, Américo Brasiliense, Brazil)) mounted on a 75 hp tractor (TT, New Holland, Curitiba, Brazil) that moved parallel to the row. Pruning aimed to control tree size, with topping performed to attain a maximum tree height (TH) of about 3.5 m and hedging performed to create a minimum free space between rows of 2.5 m to allow equipment movement within the experimental orchard.

After planting, all trees were treated with systemic insecticides (thiamethoxam and imidacloprid in rotation) at 60-d intervals following standard recommendations for drench application, up to three years after planting. In addition, foliar contact insecticides were sprayed in rotation three times a month from 2012 to 2015 and fortnightly to monthly from 2016 to 2021 for controlling the vector of HLB, the Asian citrus psyllid (ACP), *Diaphorina citri* Kuwayama. The leprosis mite was controlled by an annual preventive spray with miticides. Citrus canker and black spots were controlled by four preventive sprays with bactericides/fungicides from fruit set to maturation. Any additional pest was controlled using standard treatments according to fortnightly inspections on 1% of trees in the block. In-row weeding control was performed with paraquat and glyphosate application whenever necessary, while the between-rows were mowed five to seven times a year with a conventional mower. In the first year of planting, some trees were severely damaged by the herbicide application, notably those grafted on the Swingle 4× citrumelo, and were removed from the experiment.

2.4. Tree Size and Row Volume (RV) Estimation

In October 2020, the TH and the canopy equatorial diameter were measured with a graduated pole just before and after pruning. The mean diameter (DM) was calculated by Equation (1):

$$\mathrm{DM} = \frac{\mathrm{DP} + \mathrm{DR}}{2}, \tag{1}$$

where DP is the diameter parallel to the row and DR is the diameter perpendicular to the row. The canopy volumes (CVs) before and after pruning were estimated by Equation (2) adapted from [55]:

$$\mathrm{CV} = \frac{\mathrm{TH} \times \pi \times \left(\mathrm{DM}^2\right)}{6}. \tag{2}$$

The tree RVs, that is, the total tree CVs obtained per hectare before and after pruning at nine years of age, were estimated by Equation (3):

$$\mathrm{RV} = \frac{\mathrm{CV} \times 10{,}000}{\mathrm{SB} \times \mathrm{SI}}, \tag{3}$$

where SB and SI are the between- and in-row tree spacing measures, respectively.

2.5. FY per Tree and Productivity per Hectare

Fruit production was evaluated every year from 2014 to 2020 just after manual harvesting, usually in October/November. All harvested fruit was set in 1000 L bags and weighted by a suspended scale (500, Digi-Tron, Curitiba, Brazil) mounted on a tractor. The FY was calculated on a per tree basis (kg·tree^{-1}) considering all living trees in each plot for each harvest year and for the average of the evaluation period, and the fruit productivities (FP) for each year of evaluation and for the cumulative production (2014–2020) were estimated per hectare ($t \cdot ha^{-1}$) by Equation (4):

$$FP = \frac{FY \times 10,000}{SB \times SI}. \quad (4)$$

Early-bearing (EB) was estimated as the relation between the cumulative FP from 2014 to 2016 (initial three harvests) and the cumulative FP for the whole evaluation period by Equation (5):

$$EB = \frac{\sum_{2016}^{2014} FP}{\sum_{2020}^{2014} FP}. \quad (5)$$

Finally, the alternate bearing index (ABI) was calculated by Equation (6) as proposed by [56]:

$$ABI = \frac{1}{(n-1)} \times \left\{ \frac{|(a2 - a1)|}{(a2 + a1)} + \frac{|(a3 - a2)|}{(a3 + a2)} + \ldots + \frac{|(an - a(n-1))|}{(an + a(n-1))} \right\}, \quad (6)$$

where n is the number of crops evaluated, and a1, a2, . . . , a(n − 1), a(n) are the FYs in the respective years.

2.6. Production Efficiency and Land Use

The production efficiency of the tree canopy (PEC) in 2020 was calculated by Equation (7):

$$PEC_{2020} = \frac{FY_{2020}}{CV_{2020}}, \quad (7)$$

and the area index (AI) was calculated by Equation (8):

$$AI = \frac{\left(DM^2\right) \times \pi \times 0.25}{SB \times SI}, \quad (8)$$

to estimate the relative occupation of one hectare of cultivated area by the total canopy area projection of the citrus crop in 2020.

The production efficiency over the evaluation period was estimated as a function of the tree row volume occupation (PEV) and area index (PEA) per hectare before pruning by Equations (9) and (10), respectively:

$$PEV = \frac{\sum FP}{RV}, \quad (9)$$

$$PEA = \frac{\sum FP}{(10,000 \times AI)}. \quad (10)$$

Moreover, the land use index (LU) was also estimated by the ratio between the mean FP in the 2014–2020 period and the average sweet orange productivity in São Paulo State in the same period [57], as adapted from the equation proposed by [58] for land use intensity measurements that compare the actual productivity to a reference productivity level. All these estimations are simple to calculate and provide good surrogate measures to compare land use gains among the evaluated treatments (tree densities associated to rootstocks with distinct vigor) under the same environmental and management conditions.

2.7. Fruit Quality

Fruit quality variables were evaluated from 2017 to 2020. During the harvesting period, usually in October–November, 30-to-60-fruit samples were randomly collected from the total amount of fruit harvested per each plot in four replications. Fruit samples were immediately transported to an industrial laboratory in Matão-SP, Brazil. The following variables were measured: fruit weight (FW), expressed in grams and measured by a digital scale; the soluble solids concentration in the juice (SS), expressed as °Brix and measured with a digital refractometer (RFM 712, Bellingham + Stanley, Tunbridge Wells, UK); titratable acidity (TA), expressed as percentage, after titration of 25 mL of juice with 0.3 N NaOH and calculated by Equation (11):

$$TA = \frac{n \times 0.3 \times 64.02}{10 \times 25}, \quad (11)$$

where n is the volume of the 0.3 N NaOH solution used to titrate 25 mL of juice; the maturity index (MI), calculated by the ratio between the SS and the TA; juice content (JC), expressed as the percentage ratio between juice weight and FW, obtained after fruit squeezing in an industrial extractor with five sets of standard 0.025″ cups (291B/391B, JBT, Lakeland, NC, USA); the technological index (TI), which was calculated by Equation (12):

$$TI = \frac{JC \times SS \times 40.8}{10,000}, \quad (12)$$

thus, giving the total amount of soluble solids produced per 40.8 kg-standard industrial orange box; and the industrial yield (IY), which was calculated by Equation (13):

$$IY = \frac{660}{TI}, \quad (13)$$

to estimate the number of orange boxes to produce one ton of frozen and concentrated orange juice (FCOJ) at 66 °Brix. In addition, the soluble solids yield (SSY) was calculated by Equation (14):

$$SSY = TI \times \frac{\sum FP}{0.0408}, \quad (14)$$

to estimate the total amount of soluble solids (kg) accumulated by each of the evaluated treatments per hectare over the 2017–2020 period. Fruit quality variables were analyzed in each year and for the average values of the evaluation period. For the SSY, the FP of each replication was multiplied by the TI of the respective replicate from 2017 to 2020.

2.8. Harvesting Efficiency

The harvesting efficiency was evaluated in November 2017 to investigate the influences of the tree size and spacing on this manual operation. Fruit pickers were grouped in eight teams of five pickers each, who randomly harvested the plots, that is, alternating different treatments harvested by each team to prevent any effect of labor experience on the results. Fruit harvested per plot was weighed on a digital scale. The time required for harvesting the plot (T) was computed as the total time for each team to harvest and move within the plot (up to 24 trees). With this procedure, it was possible to evaluate the combined effect of the tree size induced by the rootstock (harvesting time due to the collection of fruit from an individual tree) and the tree density (harvesting time due to the move from a tree to another one) on the time and yield for harvesting. Then, the efficiency of harvesting was estimated by three approaches as Equations (15)–(17). The estimated time to harvest a single tree (HET) was described as:

$$HET = \frac{T \times n}{z}, \quad (15)$$

where n is the number of pickers and z is the number of harvested trees in the plot, expressed as minutes per tree per picker. The estimated amount of fruit harvested by picker (HEW) was expressed as kilograms of harvested fruit per minute per picker:

$$HEW = \frac{FY}{HET}. \quad (16)$$

The estimated time to harvest 1000 fruits (HEF) was expressed as minutes to harvest 1000 fruits per harvester:

$$\text{HEF} = \frac{1000 \times \text{FW} \times \text{HET}}{\text{FY}}. \quad (17)$$

2.9. Spray Coverage

Spray coverage was assessed in May 2018 to evaluate whether tree size and spacing interfere with the quality of spraying for pest control. For this comparison, only the most extreme tree spacings (5.00 m × 2.00 m and 6.50 m × 3.00 m) and disparate rootstocks inducing larger and smaller tree sizes (IAC 1710 citrandarin and Swingle 4× citrumelo, respectively) were used. Three spray volumes (25, 70, and 120 mL·m^{-3} of tree canopy) at different operation speeds (7.8 km·h^{-1}; 4.5 and 7.8 km·h^{-1}; 1.7 and 4.5 km·h^{-1}, respectively) were evaluated separately for each tree spacing and rootstock combination, being the rates usually recommended in São Paulo for the control of ACP, citrus canker/black spot and leprosis mite, respectively [59]. All treatments were applied using bilateral spraying, in addition to unilateral spraying only for Swingle 4× citrumelo at a tree spacing of 6.50 m × 3.00 m to evaluate the spray coverage on smaller trees using this type of spraying, which is more usual in young orchards.

Meteorological conditions during the spraying operation on the first and second days of application (7 May 2018 and 8 May 2018) were shown as follows: the maximum air temperatures were 29 °C and 30 °C on the first and second days of application, respectively, the minimum air temperatures were 16 °C and 17 °C on the first and second days of application, respectively, and the mean air temperatures were 22.5 °C and 23.5 °C on the first and second days of application, respectively; the average relative humidity values were 51.0% and 69.5% on the first and second days of application, respectively; and the mean wind speeds were 12.6 and 11.9 km·h^{-1} on the first and second days of application, respectively. The tree size was measured for five trees per plot just before spraying, and the tree row CV per hectare was estimated to determine the amount of spray volume according to the established methodology [60]. Spraying was performed with a tractor (LS 75, LS Tractor, Garuva, Brazil) and an air blast sprayer (FMCopling, Araraquara, Brazil) using Disc and Core Jacto nozzles (Jacto, Pompeia, Brazil). All parameters to calculate the different spray volumes at the three application speeds are presented in Table A1.

To evaluate spray coverage, water-sensitive paper strips were placed on trees at half TH in four positions: in the inner center of the canopy, ~1 m into the canopy (inner center); in the outer center of the canopy surface (outer center); in the end of the canopy through which the air blast sprayer initiated spraying in the direction of its displacement in the planting line (entrance); and at the end of the canopy where the air blast sprayer finished spraying in the direction of its displacement in the planting line (exit) (Figure A2). In the bilateral spraying, the air blast sprayer was positioned at the central axis of the between-row, which resulted in different distance and spraying projections in relation to the tree canopy due to the rootstock variety and tree spacing, that is, the air blast sprayer was closer to the trees in the denser orchard or with the more vigorous rootstock (Figure A2). After spraying, the water-sensitive papers were collected after the natural drying of trees and kept in paper bags after complete drying. Later, once in the laboratory, each paper was scanned at 600 dpi (LaserJet Pro 200 color MFP M276nw, Hewlett-Packard Company, Porto Alegre, Brazil), and the images were saved as JPG files. To quantify the percentage of spraying coverage, the Image J software (Image Processing and Analysis in Java, Bethesda, MD, USA) was used following the color contrast method as previously described [60].

2.10. HLB Incidence

The assessment of HLB incidence was carried out from 2014 to 2021 (except in 2015), during the winter, the time of the year with higher HLB symptom expression [61]. Annually, all trees within each plot were visually observed by trained staff for HLB symptoms, such as branches with yellow leaves, leaves with blotchy mottling, lopsided fruits, and premature fruit drop [62]. In the case of doubtful symptoms, leaf samples were collected, and quantitative PCR was performed for *Candidatus* Liberibacter asiaticus detection [63]. HLB-symptomatic trees were marked and eradicated from the experimental area upon detection without resetting. The experimental area was located at the center of the commercial farm (far from the farm edge) and comprised a total of 2016 trees that were surrounded by 17,776 trees in the same block, consisting of Valencia sweet orange grafted onto Swingle citrumelo with the same age but at a 6.5 m × 2.2 m spacing. In this surrounding block, the cumulative HLB incidence from 2012 to 2021 was of 9.15%. Nearby blocks with a similar age and tree density but with Hamlin sweet orange as scion variety had a mean cumulative HLB incidence of 15.04%. At the northern limit of the experimental block, there was an area for the preservation of natural vegetation.

2.11. Statistical Analyses

All data were submitted to variance analysis, and the means were compared by the Tukey's test ($p \leq 0.05$). All analyses were carried out using the AgroEstat software [64]. For the spray coverage evaluations, five experimental replications were selected at random, and three trees from the central lines of each experimental plot were used. The water-sensitive papers were placed on both sides of the trees in relation to the planting lines, that is, four papers on each side giving a total of eight papers per tree and 24 papers per plot. Each side of the tree was considered a replication, giving a total of six replications for statistical analyses of spray coverage treatments. Spray coverage data were transformed by arcsin of the square root of the proportion.

For HLB incidence analyses, annual disease incidence data (proportion of HLB-symptomatic trees from the total number of assessed trees) did not fit a normal distribution of residuals and were analyzed using the non-parametric Kruskal–Wallis' test ($p \leq 0.05$), and the treatments were compared by the Dwass–Steel–Critchlow–Fligner (DSCF) test. In addition, the area under the disease progress curve (AUDPC) in the 2014–2020 period was calculated by Equation (18):

$$\mathrm{AUDPC} = \sum_{i=1}^{n-1} \frac{y_i + y_{i+1}}{2} \times (t_{i+1} - t_i), \tag{18}$$

where y_i is an assessment of the HLB-symptomatic trees incidence at the i^{th} observation, t_i is the time (year) at the ith observation, and n is the total number of observations. The AUDPC was considered a measure of the HLB disease incidence once that area below the curve integrates all possible factors that affect disease occurrence in a plot [65]. AUDPC data were transformed using the box-cox method with a −0.504 lambda and submitted to the analysis of variance followed by the Tukey's test ($p \leq 0.05$) to compare the treatments. All HLB-incidence analyses were performed using the statistical software Jamovi environment, version 1.2 [66].

3. Results

3.1. Tree Size and RV Estimation

In 2020, nine years after planting, the TH was not influenced by the evaluated tree densities (p = 0.3934; Table S1). Before pruning, IAC 1710 and Swingle citrumelo rootstocks produced taller trees than IAC 1697 and Swingle 4×, which induced a TH of ~2.70 m. After pruning, a similar result was observed, although the most vigorous rootstocks were pruned back to ~3.5 m, while less vigorous ones were almost not topped (Figure 1i). On the other hand, the canopy diameter was affected by both tree density and rootstock used. In the parallel direction to the row, that is, between-trees within the row, there was a 24% decrease in the canopy diameter between 1000 and 513 trees·ha^{-1}, but pruning did not change the canopy diameter (Figure 1ii). Therefore, trees completely filled the allocated in-row tree spacing, and IAC 1710 and Swingle 4× citrumelo induced the widest and narrowest trees, respectively (Figure 1iii). Considering the canopy diameter perpendicularly to the row, that is, in the between-rows direction, the highest tree density decreased the overall tree width, with pruning leading to a significant decrease: the more vigorous the rootstock and the closer the tree spacing, the higher the pruning suppression, to a maximum of 20% of the canopy diameter for IAC 1710 at 1000 trees·ha^{-1} (Figure 1iv,v).

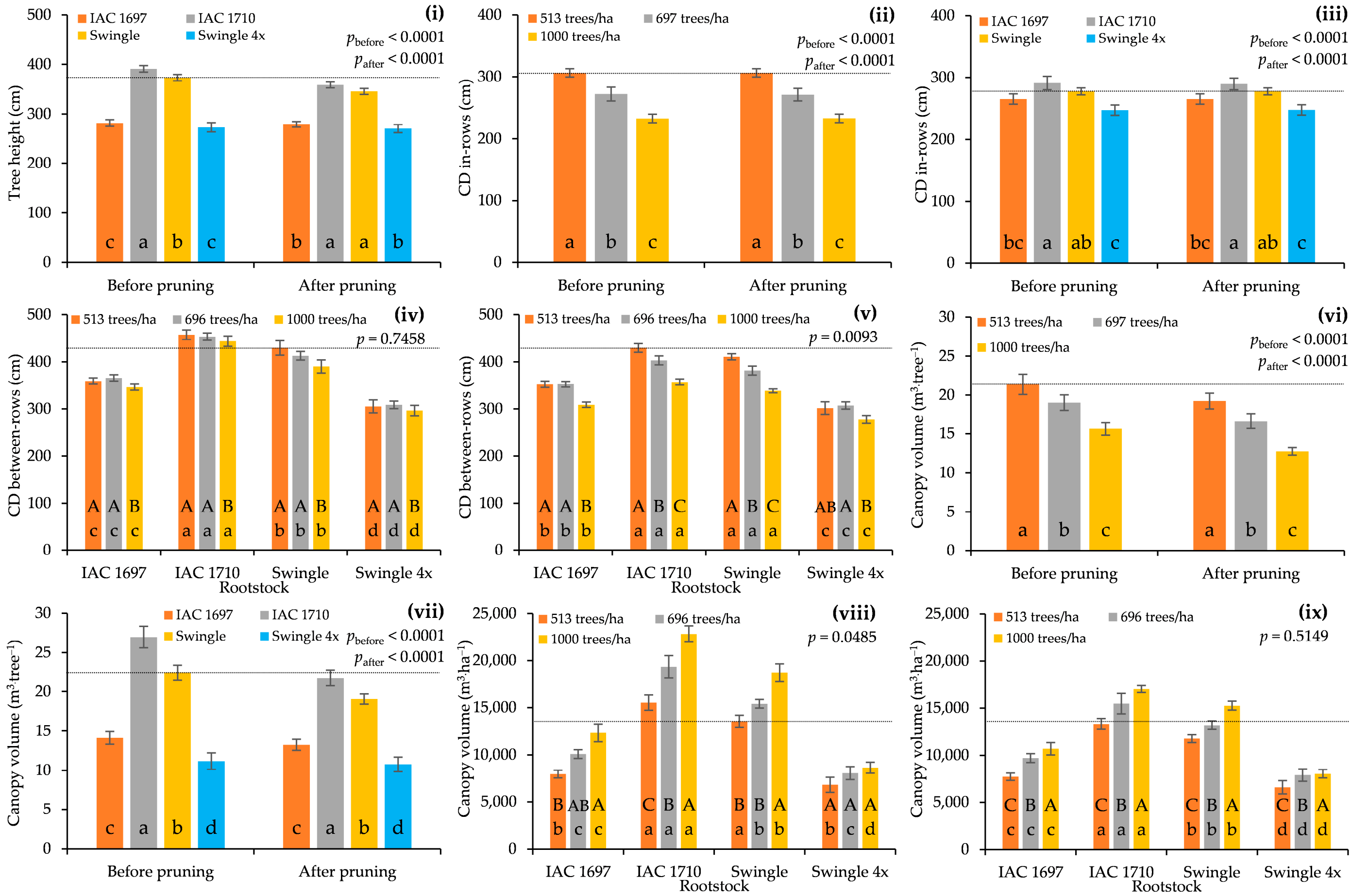

Figure 1. Tree sizes of Valencia sweet orange trees grafted onto four rootstocks and cultivated at three tree densities, just before and after pruning in 2020 (nine years after planting): (**i**) tree height; (**ii**,**iii**) canopy equatorial diameter (CD) parallel to the row line before (**ii**) and after (**iii**) pruning; (**iv**,**v**) canopy equatorial diameters (CDs) perpendicularly to the row line, before (**iv**) and after (**v**) pruning; (**vi**,**vii**) canopy volume per tree basis; and (**viii**,**ix**) tree row volumes (total canopy volume per hectare basis) before (**viii**) and after (**ix**) pruning. Gavião Peixoto-SP, Brazil, 2020. Swingle 4×, allotetraploid selection of Swingle citrumelo. (**i**–**iii**,**vi**,**vii**): Means within each pruning condition followed by different letters at the column base are different by the Tukey's test ($p \leq 0.05$). (**iv**,**v**,**viii**,**ix**): Tree density means within each rootstock and rootstock means within each tree density followed by different capital and lowercase letters, respectively, at the column base are different by the Tukey's test ($p \leq 0.05$). Bars indicate the standard errors of means (n = 7). Dotted lines indicate the variable mean for control conditions (513 trees·ha^{-1}; Swingle citrumelo rootstock) before pruning within each panel.

As a result, the individual tree CV was directly reduced by the tree density before and after pruning (Figure 1vi), and the evaluated rootstocks could be classified as the following: super-standard, IAC 1710 (mean of 26.9 m^3); standard, Swingle citrumelo (22.4 m^3); semi-dwarfing, IAC 1697 (14.1 m^3); and dwarfing, Swingle citrumelo 4× (11.2 m^3) (Figure 1vii). Although trees were smaller at higher tree densities, the RV increased by 1.54-fold with the density, on average, for all evaluated rootstocks except for Swingle citrumelo 4× (Figure 1viii). IAC 1710 resulted in a mean of 20,000 m^3·ha^{-1}, whereas Swingle 4× led to only ~8000 m^3·ha^{-1}. Pruning more effectively decreased the RVs of IAC 1710 and Swingle citrumelo rootstocks (Figure 1ix).

3.2. FY per Tree and FP per Hectare

Over the evaluation period, the FY per tree was influenced by the tree density and rootstock used, except in 2014 (the first harvest), with a significant effect of the interaction in 2016, 2017, 2020, and 2014–2020 (average values in the period) (Figure 2; Table S2). Overall, the higher the tree density, the lower the FY per tree. IAC 1710 induced the highest FY, followed by Swingle citrumelo, while Swingle 4× citrumelo induced the lowest FY, 62% and 50% lower than the former rootstocks, respectively, over the evaluation period (Figure 2xii). Interestingly, the reduction in the FY due to higher tree densities was more pronounced for the vigorous rootstocks, while Swingle 4× citrumelo and IAC 1697 were affected only at 1000 trees·ha^{-1}; indeed, in 2016 and 2017, there was no effect of tree density on Swingle 4× citrumelo at all (Figure 2v,vi).

From 2014 to 2017, the productivity per hectare increased with the orchard age, and later, it resulted in an alternate production pattern (Figure 3i,ii; Table S3). In the first harvest, the productivity was not affected by the rootstock, and in the following years, Swingle 4× citrumelo induced the lowest productivity. Initially, IAC 1697 was the most productive rootstock, but from 2017, it was surpassed by IAC 1710 and in 2018 by Swingle citrumelo, probably because the tree size of IAC 1697 was smaller (Figure 1vii). It is noteworthy that in "off-years", there was no difference in the FP among the evaluated tree densities and even the differences among the rootstocks were less pronounced. Furthermore, there was no effect of the evaluated treatments on the alternate bearing index over the 2014–2020 period (Pd = 0.8009, Pr = 0.2916; Table S2).

An opposite result was observed for the cumulative FP compared to that of the FY in the 2014–2020 period, because increasing the tree density to 1000 trees·ha^{-1} led to a substantial increase of 27% in the amount of fruit produced per hectare regardless of the rootstock, although there was no gain by increasing the density from 513 to 696 trees·ha^{-1} (Figure 3iii). On average, IAC 1710 produced the highest cumulative FP, and Swingle 4× citrumelo produced the lowest cumulative FP, for a difference of 2.5 times (Figure 3iv). When the damage to productivity by HLB-symptomatic tree eradication was considered throughout the period, a similar result was observed, that is, increasing the tree density and using more vigorous rootstocks led to higher productivities, but there was an average reduction of 10% due to the disease impact up to the 7th harvest (Figure 3v,vi).

EB is another important attribute to evaluate the production system, because it can indicate anticipation of income and, consequently, risk reduction. In this sense, increasing the tree density the most was more advantageous, resulting in 20% more production in the three initial harvests than the standard tree density (Figure 3vii). However, only IAC 1697 rootstock led to a higher EB (Figure 3viii), which may be explained by its behavior of relatively higher fruit production in the initial harvests while the other rootstocks increased production as trees got older and larger.

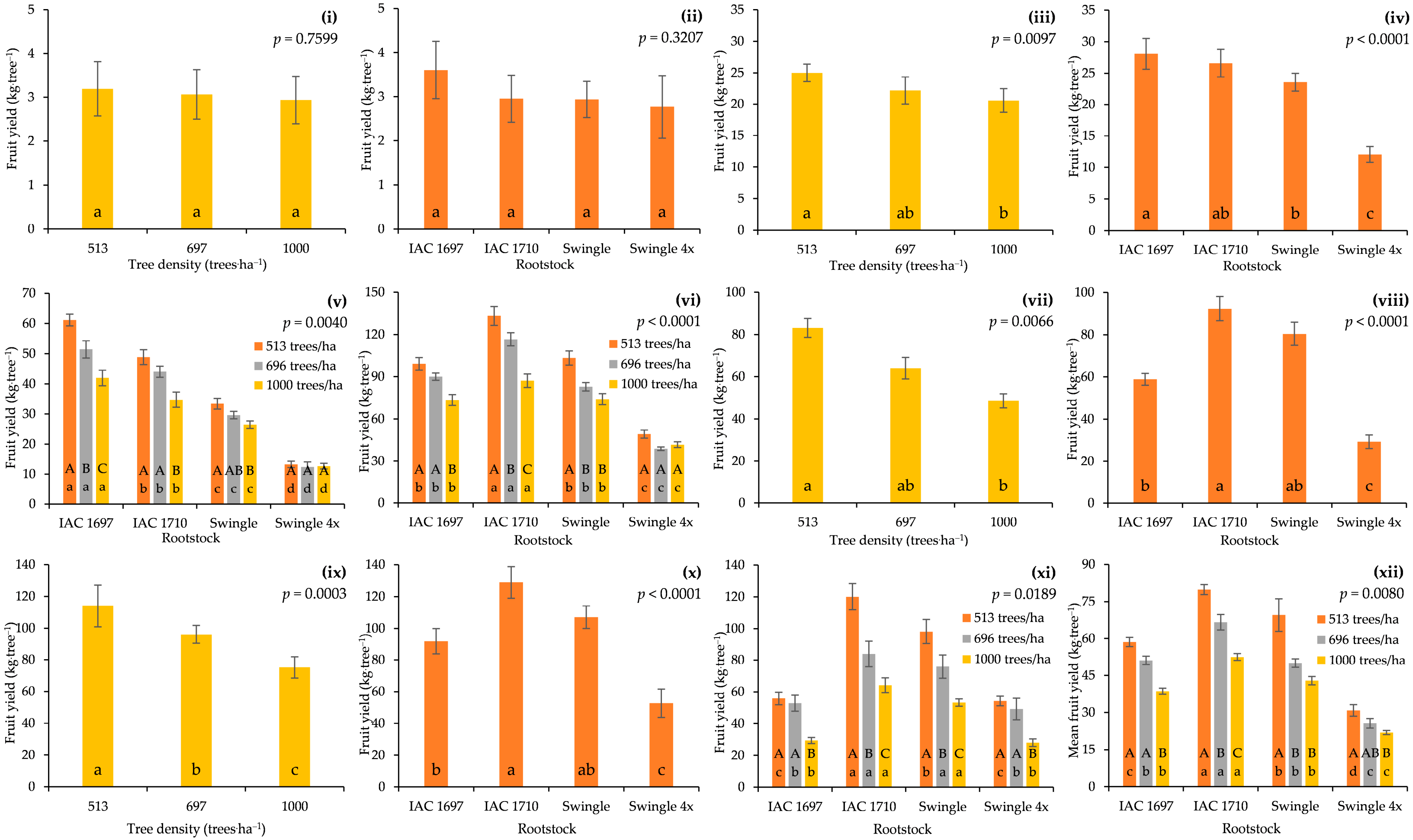

Figure 2. Fruit yield of Valencia sweet orange trees grafted onto four rootstocks and cultivated at three tree densities in different years: (**i**,**ii**) 2014; (**iii**,**iv**) 2015; (**v**) 2016; (**vi**) 2017; (**vii**,**viii**) 2018; (**ix**,**x**) 2019; (**xi**) 2020; (**xii**) mean yield in the 2014–2020 period. Gavião Peixoto-SP, Brazil. Swingle 4×, tetraploid selection of Swingle citrumelo. (**i**–**iv**,**vii**–**x**): Means followed by different letters at the column base are different by the Tukey's test ($p \leq 0.05$). (**v**,**vi**,**xi**,**xii**): Tree density means within each rootstock and rootstock means within each tree density followed by different capital and lowercase letters, respectively, at the column base are different by the Tukey's test ($p \leq 0.05$). Bars indicate the standard errors of means (n = 7).

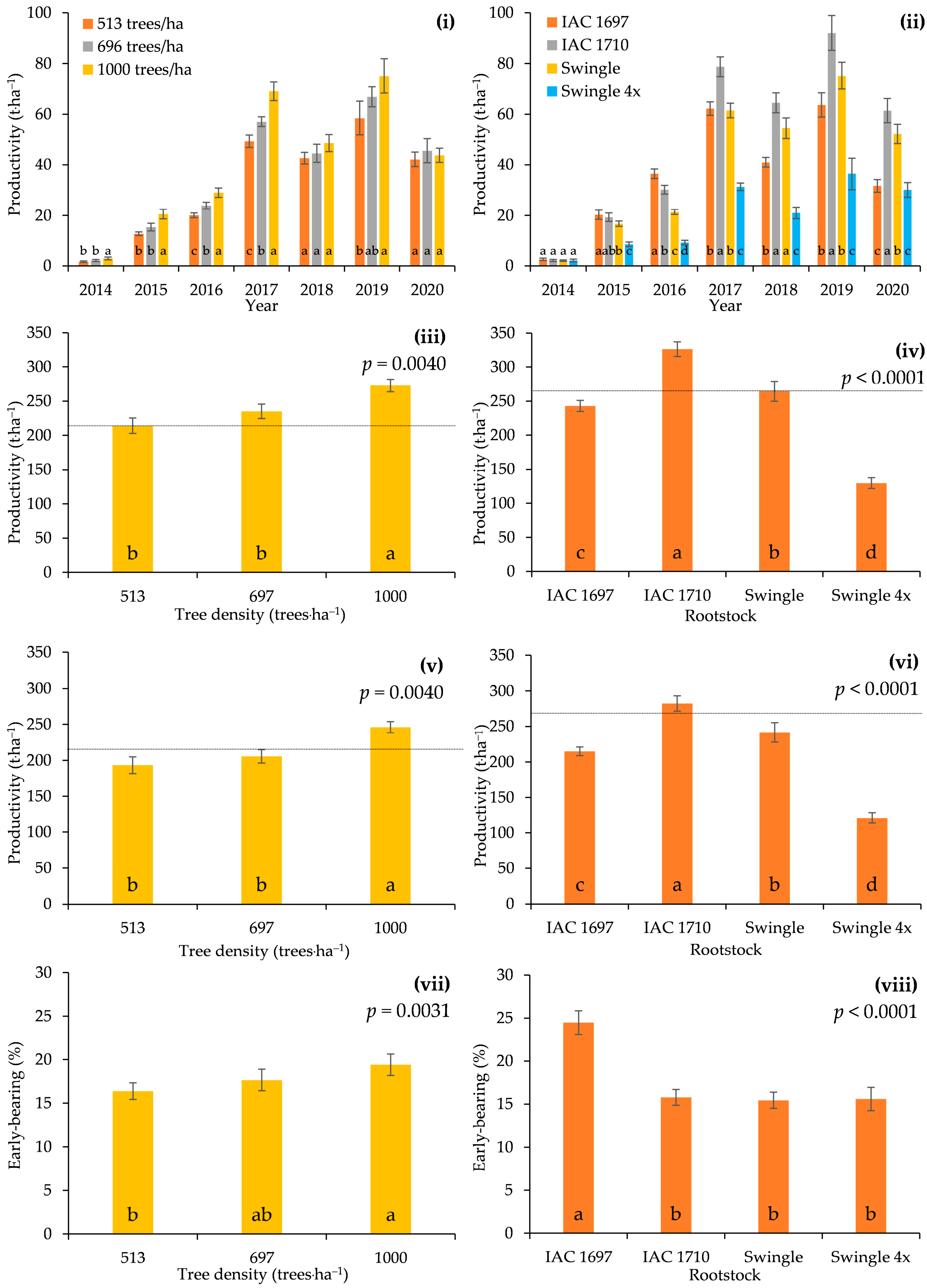

Figure 3. Performance of Valencia sweet orange trees grafted onto four rootstocks and cultivated at three tree densities: (**i**,**ii**) estimated annual productivity from 2014 to 2020; (**iii**,**iv**) estimated cumulative productivity in the 2014–2020 period; (**v**,**vi**) estimated cumulative productivity in the 2014–2020 period considering tree eradication by huanglongbing (HLB); (**vii**,**viii**) early-bearing, estimated by the relation between the cumulative productivities in 2014–2016 and 2014–2020 periods. Swingle 4× = allotetraploid selection of Swingle citrumelo. (**i**,**ii**): Means within each year followed by different letters at the column bases are different by the Tukey's test ($p \leq 0.05$). (**iii**–**viii**): Means followed by different letters at the column bases are different by the Tukey's test ($p \leq 0.05$). Bars indicate the standard errors of means (n = 7). Dotted lines indicate the mean cumulative productivity without eradication by HLB for tree density control [513 trees·ha^{-1}; (**iii**,**v**)] and rootstock control [Swingle citrumelo; (**iv**,**vi**)] in the absence (**iii**,**iv**) and presence (**v**,**vi**) of disease.

3.3. Production Efficiency and Land Use

Nine years after planting, trees were at adult bearing age, and the tree size started to be controlled by annual pruning according to the grower management. Using the canopy area projection as a criterion to estimate the relative occupation of land with a crop-productive surface, we found that about half of the land surface would be occupied by crop at 513 trees·ha^{-1}, which could increase by 42% if the number of trees per hectare was doubled (Figure 4i). Grafting Valencia trees onto the highly vigorous IAC 1710 rootstock resulted in 74% land occupation by sweet orange, whereas it was only 42% if the trees were on the dwarfing rootstock Swingle 4× citrumelo (Figure 4ii). Therefore, this type of rootstock could be more competitive in terms of productivity, if even higher tree densities were used. This could be corroborated by the tree canopy production efficiency in 2020, because 1000 trees·ha^{-1} resulted in a 23% less efficient canopy, mainly due to overshading, but only Swingle 4× citrumelo induced 1.24 more efficiency to the Valencia scion in relation to both evaluated citrandarins (Figure 4iii,iv). Consequently, the loss of efficiency per unit of CV due to higher tree density could be better compensated for by the more efficient dwarfing rootstock.

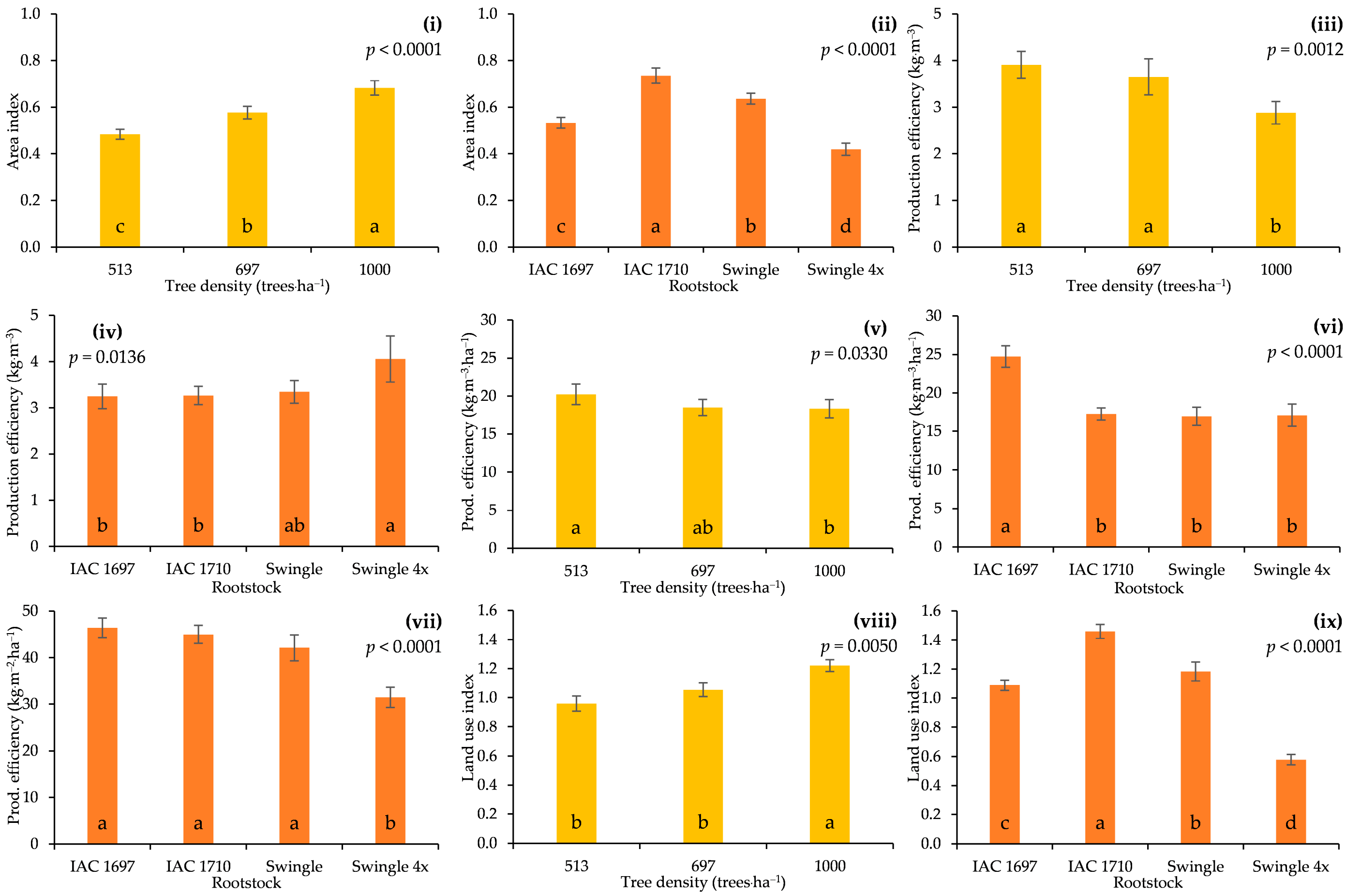

Figure 4. Production efficiency and land use indexes of Valencia sweet orange trees grafted onto four rootstocks and cultivated at three tree densities: (**i**,**ii**) area index (canopy area projection per hectare) in 2020; (**iii**,**iv**) production efficiency of tree canopy volume in 2020; (**v**,**vi**) production efficiency estimated by the relation between the cumulative production in the 2014–2020 period and the tree row volume in 2020; (**vii**) production efficiency estimated by the cumulative production in the 2014–2020 period and the area index in 2020; (**viii**,**ix**) land use index (relation between the observed productivity and the reference productivity [57]) in the 2014–2020 period. Gavião Peixoto-SP, Brazil. Swingle 4×, allotetraploid selection of Swingle citrumelo. Means followed by different letters at the column base are different by the Tukey's test ($p \leq 0.05$). Bars indicate the standard errors of means (n = 7).

However, since the season can influence the production efficiency, with the observed alternate bearing over the evaluation period (Figure 3), we estimated the production efficiency by two approaches. First, we calculated the relative cumulative production to the RV at a full-bearing age; in this case, the gain for the less dense orchard was only 10% (Figure 4v), because both the productivity and the RV were significantly lower (Figures 1 and 3). Regarding the rootstock used, it was possible to determine a higher production efficiency only for the semi-dwarfing IAC 1697 by 45% until it was nine years old (Figure 4vi), because this rootstock decreased the tree size and thus the RV to some extent (~50% on average), but with a lesser reduction of productivity (~20% on average) compared to the more vigorous, yet highly productive, rootstocks. By comparison, the FY of the truly dwarfing Swingle 4× citrumelo was poor (Figure 2). In the second approach, the cumulative productivity was related to the AI, that is, to the estimated land occupation by crop surface. In this scenario, only Swingle 4× citrumelo resulted in a lower efficiency of production (Figure 4vii), and the tree density did not influence the production efficiency ($p = 0.0959$; Table S4). This could be explained by the similar canopy area projection by the remaining rootstocks, with the TH and the CV being underestimated for the more vigorous rootstocks. Therefore, for perennial tree crops such as citrus, the production efficiency may be more practical and assertively estimated, when the crop volume per land is used, considering the complexity to measure the leaf AI of such crops.

Although the production efficiency estimations could compare the evaluated tree density and rootstock treatments among themselves, using the LU is more interesting because the observed productivity can be compared with a reference to actual management in commercial cultivation, for instance, the average productivity of sweet orange in the citrus belt in the same period (2014–2020). The tree density of 513 trees·ha^{-1} is very close to the average tree density in the citrus belt (564 trees·ha^{-1}), and as expected, the LU was close to 1, whereas 1000 trees·ha^{-1} led to a 22% more intense land use (Figure 4viii). However, the rootstock effect was much more prominent, since the most vigorous IAC 1710 could improve the land use by 46%, while Swingle citrumelo (+18%) and IAC 1697 (+9%) were also positive, but Swingle 4× citrumelo (−42%) did not meet the current productivity of the Brazilian citrus belt (Figure 4ix).

3.4. Fruit Quality

In none of the four evaluated harvests, was there an interaction between the tree density and the rootstock for any of the fruit quality variables tested (Tables 1, A2, A3 and S5–S7). Overall, while the tree density had a minimal effect on the quality over the evaluation period (2017–2020), the rootstock had a major influence on all evaluated variables (Table 1). Increasing the tree density led to lower FWs with higher soluble solids concentrations. Other fruit quality variables were not affected, but there was a trend for higher acidity and TI, and a lower ratio and IY with increased tree density. Only the cumulative SSY was substantially improved by the tree density, 27% in relation to the standard density, which was very similar to the FP gain (Figure 3). Although the fruit quality was slightly distinct in each harvest, probably due to climate aspects influencing both the density and the rootstock variety, it was consistent that IAC 1697 produced a lower FW with higher soluble solids, acidity, JC, and TI, leading to a better IY. On the other hand, IAC 1710 induced fruit with the lowest quality. Diploid and the allotetraploid selection of Swingle citrumelo induced similar quality to the Valencia fruits, but Swingle 4× citrumelo induced earlier fruit maturation and lower JC in general. However, due to the outstanding productivity, IAC 1710 was more efficient for the production of soluble solids per area over the evaluation period, with 1.17- and 2.37-fold increases compared to the standard Swingle citrumelo and its allotetraploid selection, respectively.

Table 1. Average fruit weight (FW), soluble solids concentration (SS), titratable acidity (TA), maturity index (MI), technological index (TI), juice content (JC), industrial yield (IY), and cumulative SS yield (SSY) of fruits of Valencia sweet orange grafted onto four rootstocks and cultivated at three tree densities. Gavião Peixoto-SP, Brazil, 2017–2020.

Tree Density	FW	SS	TA	MI [1]	TI [2]	JC	IY [3]	SSY [4]
(Trees·ha^{-1})	(g)	(°Brix)	(%)		(kg SS·Box^{-1})	(%)	(Boxes·t^{-1})	(kg SS·ha^{-1})
513	211 a	11.86 b	0.72 a	17.13 a	2.72 a	55.83 a	250 a	12,171 c
697	200 b	12.13 ab	0.74 a	17.02 a	2.75 a	55.21 a	248 a	14,136 b
1000	198 b	12.18 a	0.76 a	16.57 a	2.78 a	55.65 a	244 a	15,392 a
Rootstock								
IAC 1697	189 b	12.71 a	0.78 a	16.78 b	2.96 a	56.94 a	226 b	13,974 c
IAC 1710	203 a	11.38 c	0.68 c	16.90 b	2.62 b	56.22 ab	257 a	18,295 a
Swingle	210 a	11.90 b	0.77 ab	16.14 b	2.70 b	55.33 b	252 a	15,590 b
Swingle 4×	210 a	12.22 b	0.73 b	17.79 a	2.70 b	53.77 c	254 a	7739 d
p-values								
Density (D)	0.0071	0.0303	0.2749	0.5988	0.1983	0.1969	0.1839	0.0003
Rootstock (R)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
D × R	0.9796	0.6517	0.2961	0.1998	0.9213	0.3285	0.9001	0.0963
CV% (D)	4.02	2.21	9.35	9.36	3.07	1.57	3.31	7.05
CV% (R)	3.62	2.68	5.12	4.37	3.61	1.64	3.79	8.27

Averages followed by different letters in the column are different by the Tukey's test ($p \leq 0.05$). Swingle 4×, allotetraploid selection of Swingle citrumelo (n = 7). [1] MI = SS/TA to estimate the fruit maturation. [2] TI = (JC × SS × 40.8 kg)/10,000 to estimate the amount of SS per industrial orange box. [3] IY = 660/TI to estimate the number of boxes to produce one ton of frozen and concentrated orange juice (FCOJ) at 66 °Brix. [4] SSY, the cumulative production of SS per hectare over the 2017–2020 period.

3.5. Efficiency of Harvesting

Harvesting is the most expensive component of producing sweet oranges, which motivated us to study whether the tree density and the rootstock vigor would influence the efficiency of this operation. Trees grafted onto IAC 1710 required about 3-fold more time to be harvested in relation to those on Swingle 4× citrumelo (HET), whereas the other rootstocks resulted in intermediate times for harvesting (Table 2). With the exception of trees on Swingle 4× citrumelo, all trees were harvested with seven-rung ladders due to the larger size, which contributed to the decrease of the operation speed. Besides that, larger trees on more vigorous rootstocks were more productive (Figure 2). Therefore, the time to harvest was directly related to the tree size and the FY of Valencia trees on the tested rootstocks and need for ladder use. In relation to the tree density, the time for harvesting a tree was 26% higher at 513 trees·ha^{-1} (6.5 m × 3.0 m) than at denser arrangements, because the FY per tree was higher (Figure 2), and it was necessary to spend more time moving from one tree to another.

When harvesting efficiency was analyzed by the amount of fruit harvested by picker (HEW), only the rootstock had an influence (Table 2). While the time for harvesting (HET) is important to schedule the operation, HEW estimation allowed us to evaluate the operational input due to the treatments tested. This efficiency was 17% higher for dwarfed Swingle 4× citrumelo trees, which could be explained by the pedestrian harvesting and the ease of collecting fruits which were closer to the picker across the tree canopy, resulting in a faster operation per weight of fruit harvested. With these trees, it was also easier to cross the rows. This was the same when the efficiency was calculated for the time to harvest 1000 fruits (HEF), even though the HEF on Swingle 4× citrumelo was similar to that on IAC 1697 but lower than on the other rootstocks. In this case, the smaller individual weight and size of fruits on IAC 1697 (Table 1) compensated the higher FY per tree (Figure 2xii), because 1000 fruits were translated into a lower load of FW and as a result, it was faster for the picker to harvest.

Table 2. Harvesting efficiency estimated by the time to harvest a single tree (HET), amount of fruit harvested by picker by minute (HEW), and time to harvest 1000 fruits (HEF) of Valencia sweet orange grafted onto four rootstocks and cultivated at three tree densities. Gavião Peixoto-SP, Brazil, 2017.

Tree Density	HET	HEW	HEF
(Trees·ha^{-1})	(min·Tree^{-1})	(kg·min^{-1})	[min·(1000 Fruits^{-1})]
513	21.78 a	4.72 a	38.54 a
697	17.98 b	4.56 a	37.31 a
1000	16.53 b	4.40 a	40.54 a
Rootstock			
IAC 1697	19.2 b	4.61 b	35.38 b
IAC 1710	26.2 a	4.34 b	44.33 a
Swingle	20.9 b	4.19 b	43.54 a
Swingle 4×	8.6 c	5.11 a	31.95 b
p-values			
Density (D)	0.0005	0.1503	0.1313
Rootstock (R)	<0.0001	<0.0001	<0.0001
D × R	0.1846	0.0649	0.5100
CV%	15.98	12.68	14.15

Averages followed by different letters in the column are different by the Tukey's test ($p \leq 0.05$). Swingle 4×, allotetraploid selection of Swingle citrumelo (n = 7).

3.6. Spray Coverage

Since the spray volume is currently calculated by the tree RV in the citrus industry, with major impact on pest control and related production costs, it is of interest to investigate the effect of tree density and rootstock vigor on this parameter. For the lowest spray volume that was evaluated (25 mL·m^{-3}), IAC 1710 rootstock provided a higher spray coverage regardless of tree density in relation to Swingle 4× citrumelo at 1000 trees·ha^{-1} in bilateral and at 513 trees·ha^{-1} in unilateral spraying, five years after planting (Figure 5i). On average, a higher spray coverage was observed in the outer center than in the inner center of the tree canopy, while the entrance and the exit did not differ from the other positions (Figure 5ii), which was expected since this low volume is recommended for psyllid control aimed at reaching only the young shoots. When the spray volume was increased to 70 mL·m^{-3}, none of the evaluated treatments and positions affected the spray coverage (Figure 5iii,iv). However, at the highest spray volume of 120 mL·m^{-3}, the results were similar to 25 mL·m^{-3}, but lower for 513 trees·ha^{-1} within Swingle 4× citrumelo (Figure 5v), and the water-sensitive paper position on the canopy was not a significant factor (Figure 5vi). Overall, under the evaluated conditions, the spray coverage was directly related to the spray volume, with larger trees and outer canopy positions improving the coverage. Moreover, the spraying at different application speeds did not influence the spray coverage; hence, higher speeds can be used for increasing operational efficiency (Figure A3).

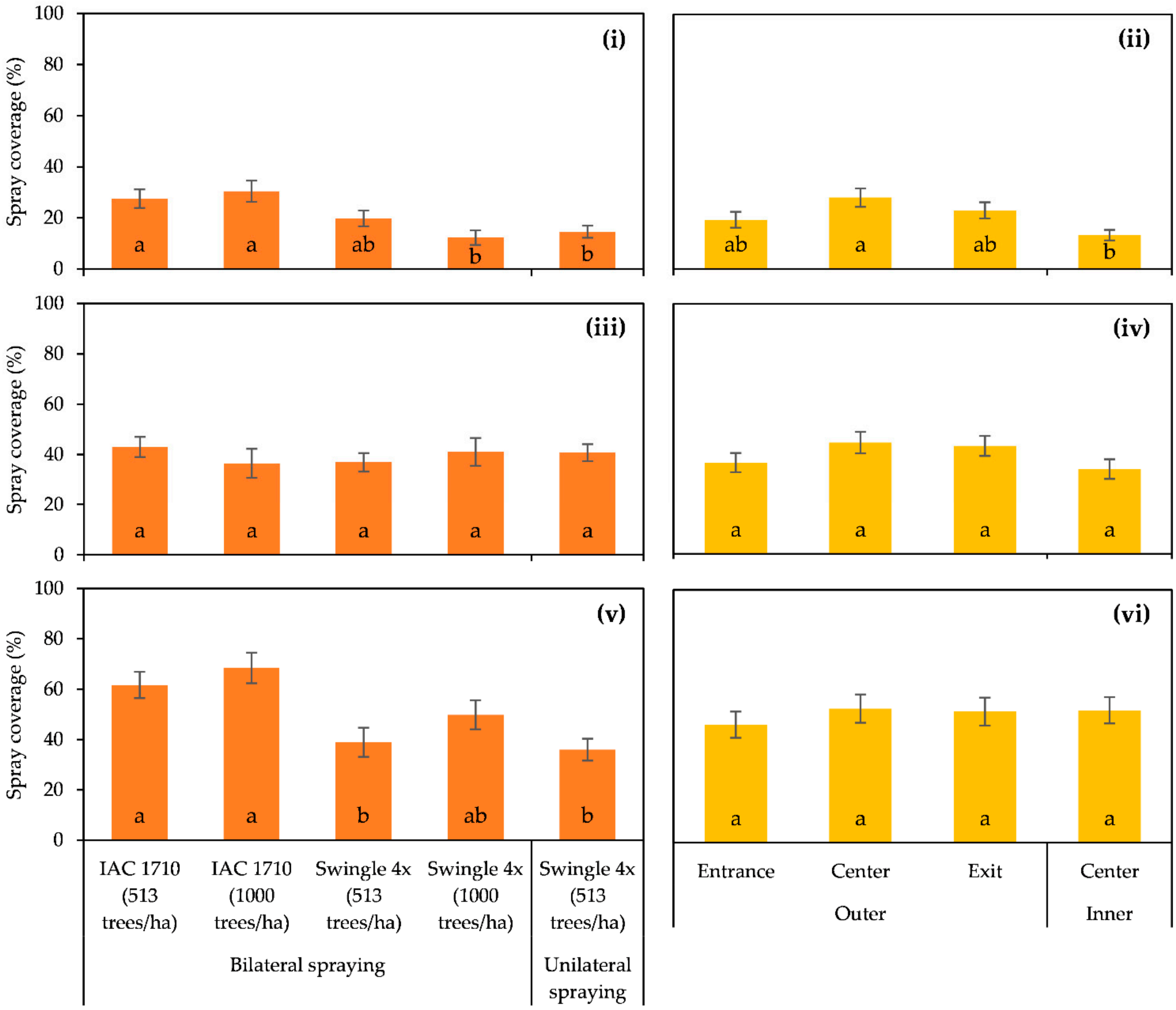

Figure 5. Average spray coverage using spray volumes of 25 mL·m^{-3} (**i**,**ii**), 70 mL·m^{-3} (**iii**,**iv**), and 120 mL·m^{-3} (**v**,**vi**) at four positions on the tree canopy (**ii**,**iv**,**vi**) of water-sensitive papers placed on the canopy of Valencia sweet orange grafted onto IAC 1710 (vigorous) and allotetraploid Swingle citrumelo (Swingle 4×, dwarfing) rootstocks at 6.5 m × 3.0 m (513 trees·ha^{-1}) and 5.0 m × 2.0 m (1000 trees·ha^{-1}) tree spacings and sprayed bilaterally (all treatments) and unilaterally (only Swingle 4× at 513 trees·ha^{-1}). Gavião Peixoto-SP, Brazil, 2018. Means followed by different letters within each panel are different by the Tukey's test ($p \leq 0.05$). Bars indicate the standard errors of means (n = 6).

3.7. HLB Incidence

The annual mean HLB incidences in the experimental area were 3%, 7%, 8%, 11%, 12%, 13%, and 19% for 2014, 2015, 2016, 2017, 2018, 2019, and 2020 (2nd to 9th years after planting), respectively. There was no significant interaction between the tree density and the rootstock on the annual HLB incidence and the AUDPC. Among the tree densities evaluated, the final disease incidence reached mean values of 16%, 21%, and 21% at 513, 697, and 1000 trees·ha^{-1}, respectively. However, among the evaluated rootstocks, the HLB incidences were significantly different in all evaluated years, except the 7th and 8th after planting, and for the AUDPC (2014–2020 period). The final disease incidence in 2021 reached mean values of 14%, 18%, 18%, and 27% for Swingle 4× citrumelo, Swingle citrumelo, IAC 1697, and IAC 1710, respectively. The HLB incidence over the evaluated period and the cumulative value of AUDPC were predominantly lower on Swingle 4× citrumelo, with mean AUDPC value 51.1%, 42.3%, and 25.0% lower than on IAC 1710, IAC 1697, and Swingle citrumelo, respectively, but not significantly differing from the latter rootstock (Table 3).

Table 3. Cumulative huanglongbing (HLB) incidence over the 2014–2021 period (2nd to 9th years after planting), except by 2015, and mean AUDPC of Valencia sweet orange grafted onto four rootstocks and cultivated at three tree densities. Gavião Peixoto-SP, Brazil, 2014–2021.

Tree Density	Cumulative HLB Incidence [1]							Mean AUDPC [2]
(Trees·ha^{-1})	2014	2016	2017	2018	2019	2020	2021	
513	0.03 a	0.08 a	0.08 a	0.10 a	0.10 a	0.11 a	0.16 a	0.62 a
697	0.04 a	0.09 a	0.09 a	0.13 a	0.14 a	0.15 a	0.21 a	0.78 a
1000	0.02 a	0.06 a	0.07 a	0.11 a	0.13 a	0.14 a	0.21 a	0.66 a
Rootstock								
IAC 1697	0.04 a	0.08 a	0.10 a	0.14 a	0.14 a	0.15 a	0.18 ab	0.78 a
IAC 1710	0.04 a	0.11 a	0.11 a	0.14 a	0.15 a	0.17 a	0.27 a	0.92 a
Swingle	0.04 a	0.07 ab	0.07 ab	0.09 ab	0.10 a	0.11 a	0.18 ab	0.60 ab
Swingle 4×	0.01 b	0.04 b	0.05 b	0.07 b	0.09 a	0.10 a	0.14 b	0.45 b
p-values								
Density (D)	0.4340	0.1920	0.3100	0.3100	0.1030	0.1970	0.1770	0.433
Rootstock (R)	0.0440	0.0080	0.0060	0.0020	0.0550	0.1120	0.0020	<0.0001
D × R	0.6220	0.1730	0.0910	0.1650	0.4000	0.1340	0.6790	0.0800
CV%	151.46	91.93	84.48	69.93	61.99	61.65	56.76	44.96

Averages followed by different letters in the column are different by the Dwass–Steel–Critchlow–Fligner (DSCF) test ($p \leq 0.05$) and the Tukey's test ($p \leq 0.05$) for the median HLB incidence and the mean AUDPC, respectively. Swingle 4×, allotetraploid selection of Swingle citrumelo (n = 7). [1] Proportion of the cumulative number of HLB-symptomatic trees from the total of assessed trees. [2] AUDPC, area under the disease progress curve.

4. Discussion

The production of sweet oranges for juice processing is one of the most competitive and efficient industries among food commodities. To achieve this, several investments have been addressed to improve processing facilities, logistics, and farming. For the latter, productivity is prioritized, as it exerts a pivotal impact on decreasing the production cost of raw materials (fruit). Notwithstanding the impressive gains in past decades, other aspects of production have emerged as equally important in the last 20 years. The demand for better quality juice (thus, better quality fruit) increases the need for more sustainable management practices in the field, especially to control limiting diseases such as HLB, in addition to the soaring replacement of labor by automation technologies, and environmental, economic, and climatic factors that may be partially addressed by liberating land for preservation and diversification. In this context, we have evaluated the performance of Valencia sweet orange trees grafted onto rootstocks with contrasting vigor, from dwarfing to super-standard genotypes (Figure A4) and their ability to produce in tree densities ranging from those currently in use with one to about double the density. Important influences of the tree density and choice of rootstock were found with an effect on the FP and fruit quality, pest management, and cropping efficiency, which are highlighted herein to help support growers and researchers' decisions.

4.1. Increasing the Tree Density Works Best, as Long as Highly Productive Rootstocks Are Available

Since the tree RV increased with the tree density, the resulting productivity was higher notwithstanding the decrease in the FY per a tree basis. Likewise, more vigorous rootstocks led to greater productivity gains, even at 1000 trees·ha^{-1}. Only IAC 1710 citrandarin resulted in about 23,000 m^3 of canopy per hectare, which is in the economic range of 20,000 to 30,000 m^3·ha^{-1} according to previously published results [14]. However, nine years after planting, it was notable the more pronounced depletion in FY and tree size of vigorous rootstocks due to the overcrowding, and it was necessary to prune trees to make operations feasible. As expected, the CV that was removed by pruning after harvesting was significantly higher for the more vigorous rootstocks. Although pruning was minimal on dwarfing rootstocks, their higher production efficiency was not sufficient to compensate for the lower FY, and at 1000 trees·ha^{-1}, there was some decrease in tree yield over the evaluation period. Hence, their productivity was always lower: Valencia sweet oranges on allotetraploid Swingle citrumelo rootstock at 1000 trees·ha^{-1} accumulated only 153 t·ha^{-1} from 2014 to 2020, even with a 40% increase over 513 trees·ha^{-1}, while trees on IAC 1710 at 513 and 1000 trees·ha^{-1} accumulated 286 and 367 t·ha^{-1}, respectively (Table S3). This clearly demonstrated that productive rootstocks are crucial to boost citrus productivity in the subtropics, with the advantage of causing minimal impact on the production cost compared with increasing tree density [20,22,67].

Therefore, dwarfing rootstocks should be evaluated at tree densities beyond 1000 trees·ha^{-1}, since the tree RV was less than the half of the other rootstocks tested, but this may be limited by economical and operational limitations and even by the limited availability of adapted varieties. Breeding more productive dwarfing rootstocks seems to be vital or better climate and management practices should be considered such as irrigation and additional fertilization on already available ones. Grafting of highly vigorous sweet orange scion varieties may be more adapted to such rootstocks, likewise the performance of the very vigorous Persian lime and lemons scions [26,31]. On the other hand, in this work, semi-dwarfing rootstocks such as IAC 1697 provided better performance and may be an intermediate solution: the productivity at double of trees per area was closer to that of IAC 1710 (Table S3), but the tree RV was still 35% lower (Table S1). Although the productivity results are favorable for the most vigorous rootstock, IAC 1710, its performance at high tree densities in the long term and/or after pruning is still to be evaluated. Mature orchards at higher densities produce the same or even less than trees at wider tree spacings, with no reason to use more than 1000 trees·ha^{-1} of sweet orange on traditional rootstocks [18].

4.2. The Rootstock, Rather Than the Tree Density, Is Decisive for Sweet Orange Quality for Processing

Over the evaluation period (four harvests), there was no relevant influence of tree density on the fruit quality, except by the trend to decrease the FW and the MI, but increase soluble solids and acidity, which was similar to previous reports in the USA [14,15]. Recently, there is an increasing concern in the Brazilian citrus industry about a notable reduction in the industrial index in the last years [68], which has been partially attributed to the increased tree density after HLB was first reported [10]. This belief is not supported by our data so far; in fact, we observed an opposite effect, as there was some improvement in the fruit quality parameters at higher tree densities. Citrus flowering is highly dependent upon exposure to radiation; hence a bearing volume is observed at a maximum of ~1 m inside the canopy [69]. Accordingly, larger trees present a greater nonbearing volume within the inner canopy. That is why the tree size and the FY per tree were reduced by higher tree densities that increase shading between trees. Production is concentrated to the portion of the CV that intercepts most sunlight, which in turn increases the fruit quality [70]. This is consistent with the observed production efficiency (production per tree CV), which was 23% higher for trees on dwarfing rootstocks but 26% lower at 1000 trees·ha^{-1}. Since the tree RV was on average 55% higher but the tree CV was 27% lower for the highest tree density, regardless of the rootstock, it may be speculated that fruit with more SS and TA was harvested on average because a higher ratio of the bearing to nonbearing volumes was attained per area and less fruit per tree competed for the available carbohydrates. However, long-term evaluations should be carried out in this regard, and putative physiological causes of this phenomenon should be further investigated as other factors such as climate conditions, HLB incidence, and irrigation are more likely to impact on citrus fruit quality than the tree density itself [69,71–73]. In addition, it must be pointed out that results herein are very relevant for the cultivation of sweet orange for industrial juice production but may not be extended to fresh fruit consumption, particularly because of the observed tendency of higher tree densities to decrease the FW and the MI.

On the other hand, the results shown here unequivocally indicated the major role of the rootstock on sweet orange fruit quality, which should be one of the main aspects to be considered by growers and processors [74]. IAC 1710 induced 2.4 times more cumulative soluble solids per area than Swingle 4× citrumelo, on average, due to its superior FY, while the relative increase due to the tree density was only 26%. Nevertheless, IAC 1710 induced lower soluble solids content and acidity in the juice of Valencia oranges, whereas IAC 1697 stood out as the preferable rootstock for inducing fruit quality for NFC processing, leading to a mean of 12.71 °Brix, a ratio of 16.78, and 2.96 kg SS·box^{-1}. Its cumulative SSY per hectare was 25% lower than that of IAC 1710, on average, because it is a semi-dwarfing, yet productive, rootstock. A similar behavior is reported for this same rootstock in Florida, where it is known as US-812 [75]. Its superior fruit quality, intermediate tree size, and good production were also observed with Valencia sweet orange in other field trials performed in São Paulo and Paraná [76,77]. IAC 1697 decrease of production over time may be related to symptoms observed that are suspicious of blight or certain local strains of citrus tristeza virus (CTV), which are under investigation, although this rootstock is reputed as highly tolerant to both diseases in Florida conditions.

4.3. Cropping Practices Can Benefit from Ultra-High Pedestrian Orchards

Apart from productivity, functionality has also become a desirable attribute for production systems of fruit crops [23–26]. Nevertheless, there are few studies on the ease of fruit harvesting due to the tree size [78–80]. In our work, it was shown that manual harvesting is faster and more efficient for scions on dwarfing rootstock. Therefore, manual harvesting has potential to be less expensive and more easily planned, if similar levels of productivity and tree RV are attained by high-density orchards on dwarfing rootstocks compared with those of traditional ones. Furthermore, smaller trees are more likely to enable mechanical harvesting of citrus, which may decrease harvesting costs by 50% [27,81,82]. This reinforces the need to breed better performing dwarfing rootstocks or improve management practices leading to higher productivities.

Pest management is another subject that could be refined in compact pedestrian orchards, because current spray volume rates are based on the tree RVs [83–86]. We expected that spray coverage would be higher for dwarfed trees due to the lower CV. Conversely, larger trees on IAC 1710 rootstock enabled a higher coverage, especially when a low spray volume was used. This was related to the type of air blast sprayer used which was not appropriate for smaller trees, resulting in a longer distance from the nozzles to the tree and higher heights of the deflector box and the turbine center (Figure A2). The use of proper equipment suitable to spray smaller trees may be more efficient and economical to reach the targeted spray coverage of $\geq$ 30% on the outer center of canopy [59]. In addition, this evaluation was carried out once in 2018, five years after planting, and trees were generally small. Hence, different results may be obtained, if spray tests would be performed on older and larger trees. In mature orchards with 4–4.5 m-tall trees, spraying 35 to 580 mL·m^{-3} resulted, in general, in a lower spray coverage at mid and top heights [87,88]. Moreover, although the spray coverage was higher for trees on the most vigorous rootstocks, there was no significant influence of the tree density at five years of age. In spite of the fact that Swingle 4× citrumelo resulted in a 64% less spray volume per hectare, the productivity was lower; thus, it would be necessary to set more trees per area and consequently increase spraying. As a result, it is more relevant to relate the spray economy with the production efficiency rather than only the RV. In this sense, less dense orchards and those on IAC 1697 rootstock produced higher FYs over the years with the least tree RV, demanding less spray volume, which may have economic and environmental implications. Therefore, improving the production efficiency of the RV seems to be determinant for the potential reduction of pesticide use.

This possibility is corroborated by the results on HLB management, because after nine years under strict vector control, the cumulative incidence of HLB-symptomatic trees on the vigorous IAC 1710 (27%) was double that on the dwarfing Swingle 4× citrumelo (14%), regardless of the tree density. In this work, infected trees were eradicated upon detection over the evaluation period without resetting; thus, the cumulative productivity was decreased by 10% on average, ranging from 13% (IAC 1710) to 7% (Swingle 4×

citrumelo). Due to the higher FY, the orchard on IAC 1710 was still more productive. It would be advisable to evaluate the disease progress for a longer period, but it was previously shown that dwarfing rootstocks resulted in a lower HLB incidence in the long term in managed orchards [89], which could be explained by their lower shoot number and length [90]. In conditions in which spray coverage is improved by using proper application procedures, it would be expected that HLB control could be facilitated by the use of dwarfing rootstocks, irrespective of their susceptibility to the HLB-associated bacteria. Indeed, HLB incidence increased over years, as trees got larger, which supports that the spray coverage may be gradually decreased for trees on the most vigorous rootstocks. The farm routinely sprayed the experimental area with equipment and spray volumes that were calculated by the conventional tree RV of the standard rootstock, namely the Swingle citrumelo. Therefore, trees on Swingle 4× citrumelo were probably over-sprayed since planting, which may explain the lower cumulative incidence as well. Another relevant aspect is that applying similar rates of systemic insecticides to all trees during the three initial years may have favored dwarfed trees. The efficacy of chemical control of ACP on scions grafted on different citrus rootstocks is a neglected subject of study, and additional research should be devoted to it.

Although it was not possible to evaluate the performance of the treatments if infected trees were kept and varietal tolerance either tree size/age at infection moment could influence, in Florida high-density orchards under HLB endemics were more productive at similar tree populations to these used in this work even if the FY was very low overall. Interestingly, among 16 rootstocks grafted with Valencia sweet orange, IAC 1710 was also one of the most infected rootstocks over seven years in the field in Florida, where it is designed as US-801 [91]. This reinforces the importance of the three-pronged, area-wide HLB management in all cropping circumstances and varieties [9], and high-density orchards on highly productive and vigorous rootstocks may be better directed at farms' edges to mitigate economic loss by the disease [21]. Taken together, these findings emphasize that besides better genetic material, ultra-high-density orchards still rely on other technological innovations in cultural practices and operations in order to attain higher feasibility and express all their potential [79]. In Brazil, some citrus growers are evaluating self-propelled equipment to spray young orchards that are able to spray up to seven rows, as it is common for crops with smaller plants such as coffee and cereals.

4.4. Intensively Managed, Improved Rootstocks Increase the Efficiency of Land Use in Citriculture

From 2014 to 2020, the average sweet orange productivity in the State of São Paulo was 31.89 t·ha^{-1} [57], which is one of the highest values for this fruit crop worldwide [1]. For a number of reasons, the technological intensification of citriculture in Brazil since the late 1980s augmented productivity, with much less use of the land area [44]. We hypothesized that increasing the tree density in association to the use of proper rootstock varieties with contrasting vigor would allow for further land use efficiency. The perfect match we were looking for should increase fruit production with a less area and better practicality of cropping. Doubling the current average of about 500 trees·ha^{-1} would save 0.22 ha for each hectare cultivated with sweet orange, but a minimal advantage would be obtained from increasing three densities by 50% to 696 trees·ha^{-1}. However, this performance was dramatically influenced by the rootstock used. Although all evaluated rootstocks increased productivity at higher tree density and, consequently, land use efficiency, grafting on the dwarfing allotetraploid Swingle citrumelo would only equate the current land use at the highest density and if only full-bearing trees were considered, from 2017 to 2020 (Table S4). On the other hand, the highly vigorous IAC 1710 improved the land use by 46% on average to a maximum of 2.4 times if only high-density mature orchards were considered. This clearly showed that high-performing rootstocks constitute very effective tools for land-saving. For instance, theoretically, if all Brazilian citrus belt was cultivated by this combination, harvested area in 2020 could be reduced from current 367,246 to 151,852 ha without any decrease of the total production.

To make the Swingle 4× citrumelo more viable and match the current land use efficiency, it would be necessary to improve the tree density and the FY per tree; in this case, it would be necessary to produce at least 32 kg·tree^{-1} compared with the observed mean of ~22 kg·tree^{-1} at 1000 trees·ha^{-1}, but only at the half tree density, this yield is possible. Besides that, there was no substantial difference of Valencia fruit quality between diploid and tetraploid Swingle citrumelos, as previously reported [92], but tetraploid selection decreased the tree size and the FY by 50% compared to the diploid one. This is an experimental genotype under breeding selection, and highly productive individuals are being selected in an attempt to address this limitation, as they can be used in the future as the mother tree to produce seed. However, it was noticed some tree phenotype variation and drought intolerance within this genotype over the evaluation period, which may also imply a low FY and the need for the irrigation of this rootstock. Since we have selected seedlings in the nursery based on morphological traits, but they were not tested with molecular markers to precisely discard all zygotic individuals, this phenotype variation may have resulted from genetic unconformity of some plants because seeds of allotetraploid Swingle citrumelo present up to 30% of zygotic embryos [93], and consequently, this genotype would be better micropropagated for use in commercial orchards. From our results, an ideal dwarfing rootstock would be 2.5 to 3.0 m in height and yield 40 to 60 kg·tree^{-1} at high tree density. Auto and allotetraploid varieties as well as 4n hybrids have potential as dwarfing rootstocks [36,92], and the tetraploidization of elite materials such as IAC 1710 should be further considered in breeding programs.

Although Valencia trees grafted onto IAC 1710 citrandarin performed well at high tree densities, there were some limitations for this management strategy. Trees were pruned only at nine years of age due to grower decision, which allowed for high cumulative productivity up to the seventh harvest, but a sharp 25% decrease in the tree size that eventually will impact on subsequent crops. Mechanical operations were very difficult, since there was no equipment properly developed for such a dense orchard, especially for spraying, which may correlate to the higher HLB incidence in trees grafted on this rootstock. Moreover, pruning may induce more shooting which in turn can expose trees to even higher infestation and thus bacterial infection rates compared to those of smaller trees. This experiment will continue to be evaluated for next years, carrying out annual pruning after harvesting to maintain the tree size suitable to the available tree spacing, and the long-term effect on the performance will be studied, as it is expected that productivity at higher tree densities decreases with time on traditional rootstocks [18]. A detailed economic analysis considering the entire lifespan of the sweet orange orchard, about 15 to 20 years, should be provided to support grower decisions beyond the potential benefit for the land use and less dependence on the labor. Additional innovations such as less expensive types of nursery trees will be likely necessary to decrease investment in high-density orchards [94]. Finally, the performance of the diploid Swingle citrumelo is worthy of mention, because it ranked just next to IAC 1710 citrandarin regarding the productivity while the tree size and the fruit quality were more favorable, and HLB incidence was not different from that of trees on the dwarfing selection. This corroborates the high utility of this rootstock as an alternative to the traditional Rangpur lime, despite its lower tolerance to drought [5]. Once Swingle citrumelo has allocated for 18% more intense land use than the current practice [57], it is expected that as the use of this rootstock increases in the Brazilian citrus belt [6], the average sweet orange productivity will raise, contributing to the sustainability of the industry.

In conclusion, the cumulative productivity of sweet orange was increased over the seven initial harvest by 27% at 1000 trees·ha^{-1} compared with the moderate 513 trees·ha^{-1}, irrespective of the rootstock. Although trees grafted on the most vigorous rootstocks required pruning that reduced the tree size by 20% at nine years of age, they produced 2.5 times more fruit than those on dwarfing rootstocks on average. Most fruit quality parameters were seldom influenced by the tree density, while the rootstock was a decisive factor in improving the quality and the soluble solids content. On the other hand, harvesting trees on dwarfing rootstocks allowed for a 17% more efficient manual collection of fruit which attested to a higher potential for mechanization. Because the tree RV per area is lower with such rootstocks, even at higher tree density, the spray volume can be reduced, although appropriate equipment should be developed for better spray coverage on smaller trees. The cumulative incidence of HLB-symptomatic trees over nine years under the strict control of the vector for trees on IAC 1710 was double those on Swingle 4× citrumelo rootstocks, which reinforces that smaller trees may be easier to manage. The results, herein, suggested that the land use efficiency in the citrus industry can be further improved by planting currently available vigorous rootstocks at moderate to high tree densities. Nevertheless, obtaining highly productive semi-dwarfing and dwarfing rootstocks is the sine qua non of making high-density pedestrian sweet orange orchards more profitable in the near future.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/agronomy11122569/s1, Table S1. Split averages of tree size variables of Valencia sweet orange grafted onto four rootstocks and cultivated at three tree densities. Gavião Peixoto-SP, Brazil, 2020. Table S2. Split averages of production variables of Valencia sweet orange grafted onto four rootstocks and cultivated at three tree densities. Gavião Peixoto-SP, Brazil, 2014–2020. Table S3. Split averages of productivity variables of Valencia sweet orange grafted onto four rootstocks and cultivated at three tree densities. Gavião Peixoto-SP, Brazil, 2014–2020. Table S4. Split averages of production efficiency and land use variables of Valencia sweet orange grafted onto four rootstocks and cultivated at three tree densities. Gavião Peixoto-SP, Brazil, 2014–2020. Table S5. Split averages of fruit quality variables of Valencia sweet orange grafted onto four rootstocks and cultivated at three tree densities. Gavião Peixoto-SP, Brazil, 2017–2018. Table S6. Split averages of fruit quality variables of Valencia sweet orange grafted onto four rootstocks and cultivated at three tree densities. Gavião Peixoto-SP, Brazil, 2019–2020. Table S7. Split averages of mean fruit quality and soluble solids yield variables of Valencia sweet orange grafted onto four rootstocks and cultivated at three tree densities. Gavião Peixoto-SP, Brazil, 2017–2020.

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Appendix A

Table A1. Tree row volume, spray volume, operation speed, type and number of nozzles, application flow (spray volume per minute and nozzle), and operation pressure for each spraying treatment on Valencia sweet orange grafted onto IAC 1710 citrandarin and allotetraploid Swingle citrumelo (Swingle 4×) at 6.5 m × 3.0 m and 5.0 m × 2.0 m tree spacings (513 and 1000 trees·ha^{-1}, respectively). Gavião Peixoto-SP, Brazil, 2018.

Rootstock (Spraying System)	Tree Spacing In-Rows (m)	Between-Rows (m)	Tree Row Volume (m^3·ha^{-1})	Spray Volume (mL·m^{-3})	Spray Volume (L·ha^{-1})	Speed (km·h^{-1})	Number of Nozzles	Application Flow (L·min^{-1}·nozzle^{-1})	Nozzle Type [1]	Pressure (psi)
IAC 1710 (bilateral)	5.00	2.00	28,682	25	717	7.8	52	0.896	AD2/AC25	116
				70	2008	4.5	52	1.448	AD4/AC25	101
				70	2008	7.8	52	2.510	AD5/AC25	158
				120	3442	1.7	52	0.938	AD2/AC25	127
				120	3442	4.5	52	2.482	AD5/AC25	154
	6.50	3.00	21,225	25	531	7.8	52	0.862	AD2/AC25	108
				70	1486	4.5	52	1.393	AD3/AC25	189
				70	1486	7.8	52	2.414	AD5/AC25	146
				120	2547	1.7	52	0.902	AD2/AC25	118
				120	2547	4.5	52	2.388	AD5/AC25	143
Swingle 4× (bilateral)	5.00	2.00	11,048	25	276	7.8	30	0.598	AD2/AC23	128
				70	773	4.5	30	0.967	AD2/AC25	135
				70	773	7.8	30	1.676	AD4/AC25	135
				120	1326	1.7	30	0.626	AD2/AC23	140
				120	1326	4.5	30	1.657	AD4/AC25	132
	6.50	3.00	7147	25	179	7.8	30	0.503	AD2/AC23	90
				70	500	4.5	30	0.813	AD2/AC25	96
				70	500	7.8	30	1.409	AD3/AC25	193
				120	858	1.7	30	0.526	AD2/AC23	99
				120	858	4.5	30	1.394	AD3/AC25	189
Swingle 4× (unilateral)	6.50	3.00	7147	25	179	7.8	15	0.503	AD2/AC23	90
				70	500	4.5	15	0.813	AD2/AC25	96
				120	858	1.7	15	0.526	AD2/AC23	99

[1] Nozzles from the Jacto, the disc, and the core, with AD as the spraying disc and AC as the core.

Table A2. Annual fruit weight (FW), soluble solids content (SS), titratable acidity (TA), maturity index (MI), technological index (TI), juice content (JC), industrial yield (IY), and SS yield (SSY) of fruits of Valencia sweet orange grafted onto four rootstocks and cultivated at three tree densities in 2017 and 2018. Gavião Peixoto-SP, Brazil.

Tree Density	FW	SS	TA	MI [1]	TI [2]	JC	IY [3]	SSY [4]
(Trees·ha^{-1})	(g)	(°Brix)	(%)		(kg SS·Box^{-1})	(%)	(Boxes·t^{-1})	(kg SS·ha^{-1})
				2017				
513	177 a	12.63 a	0.77 a	16.94 a	2.98 a	57.94 a	222 a	3536 c
697	167 a	12.87 a	0.81 a	16.19 a	2.99 a	57.02 a	221 a	4102 b
1000	170 a	12.89 a	0.78 a	16.68 a	3.07 a	58.50 a	216 a	4891 a
Rootstock								
IAC 1697	160 b	13.30 a	0.81 a	16.61 a	3.21 a	59.10 a	206 c	4790 ab
IAC 1710	187 a	11.67 c	0.67 b	17.45 a	2.79 c	58.61 ab	237 a	5100 a
Swingle	178 a	12.60 b	0.84 a	15.29 a	2.95 b	57.44 bc	224 b	4464 b
Swingle 4×	159 b	13.61 a	0.82 a	17.05 a	3.11 a	56.13 c	212 c	2352 c
p-values								
Density (D)	0.0914	0.2097	0.4364	0.5373	0.0851	0.0602	0.1090	0.0002
Rootstock (R)	<0.0001	<0.0001	0.0022	0.0760	<0.0001	<0.0001	<0.0001	<0.0001
D × R	0.5685	0.666	0.5361	0.6836	0.8311	0.0597	0.8074	0.3698
CV% (D)	6.39	3.12	10.29	11.07	3.37	2.38	3.57	9.02
CV% (R)	7.80	3.06	13.45	12.20	3.06	2.12	3.37	10.49

Table A2. *Cont.*

Tree Density	FW	SS	TA	MI [1]	TI [2]	JC	IY [3]	SSY [4]
(Trees·ha^{-1})	**(g)**	**(°Brix)**	**(%)**		**(kg SS·Box^{-1})**	**(%)**	**(Boxes·t^{-1})**	**(kg SS·ha^{-1})**
Tree density (trees·ha^{-1})					**2018**			
513	242 a	10.99 a	0.82 a	13.64 a	2.18 a	48.48 a	306 a	1978 b
697	230 a	11.23 a	0.87 a	13.19 a	2.18 a	47.55 a	305 a	2396 ab
1000	234 a	11.31 a	0.89 a	13.02 a	2.21 a	47.81 a	302 a	2563 a
Rootstock								
IAC 1697	220 b	11.82 a	0.89 a	13.43 ab	2.43 a	50.42 a	272 b	2388 b
IAC 1710	232 ab	10.75 b	0.76 b	14.19 a	2.16 b	49.11 ab	308 a	3470 a
Swingle	248 a	10.94 b	0.91 a	12.25 b	2.11 b	47.12 bc	316 a	2389 b
Swingle 4×	241 ab	11.20 b	0.87 ab	13.25 ab	2.06 b	45.13 c	322 a	1003 c
p-values								
Density (D)	0.3273	0.2560	0.2696	0.6841	0.8598	0.4797	0.8862	0.0241
Rootstock (R)	0.0101	0.0003	0.0130	0.0551	<0.0001	<0.0001	0.0001	<0.0001
D × R	0.5345	0.8756	0.8059	0.9328	0.7700	0.6584	0.8162	0.9439
CV% (D)	8.82	4.44	12.84	15.16	7.78	4.36	8.54	19.18
CV% (R)	8.29	4.83	12.59	12.35	7.75	4.24	7.97	24.71

Averages followed by different letters in the column are different by the Tukeys test ($p \leq 0.05$). Swingle 4×, allotetraploid selection of Swingle citrumelo (n = 7). [1] MI = SS/TA to estimate the fruit maturation. [2] TI = (JC × SS × 40.8 kg)/10,000 to estimate the amount of SS per industrial orange box. [3] IY = 660/TI to estimate the number of boxes to produce one ton of FCOJ at 66 °Brix. [4] SSY, the cumulative production of SS per hectare.

Table A3. Annual fruit weight (FW), soluble solids content (SS), titratable acidity (TA), maturity index (MI), technological index (TI), juice content (JC), industrial yield (IY), and SS yield (SSY) of fruits of Valencia sweet orange grafted onto four rootstocks and cultivated at three tree densities in 2019 and 2020. Gavião Peixoto-SP, Brazil.

Tree Density	FW	SS	TA	MI [1]	TI [2]	JC	IY [3]	SSY [4]
(Trees·ha^{-1})	**(g)**	**(°Brix)**	**(%)**		**(kg SS·Box^{-1})**	**(%)**	**(Boxes·t^{-1})**	**(kg SS·ha^{-1})**
					2019			
513	212 a	11.20 a	0.59 a	19.32 a	2.50 b	54.70 a	266 a	3668 b
697	208 a	11.47 a	0.58 a	19.76 a	2.55 ab	54.44 a	261 ab	4210 ab
1000	192 b	11.67 a	0.60 a	19.51 a	2.64 a	55.39 a	252 b	4877 a
Rootstock								
IAC 1697	183 c	12.54 a	0.62 a	20.29 ab	2.95 a	57.57 a	224 b	4583 a
IAC 1710	199 b	10.69 c	0.61 a	17.45 c	2.43 b	55.73 ab	272 a	5647 a
Swingle	212 ab	11.19 b	0.60 a	18.70 bc	2.47 b	54.20 b	267 a	4815 a
Swingle 4×	222 a	11.37 b	0.53 b	21.69 a	2.41 b	51.88 c	275 a	1962 b
p-values								
Density (D)	0.0151	0.1016	0.7502	0.8529	0.0501	0.0540	0.0488	0.0320
Rootstock (R)	<0.0001	<0.0001	0.0013	0.0002	<0.0001	<0.0001	<0.0001	<0.0001
D × R	0.4771	0.3575	0.0867	0.3126	0.2693	0.5327	0.1992	0.5011
CV% (D)	4.64	3.44	9.64	9.71	3.53	1.21	3.67	16.29
CV% (R)	5.75	3.15	7.13	8.56	4.72	2.93	4.81	19.11

Table A3. *Cont.*

Tree Density	FW	SS	TA	MI [1]	TI [2]	JC	IY [3]	SSY [4]
(Trees·ha^{-1})	**(g)**	**(°Brix)**	**(%)**		**(kg SS·Box^{-1})**	**(%)**	**(Boxes·t^{-1})**	**(kg SS·ha^{-1})**
Tree density (trees·ha^{-1})					**2020**			
513	212 a	12.44 a	0.65 a	19.38 a	3.15 a	61.99 a	211 a	3162 a
697	196 a	12.72 a	0.67 a	19.48 a	3.19 a	61.42 a	208 a	3652 a
1000	193 a	12.69 a	0.71 a	18.07 a	3.14 a	60.75 a	211 a	3315 a
Rootstock								
IAC 1697	189 b	13.18 a	0.75 a	17.83 b	3.28 a	60.91 a	202 a	2563 b
IAC 1710	191 b	12.23 b	0.65 ab	18.81 ab	3.06 a	61.34 a	217 a	4377 a
Swingle	203 ab	12.62 ab	0.67 ab	19.14 ab	3.20 a	62.12 a	207 a	4113 a
Swingle 4×	218 a	12.44 ab	0.64 b	20.13 a	3.10 a	61.18 a	214 a	2452 b
p-values								
Density (D)	0.1557	0.6916	0.5500	0.3949	0.9173	0.3950	0.9239	0.4181
Rootstock (R)	<0.0001	0.0123	0.0345	0.0671	0.0675	0.5341	0.0826	<0.0001
D × R	0.6294	0.5114	0.6651	0.8442	0.9436	0.5396	0.9425	0.0909
CV% (D)	12.89	7.88	24.02	15.92	10.27	3.87	10.31	29.55
CV% (R)	6.99	5.38	13.28	10.56	6.51	3.42	6.98	16.34

Averages followed by different letters in the column are different by the Tukeys test ($p \leq 0.05$). Swingle 4×, allotetraploid selection of Swingle citrumelo (n = 7). [1] MI = SS/TA to estimate the fruit maturation. [2] TI = (JC × SS × 40.8 kg)/10,000 to estimate the amount of SS per industrial orange box. [3] II = 660/TI to estimate the number of boxes to produce one ton of FCOJ at 66 °Brix. [4] SSY, the cumulative production of SS per hectare.

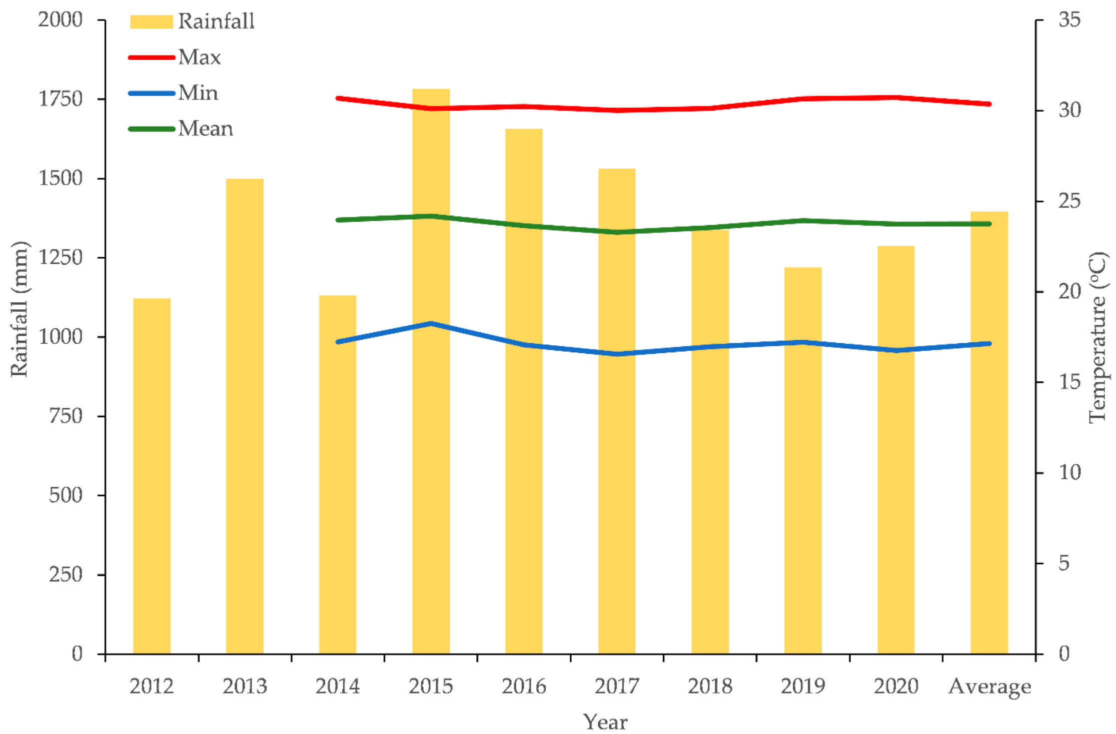

Figure A1. Annual air temperatures (maximum, minimum, and mean) and rainfalls in the 2012–2020 period at the experimental area in Gavião Peixoto, SP, Brazil.

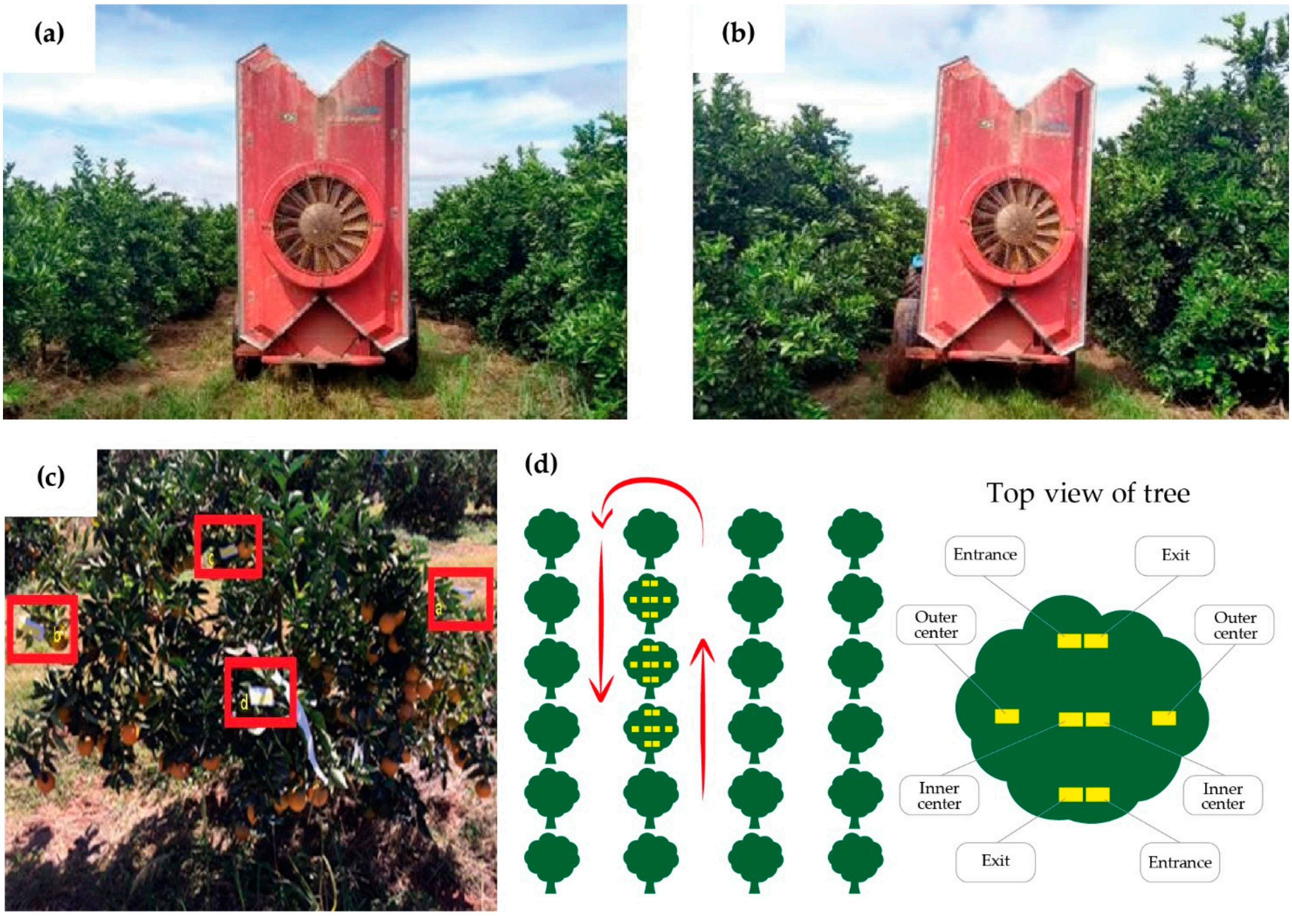

Figure A2. Experimental procedures for the evaluation of spray coverage: (**a**) positioning of the air blast sprayer during bilateral spraying in relation to the tree canopy of Valencia sweet orange grafted onto allotetraploid Swingle citrumelo (dwarfing rootstock) at a 6.5 m × 3.0 m tree spacing (1000 trees·ha^{-1}); (**b**) positioning of the air blast sprayer during bilateral spraying in relation to the tree canopy of Valencia sweet orange grafted onto IAC 1710 citrandarin (vigorous rootstock) at a 6.5 m × 3.0 m tree spacing (1000 trees·ha^{-1}); (**c**) the positioning of water-sensitive papers in the entrance (a, red square), exit (b, red square), inner center (c, red square), and outer center (d, red square) of Valencia sweet orange tree grafted onto allotetraploid Swingle citrumelo indicated by red boxes; (**d**) illustration of the experimental plot, with four parallel rows of six trees. Three central trees were used to place water-sensitive papers (yellow rectangles) in six positions on the tree canopy. Arrows indicate the direction of movement of the air blast sprayer on the plot. Gavião Peixoto-SP, Brazil, 2018.

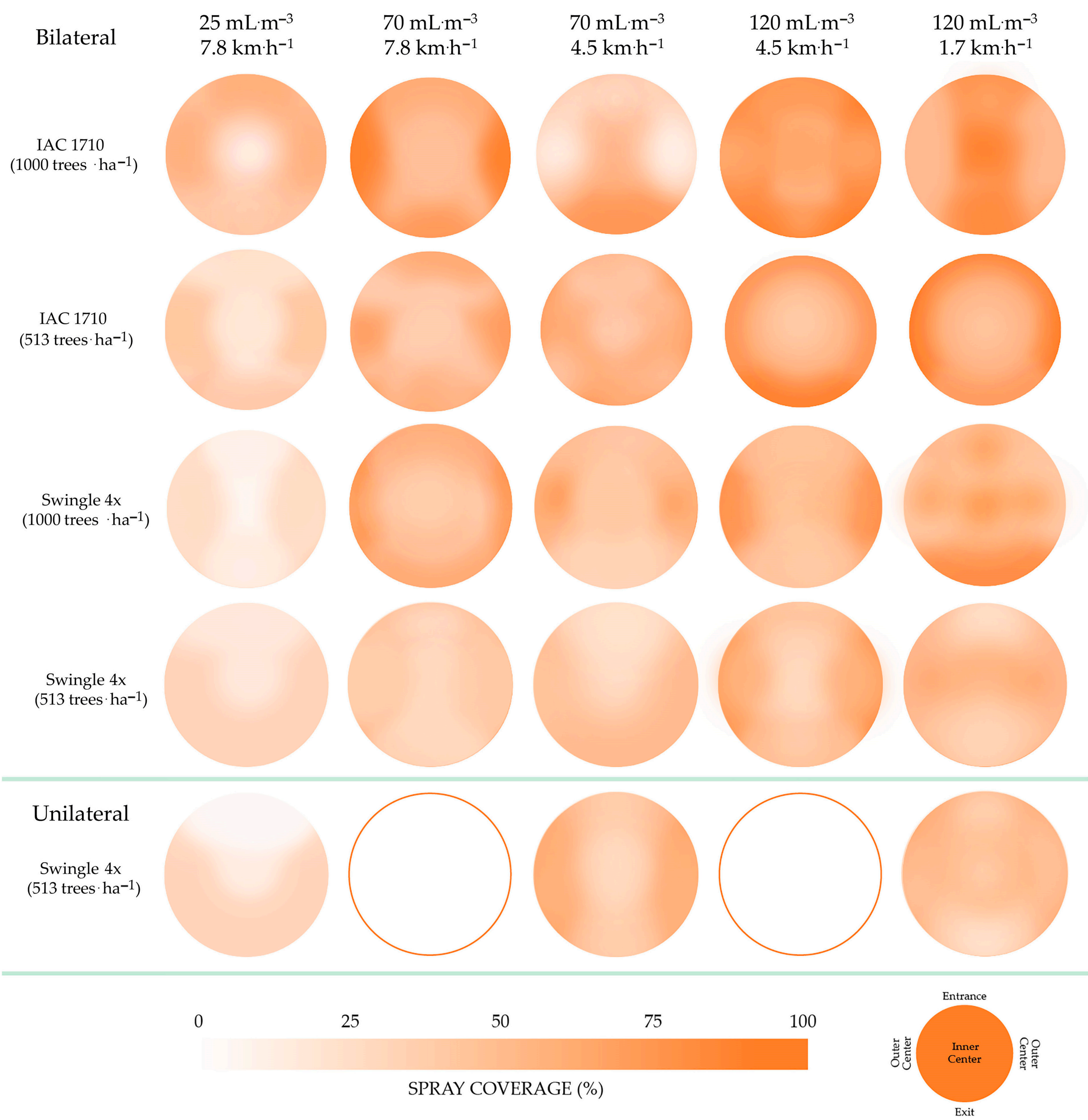

Figure A3. Top view of trees presenting the spray coverage (%) of water-sensitive papers placed at different positions on the canopy of Valencia sweet orange grafted onto IAC 1710 citrandarin (vigorous) and allotetraploid Swingle citrumelo (Swingle 4×, dwarfing) rootstocks at 6.5 m × 3.0 m (513 trees·ha^{-1}) and 5.0 m × 2.0 m (1000 trees·ha^{-1}) tree spacings and sprayed bilaterally (all treatments) and unilaterally (only Swingle 4× at 513 trees·ha^{-1}) using combinations of three spray volumes and three application speeds. White circles represent data which are not available. Gavião Peixoto-SP, Brazil, 2018 (n = 6).

Figure A4. Illustrative photos of Valencia sweet orange trees grafted onto (**i**) allotetraploid Swingle citrumelo, (**ii**) IAC 1710 citrandarin, (**iii**) IAC 1697 citrandarin, and (**iv**) diploid Swingle citrumelo rootstocks nine years after planting. Gavião Peixoto-SP, Brazil, 2020.

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