OPTIMIZING ORANGE GROVE FACTORS FOR FRUIT PRODUCTION AND HARVESTING

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ABSTRACT. *Ten hectares of oranges were planted in 1980 in an experiment to investigate optimal management practices for different tree spacings, scion, and rootstock combinations. Experimental factors included two between-row spacings (6.0, 4.5 m), two in-row spacings (4.5, 2.5 m), two scions ('Hamlin', early season; 'Valencia', late season), two rootstocks (Milam, vigorous; Rusk citrange, moderately vigorous), and two tree heights (3.7, 5.5 m).*

Conventional equipment and practices were used to provide grove care and fruit harvesting. A 2-m middle or alleyway was maintained between rows for production and harvesting equipment traffic. The oranges were manually harvested for processing using conventional fruit handling equipment.

During the 1980s, trees in the experiment endured several severe freezes which markedly reduced Florida citrus production. After nine fruit producing seasons, cumulative fruit and soluble solids yields were superior for the early orange, moderately vigorous rootstock, 6.0 × 2.5 m spacing and 5.5 height. Trees on this moderately vigorous rootstock developed smaller canopies with greater quantities of fruit per unit canopy volume. The smaller canopies allowed for a higher percentage of fruit to be harvested without a ladder, and more space for movement of pickers and fruit handling equipment. They also provided fruiting conditions which favored the use of picking aids or platforms and the use of shakers and robots. ***Keywords.*** *Oranges, Yields, Harvesting, Tree spacing, Tree growth.*

Prior to the 1980s, much of Florida's orange production was from trees that were relatively vigorous scion/rootstock combinations over 6 m in height. Most of the trees were generally managed and harvested as individual units planted at approximately 170 trees per hectare. In the 1960s, the number of trees planted per hectare (commonly termed tree density) began to increase significantly and has continued to date (Tucker and Wheaton, 1978; Commercial Citrus Inventory, 1992). This trend in tree density has resulted because of the shortage of suitable land, increasing energy costs, restrictions on water use, increasing property taxes, necessity of early income on the investment, and harvesting problems (Reitz, 1978).

For decades, the trend in deciduous fruits has been toward smaller trees and higher tree densities to increase returns per hectare by reducing production and harvesting costs (Childers, 1978). Higher density citrus plantings have demonstrated superior yields in the early bearing years, but their productivity often declined after 10 to 15 years due to crowding (Tucker and Wheaton, 1978; Koo and Muraro, 1982). Whitney and Hedden (1978) have discussed the production and harvesting advantages of smaller citrus trees at higher densities if high levels of fruit productivity can be maintained. While most production practices have been mechanized, harvesting oranges has remained an arduous manual task because the citrus industry has been reluctant to adopt picking aids and mechanical harvesters (Whitney and Harrell, 1989).

Florida growers have continued to plant higher density orange groves, even though little information is available on optimal management practices, tree spacings, scion and rootstock combinations, and their effects on productivity and harvesting. Our objective was to describe how tree growth habits, fruit production, and harvesting techniques were affected by several horticultural factors involved as treatments in a large-scale field experiment.

MATERIALS AND METHODS

Wheaton et al. (1986) have described the field experiment which was initiated in 1980 on a 10-ha site in Polk County, Florida, between Frostproof and Babson Park. Factors included in this experiment are listed in table 1. A multiple split plot design with four replications was used. Scion variety was the main plot treatment followed by smaller subplots of tree height, between-row spacing, rootstock, and in-row spacing treatments. The order of subplot treatments was arranged to help expedite the conduct of commercial grove care operations. Subplot 4 size (table 1) was 4 rows × 7 trees with the center 10 trees (2 rows × 5 trees) used for data collection.

'Hamlin' and 'Valencia' were selected as the scion varieties to represent early- and late-maturing orange

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Table 1. Experimental factors, plot designations, and levels

Factor	Plot Designation	Levels
1. Scion	Main	'Hamlin' (early orange); 'Valencia' (late orange)
2. Tree height	Subplot 1	3.7 m; 5.5 m
3. Between-row spacing*	Subplot 2	4.5 m; 6.0 m
4. Rootstock	Subplot 3	Rusk citrange (moderately vigorous); Milam (vigorous)
5. In-row spacing*	Subplot 4	2.5 m; 4.5 m

* Tree spacings 4.5 × 2.5, 6.0 × 2.5, 4.5 × 4.5, and 6.0 × 4.5 m result in tree densities of 889, 667, 494, and 370 trees/ha, respectively.

varieties. Rusk citrange and Milam were selected as moderately vigorous and vigorous rootstocks, respectively. Tree height was included as a treatment to determine if suitable fruit productivity could be achieved and managed at lower heights for any scion/rootstock/tree density combinations to facilitate harvesting.

GROVE CARE

Trees were planted in north-south rows and headed out (height on trunk where lowest limb attached) at a 61 cm height to eliminate low branches and facilitate mechanical harvesting and/or fruit handling studies. A regular commercial young tree care program was followed the first three years (Koo et al., 1984); thereafter, each application of chemicals (fertilizer and pesticides) was made at the same quantity per unit land area. Conventional equipment was used to provide grove care. Supplemental water was applied uniformly over the land area through a permanent overhead sprinkler irrigation system.

Annual hedging of the trees spaced 4.5 and 6.0 m between rows was initiated in 1985 and 1986, respectively. Initially, the straight hedging cut in the row middles was 198 cm wide near ground level and angled at 7° from vertical toward the tree top. This hedging cut reduced the tree canopy width 25 cm/m of canopy height. In 1991, the bottom width of the hedging cut was increased to 213 cm for increased clearance between grove equipment and tree limbs because the limbs being cut had become larger and more rigid.

Annual flat topping of the trees designated for the 3.7 m height began in 1987. By 1991, these trees were topped semiannually (spring, fall) to control regrowth and improve fruiting in the lower canopy of the trees on Milam rootstock. The trees designated for the 5.5 m height were topped for the first time in 1991.

TREE GROWTH

Trunk circumferences were measured annually through 1991 at a 20 cm height on the two center subplot trees. Beginning in the 1985-1986 season, horizontal canopy diameter measurements were made near ground level in the north-south (in row) and east-west (across row) directions and canopy height dimensions were measured on the two center plot trees. Tree canopy volume calculations were based on the assumption that the canopy naturally developed as one-half an ellipsoid. Modifications of canopy shape (and thus volume) by tree topping, hedging between rows, and merging canopies in row were based on these modifications of the ellipsoid shape.

YIELDS, FRUIT CHARACTERISTICS, AND HARVESTING

Fruit yield was determined by weighing the hand harvested fruit from the center 10 trees in each subplot from the 1984-1985 through the 1987-1988 'Hamlin' harvests, after which one-half plot or the five center trees in the west row were harvested to represent each plot. A sample of about 50 to 80 fruit (14 kg) was picked from each plot to make internal and external quality measurements and to measure soluble solids yield. Because of the large variation in fruit size in 1991, measurements were initiated on the diameter, weight, and specific gravity of individual fruit in each sample.

Beginning with the 1991-1992 season, fruit yield measurements were separated into two parts—that which could be harvested manually without a ladder (picker standing on the ground) and that fruit which required a ladder for harvesting. The hand-harvested oranges, which were destined for processing, were placed in conventional 10-box tubs (409 kg containers) that were emptied and handled with a conventional hi-lift truck.

RESULTS AND DISCUSSION

The trees in the experiment were damaged by a series of freezes in the 1980s which eliminated 60 000 ha of trees in the northern portion of Florida's citrus production area. Table 2 shows the freezes which delayed the growth and fruiting of the trees.

In the discussion that follows, 'Hamlin' and 'Valencia' scion varieties will be identified as early and late oranges, respectively; Rusk citrange and Milam rootstocks will be identified as moderately vigorous and vigorous, respectively. Significant differences, where stated, refer to statistical differences at the 5% level (SAS, 1985).

Table 2. Dates of Florida freezes and their effects on experimental trees planted February 1980

Date	Effect
March 1980	Frost; partial defoliation, slow recovery and tree growth
January 1981	Freeze; defoliation, bark splitting, wood damage
January 1982	Freeze; defoliation, wood damage, partial girdles
December 1983	Severe freeze; fruit frozen, defoliation, wood damage
January 1985	Severe freeze; fruit damage, leaf and wood damage
December 1985	Freeze; twig damage in top of tree, some fruit damage
March 1986	Frost; some bloom and new flush killed
February 1989	Frost; some bloom and new flush killed
December 1989	Severe freeze; fruit frozen, defoliation, wood damage

TREE GROWTH

The most vigorous scion/rootstock combination, early/vigorous, was the first requiring hedging (pruning) to control across-row canopy width and allow grove equipment movement through the middles without excessive contact damage to the equipment or tree or both. As expected, the trees at the 2.5-m in-row spacing formed hedgerows before those at the 4.5-m in-row spacing. Among the four scion/rootstock combinations, early/vigorous and late/moderately vigorous were the most and least vigorous, respectively, and the most vigorous were the first to form hedgerows and reach canopy containment size. However, there were no apparent differences in canopy sizes between trees on the two rootstocks until 1985. In 1986, tree heights averaged 3.9, 3.6, 3.5, and 3.2 m for early/vigorous, early/moderately vigorous, late/vigorous, and late/moderately vigorous, respectively. Topped for the first time in 1991, the trees designated for the 5.5 m height had average heights of 5.1, 4.0, 4.5, and 3.6 m for early/vigorous, early/moderately vigorous, late/vigorous, and late/moderately vigorous, respectively. Averaged over scions, rootstock effects on height were significant with vigorous and moderately vigorous being 4.8 and 3.8 m, respectively.

Because of the natural growth pattern of tree canopy development, the lower canopy filled its horizontal containment space before the upper canopy. The maximum horizontal dimension filled by the canopy was the hypotenuse of a right triangle with the in-row spacing and the canopy across-row dimension as the sides (fig. 1). Since the across-row dimension of the canopy was limited to 213 cm less than the between-row spacing due to hedging, the maximum horizontal dimensions to be filled by the canopy near ground level were 344, 461, 509, and 594 cm for 889, 667, 494, and 370 trees/ha, respectively. Most of the trees at 889 trees/ha had filled the maximum horizontal dimension by 1986. In 1991, trees on the vigorous rootstock at the 3.7 m height had filled the maximum horizontal dimension on all tree densities; with the moderately vigorous rootstock, the 3.7-m-high trees at 667 trees/ha had for the most part filled their maximum horizontal dimensions, while those at the two lower tree densities, 494 and 370 trees/ha, had not. Figure 2 shows the percentage of canopy containment (maximum) volume to which the trees had grown in 1993. The greater percentages were associated with the vigorous rootstock, lesser tree height, and the higher tree densities.

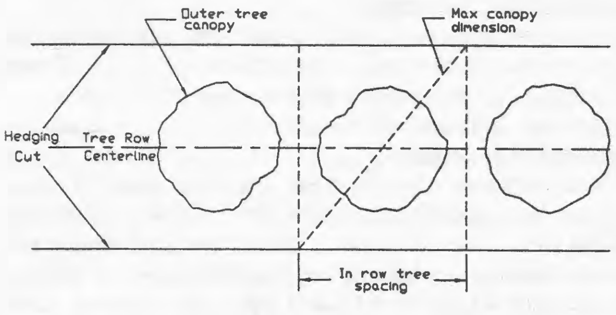

Figure 1–Plan view of tree canopies showing maximum horizontal canopy dimension.

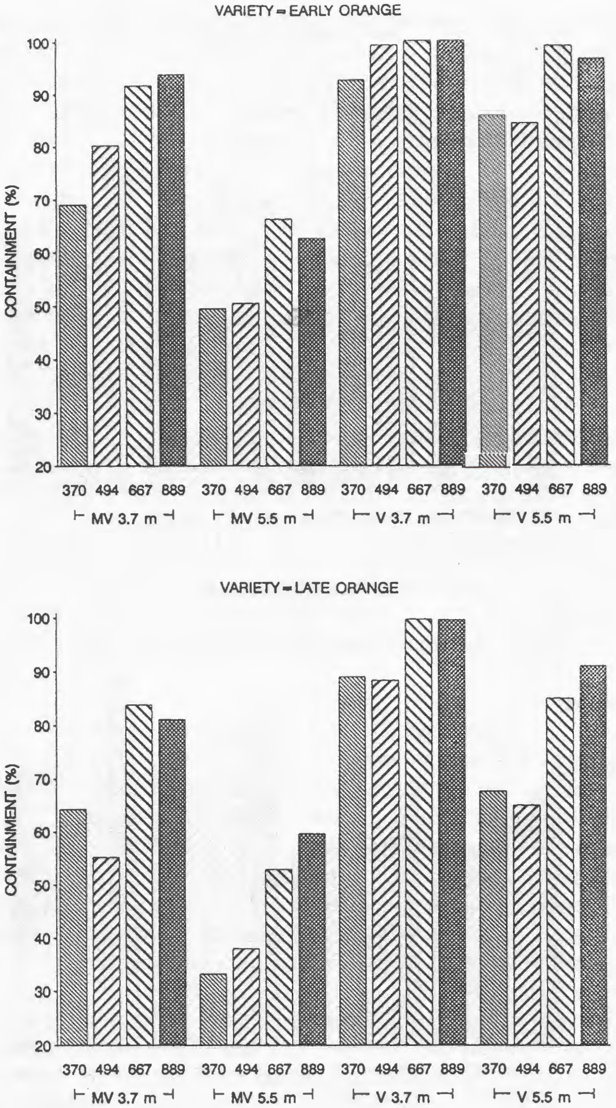

Figure 2–Percentage of canopy containment (maximum) volume to which orange trees had grown in 1993. First row of numbers is trees per hectare; second row of letters/numbers is MV (moderately vigorous), V (vigorous rootstock), and tree height.

Measurable differences in trunk diameters were first observed in 1985, after which the rate of growth was inversely related to tree density. Trees on the vigorous rootstock grew faster than those on the moderately vigorous rootstock (fig. 3). The annual rate of tree trunk diameter growth between 1988 and 1991 averaged 1.0 and 0.4 cm for the vigorous and moderately vigorous rootstocks, respectively. Over the same period at 370 and 889 trees/ha, the trunk diameters grew from 14.3 to 17.4 cm or 22% and from 12.3 to 14.2 cm or 15%, respectively. In 1991, the average trunk diameters for the vigorous and moderately vigorous rootstocks were 17.7 and 12.9 cm, respectively.

FRUIT YIELDS

Cumulatively through the 1992-1993 season, the early orange produced 36% more fruit yield than the late orange, 560 versus 412 t/ha (fig. 4). Although cumulative fruit yield/ha was related to tree density through 1991, it was greatest (512 t/ha) for 667 trees/ha through 1992-1993.

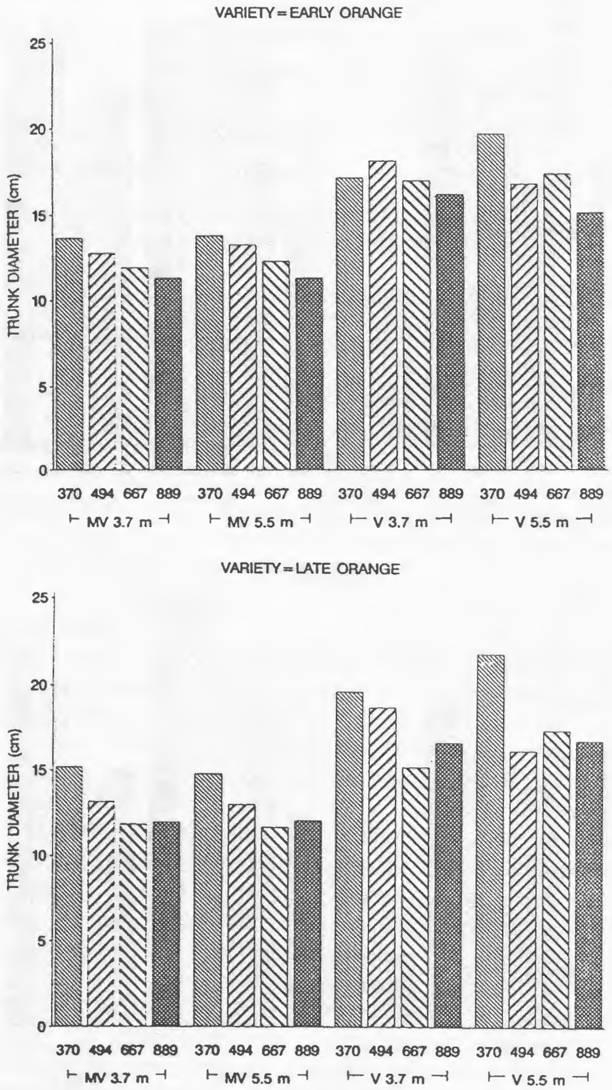

Figure 3–Trunk diameters of orange trees in 1991. First row of numbers is trees per hectare; second row of letters/numbers is MV (moderately vigorous rootstock), V (vigorous rootstock), and tree height.

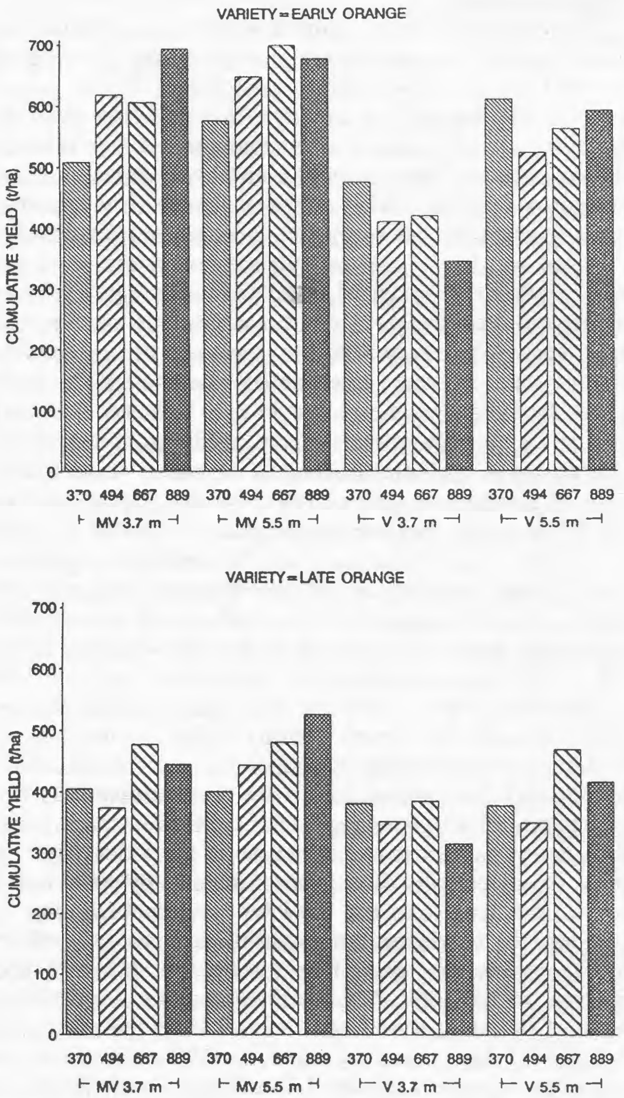

Figure 4–Cumulative fruit yield of orange trees, 1980-1993. First row of numbers is trees per hectare; second row of letters/numbers is MV (moderately vigorous rootstock), V (vigorous rootstock), and tree height.

Cumulative fruit yield of the trees on the moderately vigorous rootstock through 1993 was 536 t/ha or 23% more than those on the vigorous rootstock. Tree topping of the 3.7- and 5.5-m trees was initiated in 1987 and 1991, respectively, and the differences in cumulative fruit yields between the two tree heights have increased each year since 1987. Through 1992-1993, the cumulative fruit yields of the 5.5-m trees were 522 t/ha or 16% greater than for the 3.7-m trees.

SOLUBLE SOLIDS YIELDS

Processed oranges are sold on the basis of juice soluble solids yield. Cumulative soluble solids per hectare through the 1992-1993 season were 16% more for the early than for the late orange, 31.9 versus 27.4 t/ha (fig. 5). Cumulative soluble solids per hectare were related to tree density through the 1989-1990 season. Since then, however, the 667 trees/ha density had superior yields and was 31.9 t/ha through 1992-1993 or 6% greater than at 889 trees/ha. Because of the superior soluble solids content of the fruit on the moderately vigorous rootstock, its cumulative soluble solids per hectare through 1992-1993 was 48% higher than the vigorous rootstock (35.3 vs. 23.9 t/ha). Cumulative soluble solids per hectare of the 5.5-m trees were 31.9 t/ha or 16% higher than for the 3.7-m trees.

FRUIT CHARACTERISTICS

Fruit size and weight were significantly affected by the experimental factors only when there was a significant difference in fruit yields between the levels of those factors, i.e., fruit size and weight were inversely related to fruit yield in those cases.

Measurements initiated in the 1991 late orange harvest showed the specific gravity of the fruit was inversely related to its size (diameter). Variability in fruit weight within scion for that harvest was the greatest of any harvest during the experiment, and specific gravity was proportional to the −0.6 power of the diameter. Diameter,

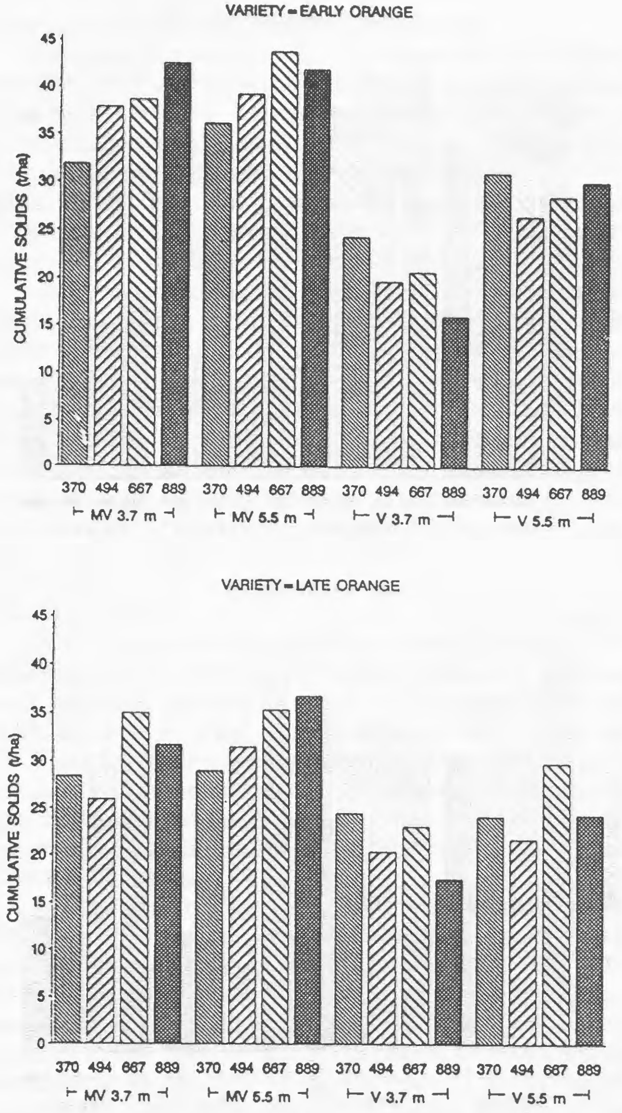

Figure 5–Cumulative soluble solids yield of orange trees, 1980-1993. First row of numbers is trees per hectare; second row of letters/numbers is MV (moderately vigorous rootstock), V (vigorous rootstock), and tree height.

weight, specific gravity, and soluble solids content of the late oranges averaged 7.4 cm, 206 g, 0.96 and 67 g soluble solids/kg fruit (6 lb solids/box; 1 box = 40.8 kg fruit) for the fruit on the vigorous rootstock, and 6.7 cm, 161 g, 1.01 and 80 g soluble solids/kg fruit (7.2 lb solids/box) for the fruit on the moderately vigorous rootstock.

These fruit characteristics affect fruit picker and fruit grower earnings. The picker is paid on a piece rate with payment based on the filling of a bulk container (0.76 m^3 or 10 boxes). The picker's main concern is the number of fruit required to fill the 0.76-m^3 container. In this regard, Miller (1991) found the packing density (percent bulk volume occupied) of 6.4- and 9.5-mm diameter spherical balls (which were 1/12 the nominal diameters of oranges and grapefruit, respectively, and were placed in 1/12 scaled pallet bins) changed less than 2% when filled with balls of either diameter or mixtures of the two diameters. McGeary (1961) also reported that at least a sevenfold difference was needed between small and large sphere diameters before any difference in void-filling (or packing density) was noted. Thus, the number of fruit in a 0.76-m^3 (10-box) container are mainly due to differences in overall average fruit diameter or fruit weight. Assuming a spherical shape, the number of fruit required to fill a given bulk volume is inversely related to the fruit diameter cubed.

In the 1991 samples discussed above, the 6.7-cm-diameter fruit would require 3,089 fruit to fill a 0.76-m^3 container (assuming a 64% packing density) or 35% more than the 2,293 required for the 7.4-cm-diameter fruit. All other things being equal, the picker would much prefer the larger fruit. In this case, however, trees on the vigorous rootstock had other characteristics which did not favor the picker. They averaged 60 cm taller than the trees on the moderately vigorous rootstock (410 versus 350 cm) and the quantities of fruit per unit canopy volume or cropping efficiencies were 3.9 and 6.7 kg/m^3 in the vigorous and moderately vigorous rootstocks, respectively. With respect to economic returns for the processed fruit grower, the trees on the moderately vigorous rootstock would be much preferred since they produced 47% more soluble solids per hectare than those on the vigorous rootstock (5.4 versus 3.6 t/ha).

CONVENTIONAL HARVESTING CONSIDERATIONS

Favorable conditions for conventional harvesting methods usually include adequate space for movement of pickers, ladders, containers, and fruit handling equipment and high numbers of large fruit per unit canopy volume which can be harvested without a ladder. From the space standpoint, the trees on the moderately vigorous rootstock provided the most favorable conditions. Figure 2 shows that the tree canopies on the moderately vigorous rootstock had filled less of their containment volume. In 1991, only trees on the moderately vigorous rootstock at the two lowest densities (494 and 370 trees/ha) still provided space in-row for picker and ladder movement and container placement, whereas the two higher densities and all densities on the vigorous rootstock had formed solid hedgerows up to 3.7 m high.

The trees on the moderately vigorous rootstock were also superior in the quantity of fruit per unit canopy volume or cropping efficiency (fig. 6) and the quantity of fruit harvested without a ladder (fig. 7). These results were for the 1992-1993 season, but were typical of other seasons. The differences in rootstocks were greater in early rather than late oranges. In general, the highest cropping efficiencies and quantities of fruit picked from the ground were associated with the two lower tree densities or the larger (4.5-m) in-row tree spacing. Thus, the trees at the lower tree densities and on the moderately vigorous rootstock were most desirable for conventional harvesting because they provided more space to operate fruit handling equipment and more fruit was harvested from the ground. They also provided a safer working environment for the picker because less ladder use was required and the ladders were shorter.

PICKING AID CONSIDERATIONS

The trees on the 4.5-m between-row spacing would be best suited for a picking platform with stationary work stations. The canopies of these trees had a maximum width of 237 cm near ground level and would allow a picker to

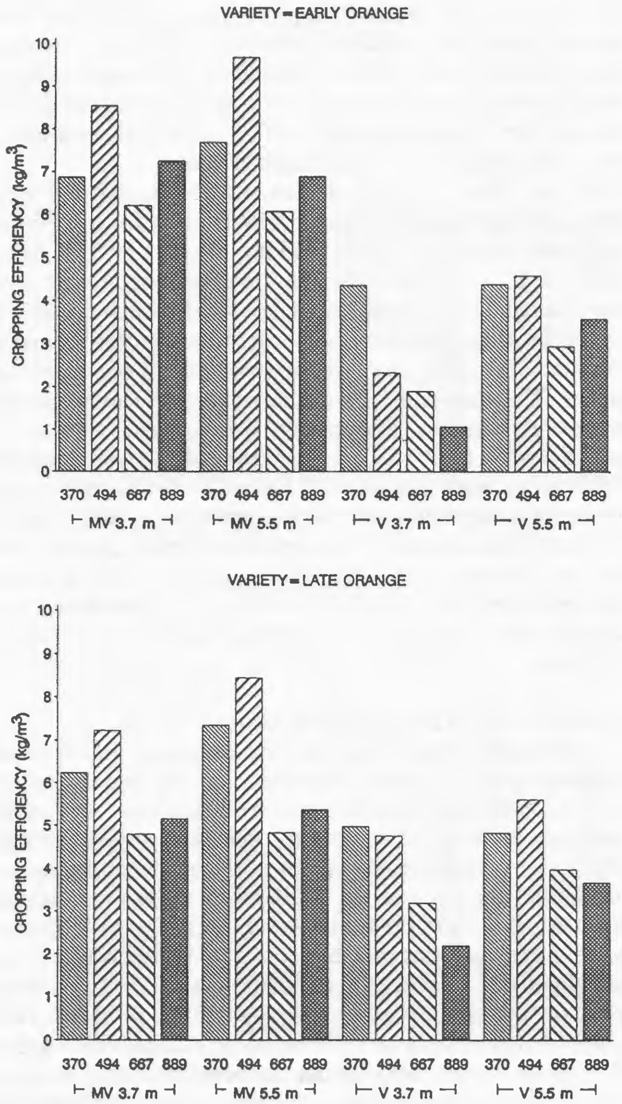

Figure 6–Cropping efficiency of orange trees in kilograms of fruit per m³ of canopy volume, 1993. First row of numbers is trees per hectare; second row of letters/numbers is MV (moderately vigorous rootstock), V (vigorous rootstock), and tree height.

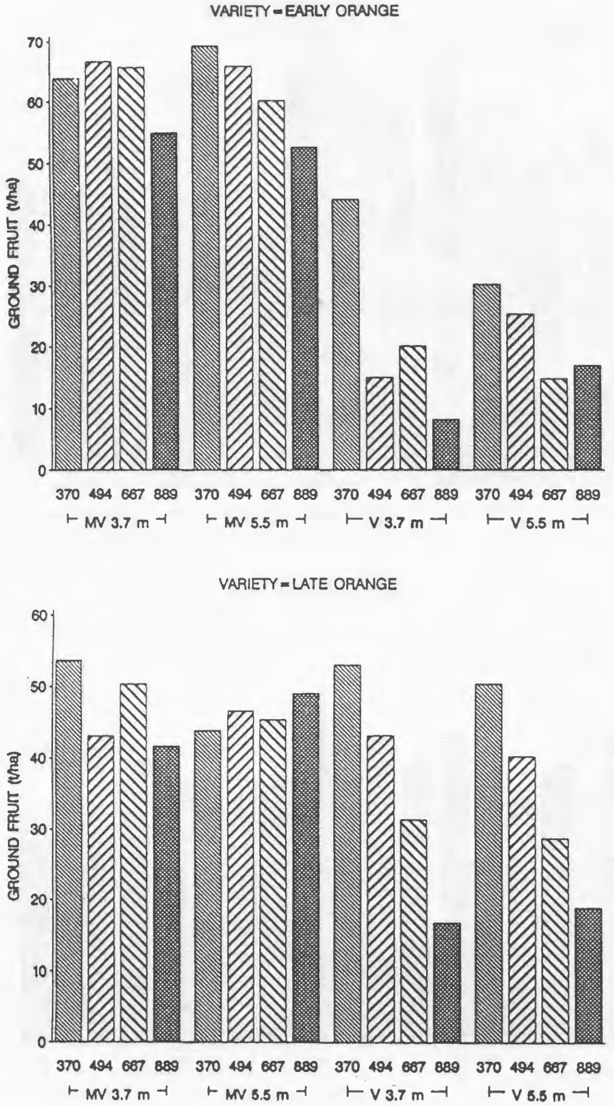

Figure 7–Fruit yield of orange trees which could be harvested by pickers standing on the ground, 1993. First row of numbers is trees per hectare; second row of letters/numbers is MV (moderately vigorous rootstock), V (vigorous rootstock), and tree height.

reach halfway (119 cm) across the canopy to harvest the fruit as the platform moved down the middle between tree rows. Trees on the 6.0-m between-row spacing (canopy 387 cm wide) would be more difficult to harvest from a platform because of the additional 0.75 m of half-width to harvest.

Table 3 shows the 1992-1993 average cropping efficiencies for combinations of rootstock, between-row spacing, and tree height. The moderately vigorous rootstock was superior at all between-row spacing and tree height combinations. The greatest difference between rootstocks was at the 4.5-m between-row spacing and 3.7 m height (7.0 vs. 2.6 kg/m³). Averaged over tree heights, the superiority of the moderately vigorous rootstock was greater at the 4.5-m between-row spacing. These results have occurred mainly because the moderately vigorous rootstock was better adapted to smaller tree spacings and heights. The amount of canopy foliage removed by hedging and topping and the amount of regrowth has been markedly greater on the vigorous rootstock trees. Overall, the moderately vigorous rootstock would be better suited for pickers on picking platforms with stationary work stations.

Table 3. 1992-1993 quantity of fruit per unit canopy volume (cropping efficiency) averaged over the early and late oranges (kg/m³)

Tree Height	Rootstock				
	Moderately Vigorous		Vigorous		
	Between-Row Spacing (m)				
(m)	6.0	4.5	6.0	4.5	Avg.
3.7	6.0	7.0	3.6	2.6	4.8
5.5*	6.5	7.6	4.0	4.4	5.6
Avg.	6.3	7.3	3.8	3.5	

* Of all trees in the experiment, only a portion of the trees on the vigorous rootstock had reached this height. Average tree heights were 5.2 and 3.8 m for the vigorous and moderately vigorous rootstocks, respectively.

MECHANICAL HARVESTING CONSIDERATIONS

Trees on the moderately vigorous rootstock have a smaller, more compact canopy structure and smaller trunks than do the trees on the vigorous rootstock. These factors should allow mechanical shakers to transmit more shaking energy to the fruit and achieve higher fruit removal efficiencies. Since the trees on the moderately vigorous rootstocks have also been superior in fruit production, they appear to be the best candidates for mechanical shaking. Catching and collecting the fruit should also be easier and these trees would also probably be the best candidates for robotic harvesting if the stiffness of the compact limb structure would not interfere with manipulation of the picking mechanism. These trees also appear to have fewer leaves per unit canopy volume to interfere with fruit visibility of the robot inside the canopy. In addition, these trees present a smaller canopy volume which must be traversed by the robotic mechanism.

SUMMARY

In 1980, trees of early- and late-maturing oranges were planted in a 10-ha field experiment on moderately vigorous and vigorous rootstocks at four tree densities (370, 494, 667, and 889 trees/ha) and controlled at two tree heights (3.7 and 5.5 m). Production and harvesting practices were done in a conventional manner. Nine frosts/freezes during the 1980s delayed the growth and fruit production in this experiment which yielded its first measurable fruit in the 1984-1985 season.

After 1985, tree canopy and trunk growth on the vigorous rootstock were greater than those on the moderately vigorous rootstock. Through the 1992-1993 season, cumulative fruit and soluble solids yields were superior for the early orange, moderately vigorous rootstock, 667 trees/ha, and 5.5 m height. Greater cropping efficiencies (kg fruit/m^3 of canopy volume) were generally associated with the moderately vigorous rootstock, two lower tree densities, and 5.5 m height. Conventional harvesting was easier in the moderately vigorous rootstock trees and two lower tree densities on either rootstock because greater quantities of fruit were harvested without a ladder and more space was available for picker and equipment movement. Fruit distribution on the moderately vigorous rootstock trees with smaller between-row spacings (narrower canopies) were best suited for hand harvesting from a picking platform with stationary work stations. Also, the moderately vigorous rootstock trees would probably be best for mechanical harvesting because of their small, compact structure, and superior yields.

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