# New Mechanical Harvesters for the Florida Citrus Juice Industry

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**Summary. Hand picking, by snapping each fruit from its stem, has been the traditional method of harvesting Florida oranges (*Citrus sinensis*) and grapefruit (*C. paradisi*) for processing. A harvest mechanization program was active from about 1960 to 1985, but mechanical methods were not adopted. In July 1994, a new harvesting research and development program was initiated by the Florida Department of Citrus. The growers are taxed about $0.01/field box of production to fund the program. An industry Advisory Council oversees the program, and recommends projects and funding. The new program has provided training videos to improve hand harvest management/productivity, developed several methods for mechanical harvesting, and discovered/evaluated several fruit abscission agents. Mechanical harvesting use is increasing, and about 6880 of the 237,498 ha (17,000 of the 586,859 acres) of oranges were mechanically harvested during the 2002–03 season. Two mechanical systems can increase labor productivity by 5 to 15 times and reduce unit harvesting cost by 50% or more. Such savings are essential for effective competition in free-trade markets and for operation with resident labor. Many old-style plantings will need to be replaced over the next 10 years. The harvesting program accomplishments are discussed.**

Florida produces more citrus fruit than all other states in the United States. In 2002, the total bearing area was estimated at 295,237 ha (729,531 acres); 237,498 ha (586,859 acres) were oranges [Florida Department of Citrus (FDOC), 2003]. Recently, about 95% of the orange production was processed. The average contract cost for hand harvesting a field box [1 FB = 40.8 kg (90 lb)] of oranges for processing was about $1.75 for the 2002–03 crop. This is the total cost for removing the fruit from the tree and placing it in a bulk highway truck. Most hand harvesting crews are supplied to growers by harvesting contractors. The pickers are paid a piece rate for each FB they harvest, usually about half of the contract harvest cost. Average hand harvester (picker) productivity is about 10 FB/h [408.2 $kg \cdot h^{-1}$ (900 lb/h)]. Harvesting crews generally consist of 20 hand harvesters, and one grove truck operator. Crews typically harvest about 1500 FB [61.23 t (67.5 tons)] of fruit in 8 h of work. The supply of domestic harvest workers is decreasing and harvest cost is increasing. Most of the hand harvesters are seasonal foreign workers.

A mechanical harvesting program was active from about 1960 to 1985, but none of the developed technologies were adopted (Whitney, 1995). In 1994, the FDOC established the Citrus Harvesting Research Advisory Council, comprised of citrus industry individuals, to run a harvesting program and develop economic harvesting technologies for juice oranges. Program goals were to reduce harvesting cost and increase labor productivity so that the Florida industry can successfully compete in free trade markets and no longer be dependent on a supply of seasonal foreign workers. The growers are taxed about $0.01/FB of production to fund the program. The new program has provided training videos to improve hand harvest management/productivity (FDOC, 1997), developed several methods for mechanical harvesting (Brown, 2002), and discovered/evaluated several fruit abscission agents (Burns, 2003). In the long run, labor productivity must increase to more than 45 FB/h [1837.1 $kg \cdot h^{-1}$ (4050 lb/h)] and contract harvest cost must decrease about 50% to ensure Florida citrus products are harvested and competitively priced in free-trade markets. In the short run, existing orange groves must continue to be harvested while the industry transitions to mechanical harvesting.

Tree age and size, trunk height and skirt height, between-row and in-row spacings, type of hedging and topping, grove floor and bed-and-swale style, irrigation and drainage design, and clear headland conditions vary greatly among the existing groves. A 2.1- to 2.4-m-wide (7 to 8 ft) equipment alley is maintained between rows by mechanical hedging. Tree height is topped at about 4.6, 5.2, or 6.1 m (15, 17, or 20 ft). The non-uniform grove conditions result in the need for several types of mechanical harvesters.

**Fruit abscission.** The fruit detachment force (FDF) for mature oranges typically ranges from 44.5 to 89.0 N (10 to 20 lbf). Hand harvesting and mechanical harvesting would be more complete and faster if FDF was less than 44.5 N. During much of the late harvesting season, Valencia orange trees have blooms and developing fruit present for the next crop. Reducing FDF, without affecting blooms, developing fruit, or leaves, should also enable a more selective mechanical harvest for 'Valencia' (Roka et al., 2003). Burns (2003) has summarized the recent abscission research progress. Commercial use of abscission is still a few years away.

**Mechanical harvesting systems.** Eight different approaches were selected for potential commercial use. They are: 1) area canopy shake-to-the-ground; 2) canopy pull-and-catch; 3) trunk shake-and-catch; 4) trunk shake-to-the-ground; 5) continuous canopy shake-and-catch; 6) continuous canopy shake-to-the-ground; 7) continuous air shake-to-the-ground; 8) mechanical fruit-pickup. Photos, design, and performance details are in cited reports for each approach. Additional information is also available in a progress report (Brown, 2002).

**Area canopy shake-to-the-ground.** These systems (J. Hosking, personal communication; R. Schlossin, personal communication) use rectangular or circular groups of plastic rods that are pushed 0.9 to 1.8 m (3 to 6 ft) horizontally into the tree canopy. Each group of rods is mounted perpendicular to a plate in the vertical plane. An eccentric moves this plate in a circular path in the vertical plane. The eccentric produces a stroke of 7.6 to 10.2 cm (3 to 4 inches) along the entire length of the rods at frequencies controlled by the operator in the range of 3 to 5 Hz (180 to 300 cycles/min). Most fruit fall to the ground within 10 s. Each

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shaker head harvests an area about 3.0 m (10 ft) high and wide, after being positioned in the canopy by a multi-jointed hydraulic arm. A harvest rate of 10 to 20 trees/h is typical. Hand harvesters pick up the fruit and glean the trees, which is a costly operation. Both developers are attempting to perfect fruit catching machines that can accompany the shakers, and result in commercial harvesters. This system works in a wide range of grove conditions. Labor productivity may double and harvest cost may decrease by 10% to 30% in older groves that are not compatible with the faster shake-and-catch systems.

**CANOPY PULL-AND-CATCH.** A 3.0-m-wide × 4.3-m-high (10 × 14 ft) grid of 900 rectangular hollow tubes is pushed 2.4 m horizontally into the tree canopy (Crunkelton, 1999). When withdrawn, small spring-loaded fingers extending from the sides of the tubes pull individual fruits from their stem. Harvested fruit fall to a harvester-mounted catching surface under the tree and are conveyed to a grove truck. This harvest approach is best suited for hedgerow style groves, although it will work when the trees are set farther apart in the row. The commercial prototype of this machine has yet to prove that it will function as envisioned. A left- and right-hand pair of self-propelled automated harvesters is projected to complete two penetrations each and a 2.7-m (9 ft) move forward every minute. Fruit removal should average 90+%, at an uninterrupted harvest rate of 65 trees/h. Labor productivity may increase by four times and contract harvest cost may decrease by 25%.

**TRUNK SHAKE-AND-CATCH.** Large-stroke low-frequency trunk shakers were developed to effectively vibrate the citrus canopy and achieve quick removal of 90% to 95% of the crop. Trunk diameter can average up to 22.9 cm (9 inches). The trees should be spaced 3.7 to 4.6 m (12 to 15 ft) apart in the rows, so they remain separated until quite mature. The shaker/deflector units are designed to operate in rows with either swales or flat middles. The deflector surface is positioned low over the shaker, so the tree skirts do not need to be cut higher than 91.4 cm (36 inches) at the dripline along the equipment alley. Fruit falling on the shaker/deflector unit roll by gravity to the collector unit under the opposite side of the tree where conveyors move fruit from the trunkline to a following bulk handling and roadside system. This is a rapid stop-and-go operation using a 5- to 15-s shake. Uninterrupted harvest rates of 120 to 200 trees/h, and averages of 90 to 140 trees/h, are now typical. Labor productivity can increase by over five times and contract harvest cost may decrease by about 50%. Coe Orchard Equipment (Live Oak, Calif.) and FMC (Lakeland, Fla.) manufacture the trunk shake-and-catch systems.

**TRUNK SHAKE-TO-THE-GROUND.** Large trunk shakers mounted on monoboom power units (like used in nut crops) shake fruit to the ground. The monoboom average harvest rate ranges from 50 to 100 trees/h in older or non-uniform groves where shake-and-catch systems can not be used. A spotter sometimes must work with the monoboom operator to help position the shaker clamp on scaffold limbs. The shaking operation is inexpensive, but hand pickup of the fruit is a costly operation. Mechanical fruit pickup machines will be required to capture the greatest savings. Orchard-Rite Ltd. (Yakima, Wash.) in cooperation with Stackhouse Brothers Harvesting (Hickman, Calif.) manufactures this system.

**CONTINUOUS CANOPY SHAKE-AND-CATCH.** Vertical-axis spiked-drum shakers engage the 4.6-m-high fruiting canopy and shake it in the horizontal row direction to remove the fruit (Peterson, 1998). A left- and right-hand pair of harvesters continuously travel along a hedgerow-style tree row at 0.97 to 1.93 km·h$^{-1}$ (0.6 to 1.2 mph). Integral catching and conveying surfaces gather, detrash and deliver the fruit to a bulk handling and roadside system. The trees should be closely spaced [>445 trees/ha (180 trees/acre)] and hedged at an early age to form continuous fruiting walls. The dense maze of fruiting branches is easily shaken by the 1.5- to 1.8-m-long (5 to 6 ft) nylon or tubular steel rods that form the shaking drum. At a travel speed of 1.93 km·h$^{-1}$, this system can harvest at least 500 trees/h, 800 FB/h [32.66 t·h$^{-1}$ (36.0 tons/h)], and 12 highway trucks of fruit in an 8-h workday. Worker productivity can increase by over 15 times and contract harvest cost may decrease by 75%. A tractor-drawn continuous canopy shaker can also quickly shake fruit to the ground in older small groves at about 200 trees/h. OXBO International Corp. (Clear Lake, Wis.) and Korvan Industries (Lynden, Wash.) manufacture the continuous canopy shakers.

**CONTINUOUS AIR SHAKE-TO-THE-GROUND.** Areas of the orange tree canopy can be vigorously shaken by a 160.9-km·h$^{-1}$ (100 mph) air stream at a pulse frequency of 1.2 Hz (72 cycles/min) (Coppock and Donhaiser, 1981). The air stream hitting the leaf area in the canopy produces limb displacements that are large and result in fruit removal. Fruit abscission compounds developed during the 1970s reduced FDF to near zero and enabled shaking up to 95% of the crop to the ground at a travel speed of 1.61 km·h$^{-1}$ (1.0 mph). Air shakers followed by fruit pickup machines will be used after a fruit abscission compound is registered for commercial use. This harvesting system should perform well in groves of large traditional trees, which are widely spaced and unhedged, and the grove floor is flat. Labor productivity would likely be lower, and cost of harvesting higher, than for the canopy shake-and-catch system. No manufacturer exists at present.

**MECHANICAL FRUIT-PICKUP.** Two rake and pickup systems and two direct pickup systems have been developed. These systems work best when the grove floor is flat and weed-free. Ground preparation (disking) is required 1 to 2 d prior to the start of harvest to remove existing trash and old fruit, and to smooth the soil surface to improve fruit recovery. Removal of skirt foliage and large limbs to 61.0 cm (24 inches) above the ground surface is required to provide operator visibility that will avoid both tree and machine damage, and to optimize pickup capacity. These pickup systems can work at 0.80 to 1.61 km·h$^{-1}$ (0.5 to 1.0 mph) in most mature groves, regardless of tree spacings, trunk heights, intersets, etc. These conditions are typical of about 50% of the Florida orange land area now in production. In 8 h of work these systems should pickup and roadside 2500 to 3000 FB [102.06 to 122.47 t (112.5 to 135.0 tons)] of fruit. Potential manufacturers now are Kennco Manufacturing (Ruskin, Fla.), OXBO International Corp., and Stackhouse Brothers Harvesting.

**FRUIT AND JUICE QUALITY.** Fruit delivered for processing must be wholesome and meet or exceed the requirements specified in Chapters 20–62 of the FDOC Rules (FDOC, 1992), to assure high quality pasteurized juice. All of the mechanical harvesting systems that catch fruit are in compliance. Mechanical pickup systems must have trash removal equipment and hand sorting stations. The processing industry has set a tentative limit of 90.7 kg (200 lb) of trash (sand and other non-fruit debris) per 500 FB [20.41 t (22.5 tons)] load of fruit. Fruit and juice quality studies will identify the necessary best management practices.

**Labor productivity.** All of the mechanical harvesting systems increase labor productivity above that of hand picking. The area canopy-shakers or monoboom trunk-shakers more than double labor productivity in older traditional groves. The canopy pull-and-catch harvesters or the trunk shake-and-catch harvesters usually increase labor productivity by 5 to 10 times. The continuous canopy shake-and-catch harvesters may increase labor productivity by 10 to 20 times. Reports for the 2001–03 seasons are available (Roka, 2002, 2003) which describe the hourly capacity and labor productivity of the harvesting systems. None of the systems have yet achieved their ultimate level of performance. But, they eventually will when well-trained crews operate durable machines in properly prepared groves, and the harvesting operations work at full capacity for regular 5- or 6-d work weeks.

**Harvest cost.** These harvesting systems offer a wide range of harvest cost savings for early- and mid-season oranges ('Hamlin,' 'Pineapple,' and 'Parson Brown') as well as late-season oranges ('Valencia'). They also work well for grapefruit harvest. The older traditional groves, having resets of various ages and conditions, will remain the most expensive to harvest, although cost savings of 20% may be possible. The area canopy-shaker and the monoboom trunk-shaker, combined with fruit-pickup machines, may be the best harvest system for such groves. When fruit abscission compounds are registered and applied, air harvesters and pickup machines may be a better choice. Mature hedged and topped 'Valencia' groves that are fairly uniform, and require selective harvest late in the season, may require the canopy pull-and-catch harvester. Cost savings of 25% may be possible, but is yet to be verified. Traditional groves up to 25 years old that are uniform and skirted, with 38.1 to 50.8 cm (15 to 20 inches) clear trunk height, are good choices for the trunk shake-and-catch harvesters. Cost savings of 25% to 50% may be possible. High-density groves that are uniform, skirted, hedged and topped, and have tall trunks are good choices for the continuous canopy shake-and-catch harvesters. Cost savings of 50% to 75% may be possible. The operating cost/h of harvesters and processing plants, divided by the FB/h handled, are both important factors. To minimize finished juice cost, both operations must run near their potential maximum capacity. Cooperation between the producer and the processor is essential when scheduling both harvest and delivery.

About 6880 ha of oranges were harvested by about 30 separate mechanical systems during the 2002–03 season. Purchase and contract harvest costs for several of these systems, as cited above, are now known by harvesting contractors. Their contract cost includes all ownership/lease costs, as well as operation/maintenance costs, labor costs, and profit for the contractor. Growers prefer to select a contractor based on their cost/FB bid. Contractors examine the grove conditions and delivery agreement, and estimate the hours of harvest system operation, prior to submitting their bid. Mechanical harvest cost/FB for a grove is determined by the ratio of total cost divided by total fruit harvested. The contractors are planing on a 5- to 7-year equipment life, 20 to 25 weeks or 750 to 1000 h of operation per year, 5% to 15% of purchase cost for annual repairs and maintenance, and delivery schedule cooperation from the processors. Growers are now reducing their harvest cost and contractors are operating at a profit. Equipment operators earn 20% to 50% more per season than they would if still hand harvesting, and workers seek these positions.

**Groves of the future.** New groves for processed orange production should be designed and grown for efficient mechanical harvesting, as well as maximum production/ha. The clear trunk height should be about 76.2 cm (30 inches) at planting, assuring 61.0 cm (24 inches) clear at maturity. This will enable fast and safe operation of trunk shake-and-catch systems or continuous travel canopy shake-and-catch systems. Tree planting densities of 346 to 445 trees/ha (140 to 180 trees/acre) may be best for the trunk shake-and-catch systems, and 445 to 618 trees/ha (180 to 250 trees/acre) may be best for the canopy shake-and-catch systems. Swale design may need to be restricted to uniform slopes from the trunkline to the swale centerline. Other factors may also prove to be critical as more experience is gained with mechanical harvesting.

**Progress.** The harvesting program funded in 1994 by Florida citrus growers to develop improved methods for harvesting has now produced at least eight different harvesting systems. These systems can be used in various compatible groves by the juice industry. Cost savings of 10% to 75% are possible in the future, depending on the type of grove and the appropriate harvesting system. Labor productivity factors of 2 to 20 are also achievable in the future. Cost savings greater than 25% and labor productivity increases greater than five times will be required for reliable harvesting and effective free-trade competition in the future, so some of these systems will only be useful during the transition years. Mechanical harvesting was used on about 6880 ha during the 2002–03 crop season, and its use will steadily increase. In 2001 the Harvesting Council funded an automated (robotic) harvester project with the University of Florida (Burks et al., 2005), and is seeking Federal funding and consortium research and development arrangements with other tree fruit industries and research groups.

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# Harvest Mechanization Progress and Prospects for Fresh Market Quality Deciduous Tree Fruits

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**ADDITIONAL INDEX WORDS.** machine harvest, labor, apple, peach, sweet cherry

**SUMMARY. Deciduous tree fruit crops such as apple (*Malus domestica*), peach (*Prunus persica*), and sweet cherry (*Prunus avium*) are not mechanically harvested for the fresh market. Attempts to mechanically harvest these fruits by mass removal techniques have not been successful due to excessive fruit damage caused during detachment, fall through the canopy, and collection. Robotic harvesters have not been commercially accepted due to insufficient fruit recovery. A U.S. Department of Agriculture–Agricultural Research Service (USDA-ARS) harvesting concept shows promise for harvesting both fresh market quality apples and sweet cherries. Successful mechanical harvesting of fresh market quality deciduous tree fruit will only occur when plant characteristics and machine designs are integrated into a compatible system. Cultivar characteristics that would facilitate machine harvesting are uniform fruit maturity at harvest, firm fruit that are resistant to mechanical damage, and compact growth habit that produces fruit in narrow canopies and on short/stiff limbs. Engineers must develop new detachment principles that minimize the energy input to effect fruit detachment, and develop durable energy-absorbing catching surfaces/conveyors to eliminate damage during collection of the fruit. As technology advances, sorting and sizing systems might be developed that can be operating on the harvester to eliminate culls in the field and deliver only fresh market quality fruit to the packers.**

The deciduous tree fruit industry is an important segment of U.S. agriculture. In 2001, apples, sweet cherries, and peaches provided incomes for orchards in the U.S. of $1,553,536,000; $286,744,000; and $495,067,000, respectively (USDA, National Agricultural Statistics Service, 2001). However, the limited availability and rising cost of a skilled workforce to harvest this fruit are major concerns of the U.S. fruit industry (Brown, 2003; Hanson, 1999a; Morgan, 2002; Warner, 1997). The gradual reduction of labor supplies and increased tree fruit acreage, particularly in the northwestern U.S., led to shortages in recent years and is expected to worsen in the future. Competition from countries with significantly lower labor costs could force U.S. producers to reduce costs or lose valuable markets. Holt (1999) suggested that increased mechanization could be an effective means of increasing worker productivity and keeping U.S. fruit industries competitive in the world market. Currently, there is no commercial mechanical harvesting of fresh market quality deciduous tree fruits in the U.S. (Sarig et al., 1999).

The objective of this paper is to describe recent research to mechanically harvest fresh market quality apples, sweet cherries, and peaches; cite reasons for lack of success; and speculate on requirements for successful harvest mechanization.

## Apple

Attempts to mechanically harvest apples by mass removal techniques (shake/catch) from freestanding trees have not been successful (Brown et al., 1983; Peterson et al., 1994) due to excessive fruit damage. This damage occurs from 1) excessive apple movement during detachment, causing apple-to-apple, and apple-to-branch contact; 2) apple-to-branch contact when falling; and 3) apple-to-apple contact on the catching surfaces, since most of the apples fall in a short time



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period (3–6 s). Narrow inclined trellis systems for apples (Fig. 1) have been developed to space primary fruiting scaffolds equally along the trellis, and from the bottom to top of the wire support (Robinson and Lakso, 1991; Robinson et al., 1990). In addition to being very productive by improving light distribution within the canopy, these trellised systems may be compatible with mechanical harvesting by providing sites for shaker attachment and an open non-overlapping branching pattern to minimize damage during apple fall. Upadhyaya et al. (1981a, 1981b) found that impacting inclined apple limbs from below in a direction transverse to the limb nearly eliminated fruit movement during detachment, which should reduce detachment damage. Colorio and Beni (1995) developed a harvesting system for narrow inclined trellises that utilized underlimb impactors and a special catching surface to harvest apples. Harvest trials produced less fruit damage than reported by shake/catch harvesting methods, but the system has not been commercialized.

More recently, Peterson et al. (1999) developed a robotic bulk harvester concept to remove apples grown on narrow inclined trellises. This system combined mechanical harvesting technology, an imaging system, and intelligent adaptive technology to identify individual scaffolds, determine fruit locations, position a rapid displacement actuator (RDA) against a scaffold, and a catching surface under the apples. When executed, the RDA supplied an impulse to rapidly displace the scaffold away from the fruit, causing detachment. Limited field testing demonstrated feasibility of the system with nearly complete fruit removal and fruit quality as good as from hand harvesting. However, they suggested that using a human operator to position and activate the RDA with hydraulic joysticks might be a simpler, more reliable, and easier solution to implement than an imaging system with controlling software. Building on this harvesting concept, Peterson and Wolford (2001, 2002) developed components for a mechanical harvesting system that had an operator using hydraulic joysticks to position the RDA, and active energy-absorbing catching surfaces to collect the fruit (Fig. 2). Trees were trained to a Y-trellis. Mechanical harvesting trials with this system on eight apple cultivars yielded 71% to 90% fresh market quality (Peterson and Wolford, 2003). Cuts and punctures were the dominant factor in lower fruit grade. In these trials, 20.2% to 57.2% of the fruit exhibited stem pulls, which has the potential to cause serious long-term storage problems. In a companion study, Janisiewicz and Peterson (data not published) found that decay on apples with stem pulls was not a serious issue on most cultivars. However, treatment with postharvest biocontrol agents minimized the decay in susceptible cultivars. Peterson and Wolford (2003) also found that cultivar growth habit and hence their adaptability to this harvesting concept varied greatly. The most suitable cultivars had compact growth habits with short fruitful laterals that required minimum training.

Intelligent systems, in the form of robotic harvesters, have been developed to pick individual fruits from trees (Bourely et al., 1990; Grand d'Esnon et al., 1987; Harrell, 1987; Kassay, 1997). However, none of these robotic concepts have been adopted commercially because of low capacity and the inability to locate and harvest all the fruit. Kassay et al. (1997) picked only 25% to 32% of the apples from a

**Fig. 1. Side view of "Y" trellis showing orientation of scaffolds and apples.**


**Fig. 2. Rear view of USDA-ARS experimental apple harvester in a "Y" trellised planting. Operators position rapid displacement actuators on scaffold to effect fruit removal. Apples are caught by "soft" moving conveyors and automatically placed in bins.**