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A REVIEW OF CITRUS HARVESTING IN FLORIDA

by
Jodie D. Whitney, Ph.D.
Professor of Agricultural Engineering, P.E.
University of Florida, IFAS
Citrus Research and Education Center, Lake Alfred

ABSTRACT

The removal of Florida citrus from the tree for harvesting is still done by handpickers on ladders and requires a work force of 20,000 to 35,000 persons. Moving fruit from the grove and subsequent fruit handling has been mechanized in the last 40 years. Factors affecting harvesting are fruit type and utilization, grove characteristics, and harvest labor requirements and costs. Although mechanical harvesting research over the past 35 years has not developed a feasible machine to replace the picker, substantial design and field performance information has been developed to mechanize the harvest of a significant portion of the crop if labor becomes unavailable or too costly. Some picking aids have been implemented to increase the productivity of pickers, but their feasibility is questionable under current conditions. Renewed attempts have been made to mechanize the harvest since 1993. A harvesting program administrator was employed by the Florida Department of Citrus in January 1995 to develop a program which will insure the harvest of future crops at a competitive cost. Record crops, low fruit prices, steadily increasing harvest costs, and more regulations are predicted for the next decade.

INTRODUCTION

Florida citrus bearing acreage (trees over 4 years old) and production have increased fairly steadily over the past 75 years except for the effect of major freezes (Figure 1). Bearing acreage peaked at 849,000 acres in 1971, then fell to a low of 508,000 acres in 1986 after the 1985 freeze, and rebounded to 668,000 acres in 1994 (Citrus Summary, 1949-50, 1964-65, 1967-68, 1982-83, 1992-93; Commercial Citrus Tree Inventory, 1994). Production peaked in 1980 at 284 million boxes, then fell to a low of 154 million boxes in 1990 after 5 major freezes during the 1980s, and is predicted to rebound to 266 million boxes in 1995 (USDA Citrus Estimate, 1995). During the past 25 years, oranges have comprised over 70% of Florida's citrus production, and Florida was the world's leading producer of oranges until 1978 when Brazil became the leader.

In the mid-1950s, the Florida citrus industry first expressed a collective concern about labor availability problems associated with harvesting because citrus acreage and production had been steadily increasing at a rapid rate for 2 decades (see Figure 1). A research project was established at the Lake Alfred CREC (then Citrus Experiment Station) in 1957 to search for possible solutions and the first and only paper (Coppock and Jutras, 1959) on harvesting presented at this Conference summarized the initial efforts of the project. The purpose of this paper is to review the developments in Florida citrus harvesting over the past 35 years (Coppock and Hedden, 1977; Whitney and Harrell, 1989), and discuss the current status and possible situations for the future. Harvesting in this discussion relates to the activities required to separate the fruit from the tree, place it in a suitable container, move it roadside, and then to the processing plant or packinghouse. Most of the information, however, will concentrate on the first 2 of these 4 activities.

Organization of the industry. There are approximately 12,000 growers whose holdings range from a few to thousands of acres. Many growers are "absentee" owners because they do not live on or near their grove property and are not involved in day-to-day grove operations. Cooperatives and caretakers are grove management organizations which mange all or part of the grove operations including harvesting for the absentee owners. Grove ownership by large corporations has become more common in the last 2 decades. One of the reasons for this is the southern movement of new citrus plantings during this time into the flatwoods areas to reduce the risk of freeze damage, and the practical development of these flatwoods areas under environmental constraints usually requires that relatively large tracts of land be considered.

The production, harvest, and utilization sectors of the citrus industry are often under different management, and ownership of the fruit can change as it moves from one sector to another. The production and utilization sectors are mechanized while the harvest sector requires fairly large numbers of seasonal hand laborers to remove fruit from the tree and place it in a fruit handling container.

Fruit handling. Fruit handling systems for moving fruit from the field container to roadside have been successfully mechanized since Coppock and Jutras presented their paper in 1959, and have been described in some detail by Hedden and Churchill (1984). Until the late 1950s, fruit was handled in the standard 90-lb field boxes, twowheel trailers, other specialized equipment, and was very labor intensive. Since that time, both the fresh and processed fruit handling systems described below have reduced labor requirements at least two-thirds with container costs also reduced.

For fresh fruit handling in the grove, the current system of pallet bin containers (10 field boxes) and flat-bed trucks with grapple-type loader booms was adopted (Figure 2). At roadside, the pallet bins are usually transferred to a flat-bed, semitrailer for transportation to the packinghouse, unless the packinghouse is a relatively short distance from the grove. The majority of the pallet bins are constructed of wood, but some utilize a steel frame and flexible liner, and in recent years, plastic bins have seen increased use.

For processed fruit, wire baskets (10 field boxes) first replaced field boxes as field containers. The baskets were handled and emptied with loader booms mounted on trucks having high-lift bulk bins with capacities from 60 to 100 field boxes. At roadside, fruit in the bulk bin was dumped, as it is today, into a semitrailer (500 field box capacity) which is pulled to the processing plant. In the early 1970s, the round, molded polyethylene tub (Figure 3) which is in use today began replacing the wire basket. The tub, produced in 8 and 10-field box capacities, is somewhat lighter and much easier to handle.

FACTORS AFFECTING HARVESTING

Fruit type and utilization. Over the past 20 seasons, Florida citrus production has averaged 71% oranges, 23% grapefruit, and 6% specialty fruits (Citrus Summary, 1992-93). Since 1988, 83% of the citrus was processed, 93% of the orange, 55% of the grapefruit and specialty fruit. This left 17% of the citrus utilized as fresh, and with an average packout of 65%, 17/0.65 or 26% of the crop was harvested destined for the fresh market. All fresh market fruit must be handled with care, especially the specialty varieties which have thin and fragile peels. All citrus harvested by hand is separated from the tree with a twisting, snapping motion except for tangerines which are often clipped to reduce peel damage. Productivity of the picker depends on the fruit type (size) and utilization (fresh generally lower than processed). A survey done during the 1967 season showed the productivity of the citrus picker in boxes/h averaged 11 in grapefruit, 7.3 in oranges, 4.9 in murcotts and tangelos, and 2.7 in tangerines (Florida Industrial Commission, 1967).

The harvest season for fresh fruit can last from September to July, whereas the main thrust of the processing season is usually December to May. Valencia or late oranges have historically been slightly less than half the total Florida orange production and is the only cultivar normally harvested after citrus trees bloom in the February-April period. Thus, Valencia has the mature and young (next year's) fruit on the tree at harvest time. Selective harvest of the mature fruit presents no particular problems for hand harvest, but is a significant problem for mechanical removal devices and fruit-loosening abscission chemicals.

The trend in the relative percentage of early/mid-season vs. Valencia orange plantings has changed somewhat over the past 15 years, probably in reaction to the freezes in the 1980s. Tree inventory data in 1994 (Commercial Citrus Tree Inventory,

1994) showed that for orange trees planted prior to 1981, Valencia was 48% of the total orange acreage. From 1981 through 1993, Figure 4 shows the existing acreage planted in early/mid-season vs. Valencia oranges after 1980. More early/mid-season orange acreage existed for most of the years trees were set. The greater acreage of all orange trees planted from 1986 to 1992 was due mostly to new plantings in South Florida in reaction to the freezes in the 1980s, while the downward trend in 1992-1993 was probably a reaction to low fruit prices. Currently, the total acreage in existence for early/mid-season and Valencia oranges are 334,000 and 301,000, respectively.

Also, as a result of the 1980s' freezes, consideration has been given to planting specialty cultivars in the colder Northern and Central production areas (see Figure 5) because these cultivars are harvested as early as October and the trees tend to be more tolerant of cold temperatures than orange and grapefruit trees. This is illustrated by specialty tree acreage increasing from 42,000 to 53,000 from 1988 to 1994 (Commercial Citrus Tree Inventory, 1994), and was mainly due to increases in Northern and Central production areas. However, the market for some specialty fruits tend to be somewhat unpredictable and some cultivars have unique production problems.

Grove characteristics. Most of the trees have been planted in a rectangular pattern. Before the freezes of the 1980s, other patterns such as the diamond existed in the Northern production areas. Along the coasts of the Southern production area, the soil is poorly-drained and is bedded between ditches to control the water level around the tree root system. Trees are planted in rows parallel to the ditches on or near the top of the beds. The number of rows per bed varies from 1 to 8, but the most common is 2. The slope of the beds adjacent to the ditches and the effect of water on soil condition in the vicinity of the ditches pose problems with trafficability for fruit handling trucks and pickers setting their ladders for harvesting. Mechanical harvesting equipment would also encounter problems with this type of terrain. By comparison, the relatively flat, well-drained sandy soils in the Central and Northern production areas also pose flotation problems for equipment.

As a result of the 1980s' freezes, Figure 6 shows a major shift in orange acreage from the Northern to the Southern production areas between 1978 and 1994 (Commercial Citrus Tree Inventory, 1978, 1994). Losses in the Northern production area were about 30,000 acres greater than the gains in the Southern production area. Considering the Western, Indian River, and Southern production areas as principally bedded groves, the percentage of the total orange acreage which was bedded increased from 44% in 1978 to 69% in 1994.

Harvest rate and working safety of pickers are generally inversely related to tree height. Many of the older, taller trees in the Northern and Central production areas were lost in freezes of the 1980s. In recent years, the maximum tree height has been limited to 18 or 20 ft. by regularly scheduled tree topping programs. The need for tree topping has been alleviated somewhat by the increased acreage in bedded groves in which shallow root systems tend to limit tree height. Many factors must be considered in determining the appropriate tree height. Most of the citrus cultivar/rootstock combinations are relatively vigorous in nature and limiting tree height by tree topping can limit fruit yields. Growers tend to maximize tree growth for healthy-looking trees with the latest irrigation and fertilization techniques, and hope this will maximize fruit yields. The trade-off is that growers may be reluctant to limit tree height because fruit yields may be limited, but to allow the tree to grow taller will usually mean higher harvesting costs per box and sometimes greater difficulty in getting pickers to harvest the fruit. Another consideration is that in taller trees, most pickers would rather not use picking bags because of ladder stability or safety concerns, and thus will prefer to drop fruit to the ground. While dropping fruit to the ground has been practiced in processed fruit harvesting for many years, it is being discouraged today because of the increased contamination concerns at the processing plant and potential reductions in pounds solids yields from bruised and damaged fruit. In fresh fruit harvesting, it should not be practiced at all, but it is, and contributes to lower fresh fruit packouts. From this discussion, one can see that the goals of the production, harvesting, and utilization sectors may conflict, and many times communications between the 3 are minimal to nonexistent.

Tree spacings vary considerably between groves. Because of the necessity of grove vehicular traffic, between-row spacings have remained relatively constant at 25 to 30 ft. in older groves, with some reductions to between 20 and 25 ft. since 1960. In-row spacings have been less and reduced with time, but are quite variable. Older groves had in-row spacings of 25 ft. or more, but many have been interset at closer spacings, and the current average ranges between 10 and 15 ft. The move toward closer spacing reflects the grower's attempt to maximize fruit yields with more trees per acre. Figure 7 shows the general trend in increased trees per acre with the later crop year set and the 1994 orange acreage accumulated by crop year set (Commercial Citrus Tree Inventory, 1994). In 1993, the average number of orange trees set per acre was 141, which is equivalent to an in-row spacing of about 12 ft. if the between-row spacing is 25 ft. Figure 7 also shows that over half the orange acreage in 1994 has been planted since 1986 when the number of trees planted per acre averaged 131.

Pruning or hedging between rows is a common practice to maintain an alley way for tractors, trucks, sprayers, etc. Crosshedging or pruning between adjacent trees in-row is sometimes done to provide space during harvesting for placement of fruit containers and the movement of pickers and ladders around the tree. Some growers feel that crosshedging increases fruit yields because of the additional fruit bearing surface area created on the canopy between trees. A 5-year research study (Wheaton et al., 1984) has shown, however, that crosshedging (or tree removal) does not increase fruit yields compared to hedgerows. The trade-off, then, is the cost of crosshedging and fruit yield reductions vs. the convenience of the spaces for fruit container placement and picker movement at harvest. In existing hedgerows, the fruit container must be moved through the tree canopy for placement or retrieval, and if the grove is harvested in a conventional manner with the picker moving across rows, then the ladder must be lowered below the bottom of the tree canopy to move across the row. Fruit containers have been handled with some difficulty in hedgerow conditions. Extra care must be exercised for fresh fruit harvesting, particularly for specialty fruits, to minimize fruit damage from the container and the loader boom colliding with the fruit as they are moved through the canopy. Tree skirting or removal of the lower canopy, which is becoming

One alternative to handling fruit containers underneath the tree canopy is the straddle-type fruit handling equipment. Preliminary field trials with available commercial, straddle-type equipment for fresh fruit handling were conducted by the author in 1987. It was projected that the cost of fruit handling would significantly increase over conventional loader boom equipment because of the lower fruit handling capacity and reduced mobility of straddle-type equipment.

Harvest labor and costs. The picker is an essential part of the citrus harvesting system and is paid on a piece rate basis. The work is seasonal in nature and is often not full-time during the season because of inclement weather and when the capacity of the packinghouse or processing plant is a limiting factor. The makeup of the work force and the number of persons required have changed considerably over the past two decades. For the 1973 season, Fairchild (1975) reported 75% of the work force were residents of Florida while the remaining 25% were out-of-state residents or migrants. Since that time, migrants from Mexico have steadily increased as a percentage of the citrus harvesting work force and at present, it is estimated that two-thirds of the pickers are from Mexico.

The number of pickers required has depended on the size of the crop and the time within the season. A survey for the 1967 season (Florida Industrial Commission, 1967) showed the peak labor requirement was greater than 20,000 pickers between December and April, the peak harvest period for processing oranges. For a total production of 195 million boxes that season, the peak and average rates of harvest were 8 and 5 million boxes per week, respectively. The peak work force for the 284 million box crop in the 1980 season was 35,000 (Citrus Industrial Council, 1980).

Figure 8 shows that harvest costs have risen steadily over the past 3 decades (Hooks, 1986; Polopolus et al., 1993) and delivered-in or gross prices have fluctuated greatly (Florida Citrus Processors Association, 1994) in response to the normal influence of supply and demand. The industry has usually become concerned about harvest costs and interested in mechanical harvesting when the differences between gross returns and harvest costs were minimal. Until the late 1970s, the minimal differences usually coincided with periods of high production such as 1960-62, 1967, 1971, and 1977. During the decade of the 1980s, concerns about harvesting were minimal for several reasons. Florida's production was limited by the freezes, the labor supply was abundant at a reasonable cost, and even though Brazil controlled orange juice prices, they were relatively good. Since the last severe freeze in 1989, orange production has steadily increased to the 196 million boxes predicted for 1994-95, prices dropped sharply to current levels after the 1991-92 season, and the forecasted grapefruit crop for 1994-95 is a record 55.5 million boxes. Early in 1991, some industry people could foresee record crops before the end of the decade coupled with projected depressed prices resulting from an excessive worldwide supply of citrus. Again, anticipated record crops and low fruit prices have developed a renewed concern about harvesting and fostered the current collective effort to ensure the future crops will be harvested at a cost which will keep the industry competitive worldwide.

Much of the citrus harvested for processing is removed from the tree, dropped to the ground, and picked up later. As mentioned above, this practice is being discouraged and is utilized to avoid carrying the bag with fruit on the ladder, particularly in taller trees. Family or picking units have used this technique where the stronger member(s) of the unit remove the fruit from the tree while the other members gather the fruit from the ground. For independent pickers, however, it is doubtful whether this technique can improve their productivity, except perhaps where the bonding strength of the fruit to the tree is relatively low and the fruit removal rate can be significantly increased by shaking the limbs. This may occur naturally, e.g., in Pineapple oranges late in the harvest season.

In the 1970s, abscission chemicals which were developed to loosen fruit and make mechanical harvesting more efficient, were used to a limited extent as an aid to hand harvesting. Although they were found to increase picker productivity by as much as one-third (Coppock and Hedden, 1977), pickers were not usually willing to accept lower piece rate wages to offset the cost of using the chemical. Because the chemicals hastened fruit senescence and scarred the peel, they could be used only for processed fruit. The fruit usually had to be processed within a week or 10 days post spray, or it would deteriorate and not be usable. The scheduling of harvest operations that far in advance was very difficult. In addition, fruit was often stored on trucks at processing plants for several days to provide a supply of fruit when harvesting was interrupted by inclement weather or other factors. Compared to unsprayed fruit, the allowable storage time for chemically-sprayed fruit was considerably less and thus reduced the storage supply of fruit at the plant. Abscission chemicals were also investigated for fresh market fruit to eliminate the need for clipping of some specialty cultivars. Loosening results were inconsistent and the 5 to 7 day delay between application and harvest was not compatible with conventional scheduling procedures of most packinghouses.

MECHANICAL HARVESTING RESEARCH

Over 30 years of research and development efforts have gone into methods to improve and mechanize the harvesting of Florida citrus. Much of the significant work has been described in several publications (Coppock and Hedden, 1977; Wilson et al., 1977; Whitney and Sumner, 1977; Sumner and Churchill, 1977; Hedden and Coppock, 1977; Sarig and Coppock, 1986). Time and motion studies were made of handpicking operations to understand what might be done to improve productivity of pickers. Generally, it was found about 25% of the picker's total time was spent on activities commonly referred to as nonproductive, or other than picking fruit. Various picking aids were evaluated to minimize or eliminate the nonproductive activities of the picker and reduce the arduous nature of the picking task. While some of the aids did improve picker productivity and make the picking task easier, none were found to be feasible for alleviating anticipated harvesting problems. Mechanical methods in the form of contact devices (those which contact the fruit to separate it from the tree, see Figure 9), except the robotic approach, were then investigated in the early 1960s, but showed little potential for acceptance. This led to the initial research and development on machinery for mass removal harvest systems, which appeared to have potential to harvest fruit acceptable for processing at a rate commensurate with cost.

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process. Because fruit loosening by the chemicals usually resulted in considerable preharvest fruit drop, systems were developed to remove fruit to the ground and to pick it up mechanically.

Interest in mechanical harvesting increased during the late 1960s and early 1970s for several reasons. The importation of offshore labor was restricted, non-agricultural industries were competing for available domestic labor, production was increasing rapidly, and profit margins were small. One of the main reasons for the shortage of labor was the construction labor demands in Central Florida in preparation for the opening of Walt Disney World near Orlando in 1971. Also at that time, the bulk of Florida citrus was being produced in the Northern and Central production areas (see Figure 6) and 75% of the pickers were Florida residents (Fairchild, 1975). Some growers experienced difficulty in getting Valencia oranges harvested and the concerns about harvesting problems became severe enough that the Florida Department of Citrus initiated an accelerated research and development program subsidized by a tax on all harvested citrus. Up to 1977, production continued to increase and profit margins continued to be small (see Figures 1 and 8). In 1973, an abscission chemical (Acti-Aid by the Upjohn Co.) was approved for use on processed oranges, but it was only suitable for use on only early and midseason oranges. The volume of mechanically harvested oranges (mostly early and midseason) on a semi-commercial basis reached a peak in 1974-75 at 220,000 boxes, or slightly more than 0.1% of the orange crop. Most of the harvesting systems utilized abscission chemicals with limb, air, or trunk shakers (Figures 10-13) to remove the oranges to the ground and machinery to gather, pickup, and load them (Figures 14 and 15). Limbshaker-catch frame systems (Figure 16) were used on old, highly-skirted trees (mainly seedlings) where visibility was good for limb shaker operation and catch frames minimized fruit damage on oranges falling from trees over 20 ft. high.

Numerous problems were encountered with these systems. Because of non-uniforn and inconsistent fruit loosening by the abscission chemicals and losses in fruit collec- tion, harvest efficiencies were frequently less than 95%. The cost of the chemical plus application ranged from $0.10 to $0.25 per box. High rates of chemical caused exces- sive defoliation. As mentioned above, once the chemical was applied, the fruit usuall had to be processed in a week or 10 days. Because of this, equipment breakdowns anc inclement weather could easily create a crisis in meeting the time schedule imposed b the chemical. Mechanical pickup equipment had difficulty handling fruit on unever terrain or when yields were over 600 boxes/acre. Tree damage from the chemical and or fruit removal devices were defoliation, small and large limb breakage, and bar damage.

Mechanical harvesting efficiencies in Valencia oranges were low, mainly becaus the efficiencies of the removal devices were low. Harvesting efficiency as discussed i this paper was defined as the percentage of the crop that could be recovered whe compared to hand harvesting. This mainly involved fruit removal percentages of th mechanical devices and yields. Thus, a fruit removal of 90% and a yield reduction c 10% (90% of hand harvested yield) resulted in a 0.9 x 0.9 or 81% harvesting efficienc

Since the peak in mechanical harvesting activity in 1975, the above problems and other conditions (discussed in the previous section) reduced interest in mechanical harvesting until recently. Other factors also affected industry acceptance of mechanical harvesting. Management of a mechanical harvesting system extended over all sectors of the industry—production, harvesting, and utilization. If the chemical failed to loosen the fruit for whatever reason (cold weather, improper application, rain washing off chemical within a few hours after application, etc.), the entire harvesting schedule was upset. In many instances, mechanically harvested fruit delivered to the processing plants required immediate handling to prevent spoilage because of chemical and/or mechanical damage to the fruit. All in all, considerable management skill was required to effectively utilize the chemicals.

In a 5-year study completed in 1985, Whitney and Wheaton (1987) found the overall harvesting efficiency of abscission chemicals with an air shaker was only 75 to 78% in oranges, while the efficiencies of abscission chemicals with a commercial trunk shaker were 93% in Hamlin and 81% in Valencia oranges. In another 5-year study completed in 1986, Whitney et al. (1986) reported harvest efficiencies of near 100% in Hamlin oranges and 91% in Valencia oranges (prior to a young fruit diameter of about 0.5 inches) using abscission chemicals with low frequency (5 Hz) linear trunk shaking for 7 seconds. The possibility of improving harvest efficiency in Valencia oranges by decreasing the shake time to less than 7 seconds was suggested since most mature fruit was removed in the first few seconds of shaking and the damage to young fruit would be reduced.

ROBOTIC HARVESTING RESEARCH

Research on robotic citrus harvesting began in Florida in 1983. When compared to previously researched mechanical harvesting systems, this approach offered some significant advantages. Abscission chemicals would not be needed. Mature Valencia oranges could be harvested selectively from the younger fruit. Fruit could be harvested for fresh or processed market. Harvesting could be accomplished any time of day or night and during inclement weather, unless handling of fresh fruit under these conditions were detrimental.

Harrell et al. (1985) developed a single arm system with machine vision that picked fruit with simple three-degree-of-freedom arms. A second generation arm (the Florida picking robot arm, Figure 17) designed by Harrell (1987) pivoted in a Hook-joint base about intersecting and perpendicular axes. A prismatic link, mounted on the Hook-joint, provided motion in and out of the citrus canopy. Arm actuation was accomplished with two rotary actuators and a hydraulic motor. A rack and pinion drive was used to obtain linear motion from the hydraulic motor. High performance servo valves, controlling actuator flow, were used to achieve the dynamic performance required for picking fruit.

Attached to the end of the sliding link was a rotating lip picking mechanism. A solid state color camera, ultrasonic range sensor, and incandescent lamp was incorporated into the picking mechanism for fruit identification and location. Color machine vision enabled the picking arm to rapidly distinguish between the various hues present in a citrus canopy.

When a fruit was detected by the vision system at the start of a pick cycle, angular velocities of the two rotational joints were regulated, maintaining the targeted fruit's projection in the center of the image plane. The sliding link was actuated, extending the picking mechanism towards the targeted fruit until it was close enough to detach the fruit from the canopy. Once detached, the sliding link was retracted from the canopy and the fruit was dropped (intended for a fruit collection system), and the next pick cycle was started. The picking arm was designed to complete a worst case pick cycle (i.e., a targeted fruit at the extreme edge of the arm workplace) in 1 second. Florida field tests on young orange trees demonstrated continuous harvest rates of 3 to 4 seconds per fruit.

Harrell (1987) made an economic analysis of citrus harvesting assuming 10 robotic arms mounted on a self-guided gantry vehicle. Some of the other assumptions made were: delivered-in fruit price = $6.70/box; harvest efficiency = 85%; average pick cycle time = 3 seconds. The harvest cost (pick, roadside, and haul, and including the cost of 15% of the fruit not harvested) was $2.30/box or about 35% greater than the orange harvesting cost at the time. Robot harvest cost was most sensitive to harvest efficiency and an efficiency of 93 to 99% was required for the robotic harvester to break even with hand harvesting costs.

Sarig (1993) had made a state-of-the-art review of robotics in fruit harvesting. He states there is no consensus on the viability of the robotic harvesting system as an alternative method for the current manual picking operation. While major progress has been made in systems to identify and locate fruit on the tree, only about 75% of the oranges have been properly identified. Further, not all of the identified oranges can actually be picked because the tree structure hinders free movement of the picking arm. Thus, to increase the efficiency of picking, the tree structure should be modified and an obstacle-avoidance algorithm incorporated in the picking arm movement. Finally, the proper end effector on the end of the picking arm must be developed to grasp, remove, and handle the oranges. While the commercial implementation of a fruit-picking robot may be years away, the increasing costs of labor and decreasing costs of computers, vision systems, and robotic equipment hold out hope for robotic harvesting with a favorable cost/benefit ratio. As mentioned above, the success of robotic fruit harvesting will depend greatly on tree structure modifications which will minimize the fruiting depth from the outer canopy edge and the number of fruit which are inaccessible from the outer canopy edge because of the canopy structure.

CURRENT STATUS

Picking aids. There are approximately 50 man-positioner boom machines (Harvesting Systems, Ltd., U.S. Patent No. 3,878,957; Figure 18) being operated as a group to harvest Florida oranges for processing in bedded groves near Fellsmere. This machine has been under development in Florida since the late 1960s. Each machine is self-propelled and operated by one picker in a bucket at the end of a boom. The picker has complete control of the machine and positions himself/herself around the tree canopy with leg and foot controls in the bucket. Oranges harvested by the picker are placed in a collector on the bucket and are pneumatically conveyed through a round tube to a storage bin at the rear of the machine by pulling a vacuum in the bin. The picker is paid for each harvested orange which is counted as it moves through the tube. The storage bin is emptied periodically into a conventional fruit handling truck (goat) without its loader boom. Lights on the machine make night harvesting possible. Down-the-row picking rates of 2400 oranges per hour have been observed and the manufacturer has claimed higher rates. The machine can be used in most any type of grove picked in a conventional manner but is best suited for tall trees with all oranges at least 6 ft. above ground level. In bedded groves, the picker does not have to work on the often treacherous ground conditions found in the ditches. Conventional pickers with fruit bags are sometimes needed where oranges on the tree are on or near ground level. The machine has been used for other grove jobs such as selective hand pruning of freeze-damaged trees and is considerably safer than conventional means of performing this task. The industry has resisted acceptance of the machine because of concerns about its cost and lack of mobility.

In the last 2 or 3 seasons, 2 other machines have been introduced mainly to assist with harvesting processed oranges from the many young, low-yielding trees in bedded groves which have been planted in recent years. They are the New Way Loader (built by James Andrews, Lorida, Florida; Figure 19) and Harvesting Systems, Ltd. pan machine (U.S. Patent No. 5,187,928; Figure 20). Both machines essentially provide a moving storage bin for a group of pickers and minimize the distance pickers have to carry oranges to dump their fruit bags. Using a conventional harvesting system in low-yielding trees, the picker must either carry fruit a long distance between tubs or the fruit handling truck must move partially filled tubs closer to the picker.

The New Way Loader is a fruit handling goat truck, without a loader boom, with a conveyor system added to transfer fruit from a receiving conveyor in front of the truck to the bulk storage bin at the rear of the truck. Usually, 6 to 8 pickers harvest fruit from 2 adjacent rows and dump their fruit onto the receiving conveyor as the driver moves the unit down the row middle. The driver has access to the conveyor system and can grade out undesirable fruit if needed. When the storage bin is full, the truck is driven to roadside for dumping. The Harvesting Systems, Ltd. pan machine is mounted on a chassis similar to the boom machine described above and pneumatically conveys fruit from the pan (where pickers dump fruit) at the front of the machine to the storage bin at the rear of the machine. The machine driver and pickers operate similar to that described for the New Way Loader, except the driver does not have access to the conveying system for fruit grading purposes. As with the boom machine, fruit in the storage bin is usually dumped into a conventional fruit handling truck (goat) for transport to roadside. These machines should ease the fruit-carrying burden on pickers in young, low-yielding trees and have seem limited use in taller, more productive trees. With both the New Way Loader and pan machine, pickers and driver must work as a team and be paid as a team since no feasible methods has been devised to account for the productivity of individual team members and pay them by the conventional piece rate. Except for families working as a team, many pickers (particularly those with high productivities) prefer not to work in a team because they are not independent and cannot get reimbursed for their individual efforts. Time and motion studies in field tests with these machines during the 1992-93 season indicated pickers spent at least 90% of their time picking oranges in young low-yielding trees which did not require ladders (Florida Department of Citrus, 1993). No direct time and motion comparisons under similar grove conditions were made with the machines and conventional harvesting operations, but conventional pickers spent about 80% of their time picking oranges in trees 12 to 15 ft. tall with 6 to 10 boxes per tree.

Even though these machines have not been used for fresh fruit harvesting, they have the potential for doing so, and preliminary fruit quality tests indicated higher peel abrasion levels on Valencia oranges off the machines than measured in conventional harvesting operations (Miller et al., 1993). These higher abrasion levels were thought to be due to the sand which accumulates in the fruit handling system of the machines.

Fruit quality. Other fruit quality research conducted on conventional harvesting operations during the 1992-93 season showed that fresh fruit picked and dropped on the ground (still practiced on a wide scale, mainly for processed citrus) averaged 21% decay after 4 weeks storage vs. 8% for fruit picked into a bag (Miller et al., 1993). Comparing oranges delivered to the processing plant (Table 1), those picked and dropped on the ground averaged twice the defective fruit, more trash (leaves and twigs), 5 times the surface microflora, and twice the surface sand as those fruit bagged (Florida Department of Citrus, 1993).

Mechanical harvesters. Late in the 1992-93 season, Fruit Harvesters International, Inc. introduced a trunk shaker-catchframe from Israel. Trunk shakers had been used for harvesting Florida citrus previously, but not a trunk shaker-catchframe combination. This harvester had 2 units, 1 on either side of the tree row—a self-propelled shaker/deflector frame unit and a tractor-towed catchframe unit for collecting the fruit to be conveyed to a portable storage bin. In preparation for the harvester, several acres of Valencia orange trees on 2-row beds in South Florida were skirted, which involved removal of the lower tree limbs by sawing to provide operating clearance underneath the canopy for the harvester. The clearance above-ground was 18 to 24 inches at the trunk line increasing to 36 to 48 inches at the canopy edge farthest from the trunk line. Skirting removed an average of 6% of the oranges from these trees which were 20 ft. tall. A few acres were harvested to determine what changes were needed to make the harvester better suited for Florida citrus. Replicated plot harvest tests (unpublished data) conducted by the author during April/May indicated the shaker removed an average of 70% of the mature oranges on trees 20 ft. tall with 3 box yields and 12-inch diameter trunks. Mature fruit yields in the 1993-94 season were not reduced when compared to handpicked check trees (also skirted). It should be noted the trees had a blossom blight infection in 1992-93 and 1993-94.

During the 1993-94 season, the company introduced 5 completely redesigned harvesters, each with 2 self-propelled units (Figure 21). One person was required to operate each unit and several persons usually followed each harvester to handle the collapsible fruit storage containers, and glean ground fruit not collected by the catchframe and fruit left on the tree by the shaker. The collapsible fruit storage containers were lightweight and easy to handle when empty and held about 10 boxes of fruit. When full, these containers were moved out of the grove and emptied with a tractor-mounted forklift, but this system proved to be too slow. Approximately 20,000 citrus trees were harvested including grapefruit and early, mid-season, and late oranges. Harvesting efficiencies overall were estimated between 75 and 95%. The harvesters operated in bedded groves which had been skirted, and when the trees were skirted with adequate clearance for catchframe and trunk shaker maneuverability and operator visibility, harvest rates of 60 trees per hour were achieved. Replicated plot harvest tests (unpublished data) on Valencia oranges in May resulted in 87% mature fruit removal on young trees with 2-3 boxes and 5-inch diameter trunks, and 77% mature fruit removal on older trees with 4-5 boxes and 9-inch diameter trunks.

There were some unique features about the harvesters. The manufacturer claimed the speed, duration, and pattern of the shake could be programmed on and controlled by an on-board computer. The unbalanced masses and/or their eccentricities were large enough for the shakers to vigorously shake trees with trunk diameters from 6 to 10 inches at frequencies less than 10 Hz (most commercial trunk shakers operate at 15 or more Hz for shaking). Slatted cross conveyors moved the fruit from the trunk row line of the collection catchframe to a longitudinal conveyor which moved the fruit to the fruit storage container at the rear of the catchframe. Each unit was mounted on low-profile rubber tracks to lower the catching surfaces as much as possible.

There have been some problems associated with the acceptance of the harvesters. Growers have been reluctant to skirt the lower limbs off the trees because of the lost fruiting canopy. As stated above, skirting reduced fruit yields by 6% on mature trees. The author estimates this percentage may increase to at least 15 on young, shorter trees. However, the effect of such skirting on future yields is not known. Another problem with the harvesters has been visible tree trunk bark damage caused by the clamp pads of the shaker. Growers are understandably concerned about this damage because of the possible detrimental effects on the productive life of the tree. In this regard, Whitney and Wheaton (1987) conducted 5-year shaker harvest trials near LaBelle in the early 1980s. Seven-year-old Valencia orange trees were shaken with a commercial trunk shaker for 5 successive years and severe bark damage (whole slabs of bark removed) occurred on about one-third of the shaker trees the first year. Examination of the yield data for all years indicated there was no difference in the yields of the severely barked trees and those with little or no apparent bark damage. The author examined these trees during the 1993-94 season and found no apparent difference in canopy appearance between the ones which had been severely barked, little or no apparent bark damage, and the handpicked check trees. Further, the percentage of trees lost from blight, etc. were not different between these 3 sets of trees. The author does not condone tree bark damage as an acceptable result of tree shaking, but states the evidence from this harvest trial suggests tree bark damage may not be as detrimental as many growers might think. Still another problem has been many of the existing bedded groves have 10 to 30% of the trees which do not have adequate trunk height for making a suitable clamp with the shaker clamp pads. These trees must be left for handpickers and create a harvesting management problem since the trees are usually scattered throughout the grove.

For the 1994-95 season, Fruit Harvesters International, Inc. has been operating 5 redesigned harvesters. The harvested fruit was stored in a 60-box bulk trailer towed behind the collection catchframe. When full, the trailer was dumped into a grove similar to the conventional fruit-handling goat. Changes have been made in the shaker design to lower its overall profile (less height) for accommodating short trunks and to the shaker pads in an attempt to minimize bark damage. According to the manufacturer, the mechanical harvesters are damaging less than 1% of the trunks and remove at least 90% of the fruit from the trees.

By way of comparison, Table 2 shows the extent to which other tree fruits are mechanically harvested in the United States (O'Brien et al., 1983). The 2 tree fruit which utilize mechanical harvesting to the greatest extent are red tart cherries and prunes (dried).

Conventional harvesting. Figure 7 shows the upward trend in the number of trees per acre growers are planting to get early returns on their investment and hopefully maximize their long-term yields. Some growers have encountered problems managing the higher density groves as the trees reach containment size. If the scion variety/rootstock combination is too vigorous for the closer tree spacings, excessive hedging and topping will be required to maintain the trees within the containment bounds and vigorous regrowth will be substituted for good fruit yields. Low fruit yields are not good for the grower's gross returns and are generally more expensive to harvest.

In an attempt to answer some questions about the management and harvesting of higher density plantings, a research team at the Lake Alfred CREC planned and planted a 25-acre orange experiment in 1980 near Babson Park in cooperation with the Coca-Cola Company (Wheaton et al., 1986). Even though no mechanical harvesting has been done to date, the trees were headed out (height of lowest limb above ground) at 24 inches when planted to provide accessibility for mechanical harvesting equipment to the trunk and underneath the canopy.

Nine seasons of results with Hamlin and Valencia oranges on Rusk citrange, a moderately vigorously rootstock, have produced superior cumulative fruit and pound solids yields compared with the trees on Milam, a vigorous rootstock similar to many in production today (Whitney et al., 1994). The trees on Rusk have only grown to a 12 to 14 ft. height, will probably not grow much larger, and have adapted fairly well to all tree densities (150 to 360 trees/acre). At the 2 tree densities with the 15 ft. between-row spacing (15 x 15 ft., 200 trees/acre; 15 x 8 ft., 360 trees/acre), the trees on Rusk have developed a fruiting canopy 8 ft. wide and may be suitable for picking from a platform since the pickers can reach halfway through the canopy as the platform moves down each row middle. The trees on Milam have produced fairly good fruit yields at the widest spacing, 20 x 15 ft. or 150 trees/acre. Important for conventional harvesting, 65% of the oranges on the Rusk trees can be picked without a ladder, and there is still space around the trees for fruit container and picker/ladder movement at the 20 x 15 ft. spacing (150 trees/acre) and the 15 x 15 ft. spacing (200 trees/acre). In addition, harvesting trials conducted by the author during the 1993-94 season showed the picker harvest rates on the Rusk trees were at least 10% higher than those on the 18 ft. tall trees on Milam, and picker harvest rates increased with increasing fruit yield and fruit weight (unpublished data).

FUTURE TRENDS

The renewed interest in harvesting in 1991 eventually resulted in a citrus harvesting think tank conducted at the Lake Alfred CREC in March 1994. The report from this think tank emphasized the following points in its executive summary:

1. The FDOC should immediately hire a harvesting program director, and budget funds from the Citrus Advertising Trust Fund to establish a citrus harvesting

research and development program (this person began employment January 1995).

2. Establish an equipment/idea database at the CREC, Lake Alfred.
3. Develop incentives to encourage companies and individual investors to direct their efforts toward development of new and improved harvesting aids, mechanical removal devices, and technologies for loosening fruit.
4. Pursue more efficient use of harvesting labor and upgrade the position of citrus harvester by making the job easier, more productive and rewarding.
5. Modify existing groves by appropriate hedging, topping, and adjustment of skirt height, and design future groves for more effective harvest by both conventional and mechanical means.
6. Resume testing of fruit loosening chemicals with emphasis on materials already registered on food crops to minimize registration and regulatory problems.
7. Enlist help from outside the citrus industry, including technical personnel from other commodity groups and from the aerospace industry.
8. Investigate long-range research options including new technologies developed within and outside the industry.

As the above program gets underway, there are regulations which will affect harvesting. The majority of the citrus is harvested by crews under the control and direction of labor contractors. These contractors are hired by growers and until recently, the contractors were solely responsible for the pickers. Recent federal legislation has made the grower and contractor jointly liable for the picker's activities if it can be shown the grower is a joint employer by influencing the harvesting operation in any way, even though the pickers are hired by the contractor. This legislation will provide an incentive for the grower, if he/she is concerned or not satisfied with harvesting, to either get involved in the harvesting operation and make a difference or to minimize liability responsibilities by not doing anything which could be misconstrued as influencing the harvesting operation. If profit margins continue to shrink in the future, the grower will have an incentive to get involved and should make the working environment better and safer for the picker.

In recent years, OSHA has been studying working conditions, injuries, causes, etc., for agricultural and nonagricultural workers. They may soon develop worker environment requirements which will deal with remedies for such injuries from repetitive tasks, improper and strenuous lifting, etc. Cavaletto et al. (1994) reported that California has proposed an ergonomics regulation to be implemented in January 1995 to address problems of cumulative trauma injuries. They state the regulation will have wide ranging impacts including how medical treatment will be conducted and when, by whom, and how work sites and procedures must be evaluated for potential problems. These requirements may require the citrus industry to develop programs which will address common picker injuries, e.g., back injuries from lifting heavy fruit bags and ladders, bodily injuries from falling off ladders, etc.

A factor which may influence the cost and availability of migratory pickers for harvesting is general public consensus that they should not provide medical and educational services for these people. Overwhelming voter approval of Proposition 187 in California during the 1994 elections was a case in point. If such initiatives continue and spread to other states utilizing substantial numbers of migrants (such as citrus harvesting), the Florida citrus industry could be asked to provide a subsidy to support the medical and educational services for migrants, adding to the cost of harvesting.

Figures 1 and 8 show that record crops, low prices, and increased harvesting costs are forecast in the next decade. The degree to which the above regulations are adopted, smaller profit margins for the grower, higher conventional harvesting costs, and reduced labor availability will be incentives for the adoption of picking aids and mechanical harvesters. Labor availability is the most important factor. Polopolus et al. (1993) predicted 10,000 additional pickers will be required to harvest the record Florida citrus crops during the next decade. The picking aids described earlier in this paper could help alleviate the need for pickers if they are proven feasible. With the Harvesting Systems Ltd. boom machine, the investment per picker is high and the picker must be willing and able to become proficient in the operation of the machine. With the Harvesting Systems Ltd. pan machine and New Way Loader, a team effort is required and the maximum number of pickers who can effectively work in the vicinity of the machines is probably 8 to 10. Compared with a conventional harvesting crew, a fruit handling truck can load the fruit picked by 20 to 30 pickers, and thus lower the fruit handling cost by substantially increasing the volume of fruit moved by a driver and truck. If and when mechanical harvesting is adopted to deliver significant quantities of fruit into the processing plants, no major changes are anticipated at the plants if no abscission chemicals are used and the fruit is caught in a suitable collection unit without touching the ground. Equipment for trash elimination, de-stemming, and bounce grading are installed in many plants. If abscission chemicals are used and/or fruit is dropped on the ground, then the plants may be required to process the fruit in a more timely manner and handle greater quantities of sand, trash, and unsound fruit. Currently, clearance of an abscission chemical could take up to 10 years and cost $30 to $50 million.

It appears one of the best long-term solutions to the harvesting problem is to develop smaller, productive trees which are easier and faster to harvest by hand and more feasible for mechanical harvesting. Additional research is needed to develop suitable, moderately vigorous rootstock/cultivar combinations and techniques to manage them. To stabilize or reduce the cost of harvesting, the trees must be planted and cared for with harvesting considerations in mind, something the industry has not done in the past. The trees should be headed out at least 30 inches high and the trunks maintained free of sprouts and as smooth as possible to accommodate mechanical harvesting. In-row tree spacing should probably not be less than 10 ft. and between-row spacing will be determined by the vigor of the rootstock/cultivar combination. Development of fruit handling equipment to handle fruit containers in the row middle rather than beside the row middle (underneath the tree canopy in hedgerows) would increase the speed and efficiency of this operation. This development will be particularly beneficial in the future since most of the groves will be hedgerows at an early age and the row middle width for equipment operation may be reduced in higher density plantings.

SUMMARY

Since the mid 1950s, the Florida citrus industry has been concerned about harvesting during periods of low profit margins which have usually coincided with substantial increases in production. Factors discussed which affect harvesting include fruit type and utilization, grove characteristics, and harvest labor and cost. Moving citrus in containers out of the grove has been mechanized, but removing citrus from the tree is still done by handpickers after numerous attempts to mechanize this part of the operation. There are a few picking aids in use, but for all practical purposes, the citrus crop is picked by handpickers with bags on ladders. Once again, in the decade ahead, the industry is faced with predicted record crops and low prices, and has initiated a harvesting program in the Florida Department of Citrus to insure the future crops are harvested at a competitive cost.

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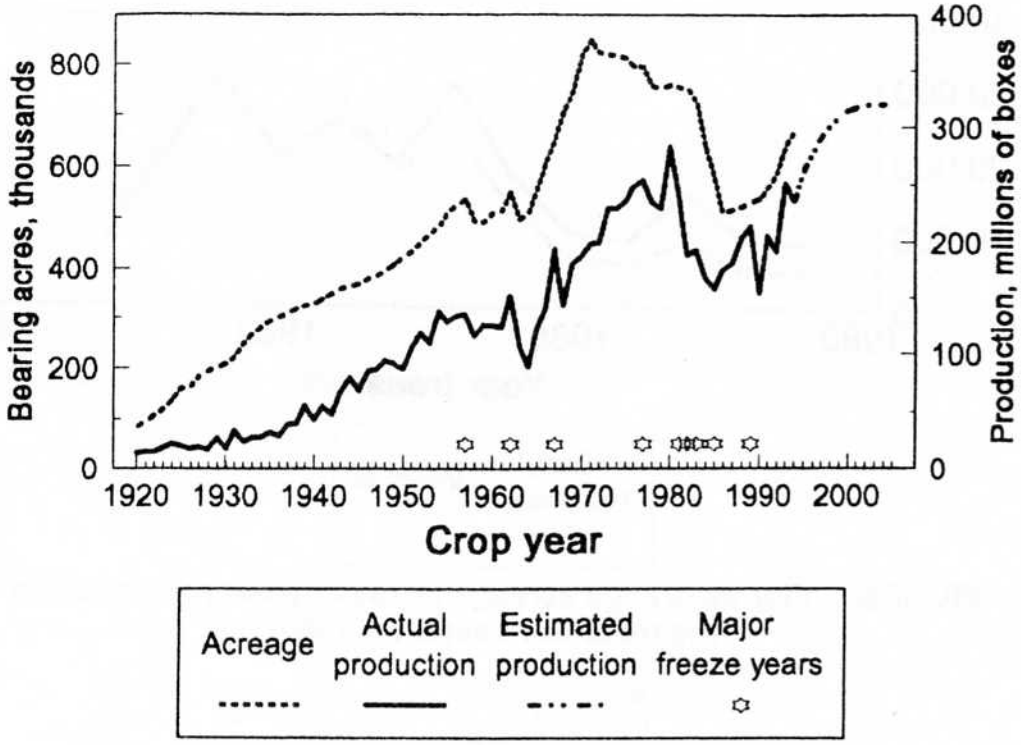

FIGURE 1. Florida citrus bearing acreage, fruit production, and major freeze years.

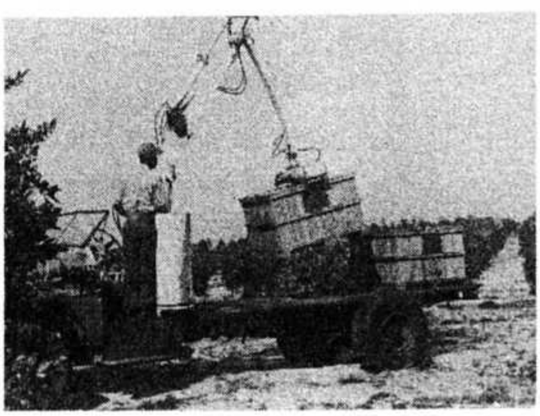

FIGURE 2.Flatbed truck with grapple-type loader boom to handle fresh market pallet bins.

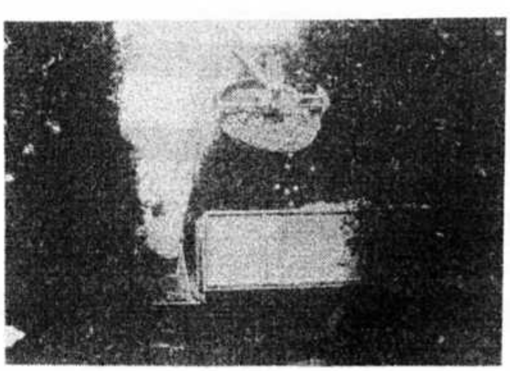

FIGURE 3. High-lift truck with grapple-type loader boom to handle processed fruit in conically-shaped, molded polyethylene tubs.

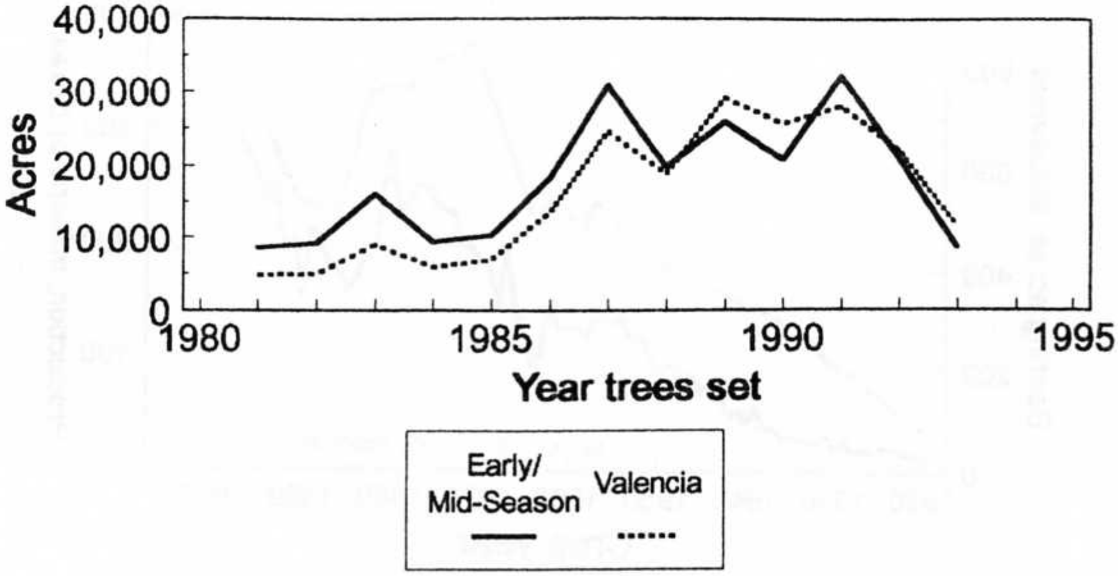

FIGURE 4. Florida orange acreage in 1994 by the year in which the trees were set after 1980.

FIGURE 5. Designated boundaries of Florida's commercial citrus production areas—Northern, Central, Western, Indian River District, and Southern.

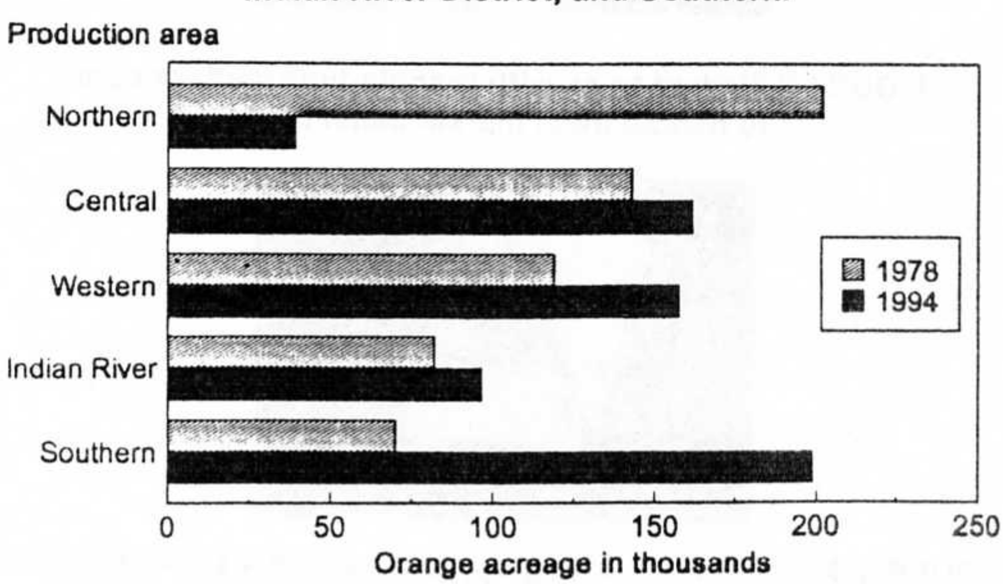

FIGURE 6. Florida orange acreage by commercial production areas in 1978 and 1994.

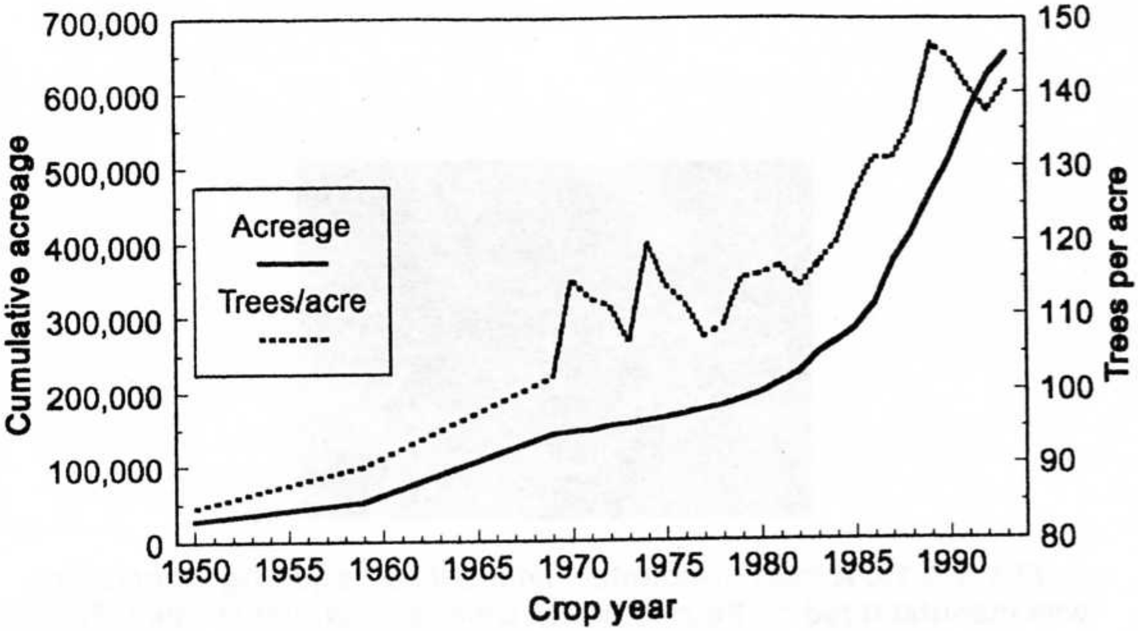

FIGURE 7. The average number of Florida orange trees planted per acre by crop year set and the Florida orange acreage existing in 1994 accumulated by crop year set.

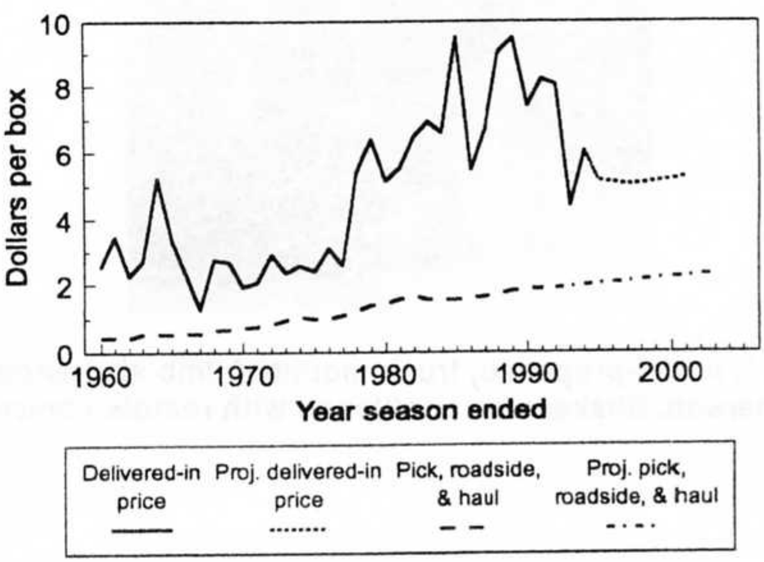

FIGURE 8. Florida processed orange delivered-in prices and harvesting (pick, roadside, and haul) costs.

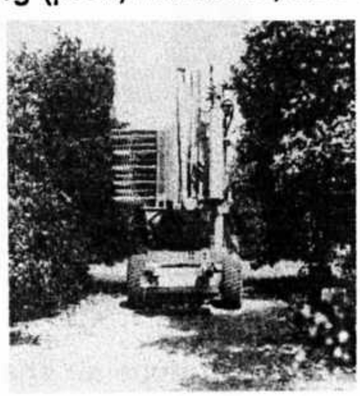

FIGURE 9. A contact harvesting device with a blank of flexible, rotating augers for inserting into tree canopy to twist and pull the fruit out.

FIGURE 10. A tractor-mounted, limb shaker requiring 2 operators was manufactured by Pounds Motor Company, Winter Garden, Florida.

FIGURE 11. A self-propelled, truck-mounted limb shaker operated by 1 person. Shaker was positioned with remote controls.

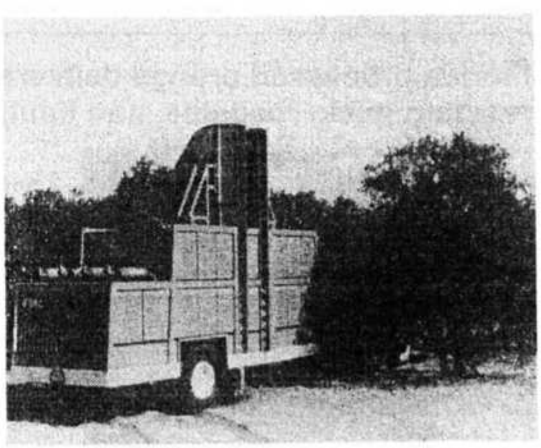

FIGURE 12. Tractor-drawn prototype air shaker requiring 1 operator was manufactured by FMC Corporation, Ocoee, Florida.

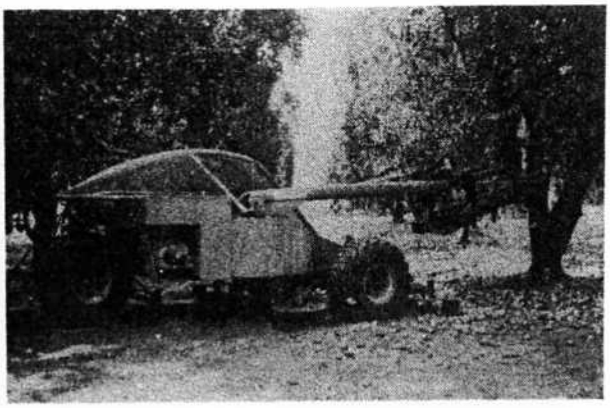

FIGURE 13. A self-propelled trunk shaker requiring 1 operator was manufactured by OMC Corporation, Yuba City, California.

FIGURE 14. A self-propelled fruit windrow rake requiring 1 operator was manufactured by FMC Corporation, Ocoee, Florida.

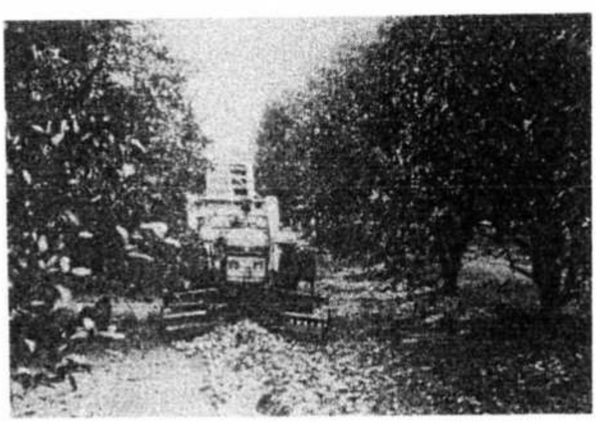

FIGURE 15. A tractor-drawn fruit pickup machine requiring 1 operator was manufactured by FMC Corporation, Ocoee, Florida, and loaded fruit directly into a high-lift "goat" truck.

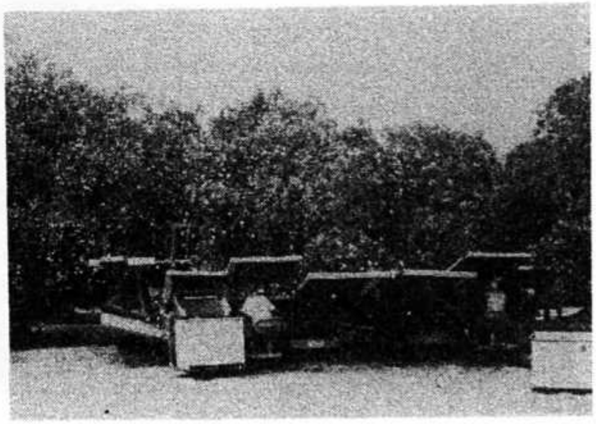

FIGURE 16. A limb shaker catchframe harvester requiring 2 operators, 1 for each half of the harvester, was manufactured by Perry Harvester, Inc., Gasport, New York.

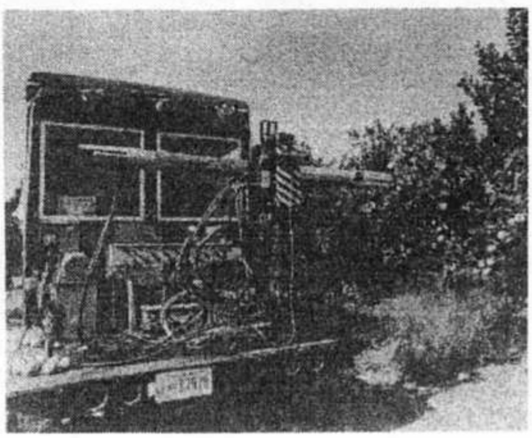

FIGURE 17. The Florida picking robot arm.

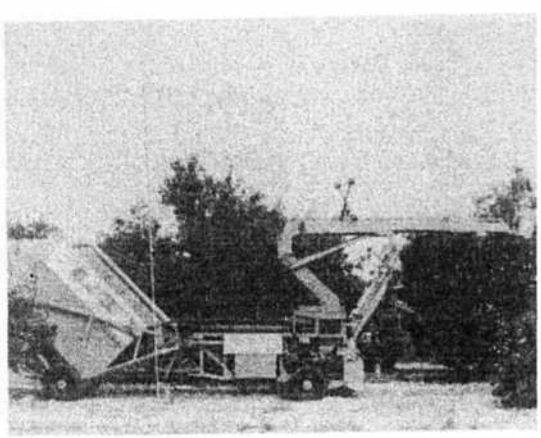

FIGURE 18. A self-propelled man-positioner for 1 operator was manufactured by Harvest Systems, Ltd., Mayfield Heights, Ohio. Note operator (picker) on machine at right near tree top and fruit storage bin on the left.

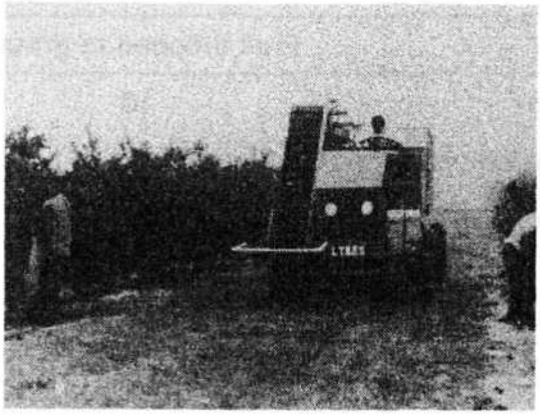

FIGURE 19. New Way Loader requiring 1 operator was manufactured by Jim Andrews, Lorida, Florida.

FIGURE 20. Pan machine requiring 1 operator was manufactured by Harvest Systems, Ltd., Mayfield Heights, Ohio.

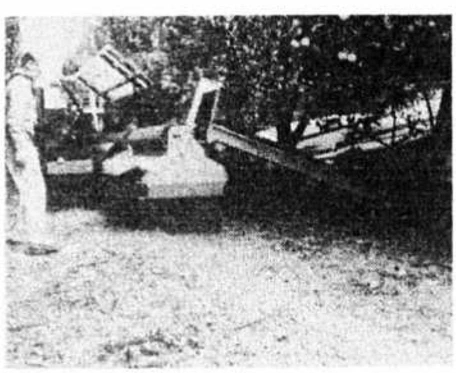

FIGURE 21. Trunk shaker-catchframe harvester requiring 2 operators, 1 for each side of harvester, was designed and constructed in Israel and assembled in Florida by Fruit Harvesters International, Inc.

Table 1. Processing orange quality attributes at the plant as affected by dropping fruit on the ground vs. bagging fruit in a conventional harvesting operation, 1993.

Attribute	Fruit dropped to ground	Fruit bagged
1. No defective fruit/box	10	6
2. Lb. leaves and twigs/500-box load	121	103
3. Microflora in colony forming units/cm^2 fruit surface area	44×10^3	8×10^3
4. Lb. sand on fruit surface in 500-box load	29	13

Table 2. Estimates for acreage, processed utilization, and use of mechanical harvesting on deciduous tree fruits in the United States, 1978 crop.

Crop	Bearing acreage	Processed acreage, %	Mechanically harvested acreage, %
Apple, standard	360,000	50	5
Apple, size controlled	146,000	30	2
Apricot	30,000	93	10
Cherry, red tart	62,000	97	85
Cherry, sweet	57,000	77	15
Nectarine	17,000	2	0
Peach, clingstone	101,000	45	8
Peach, freestone	148,000	15	0
Pear	94,000	60	<1
Plum and prune	47,000	48	15
Prune (dried)	79,000	100	90