Field Test Results with Mechanical Harvesting Equipment in Florida Oranges

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Abstract. *During the 1996-1997 season, mechanical harvesting tests were conducted with a canopy shaker, a trunk shake-catch harvester, and a fruit pickup machine. The canopy shaker, which moved continuously down one side of the tree row canopy, operated at 1.2 to 2.4 km/h. Orange removals ranged from 55% in larger diameter tree canopies to 95% in smaller tree canopies with machine capacities up to 25 t/h. The trunk shake-catch harvester removed 84 to 94% of oranges shaking 5 to 10 s per tree with machine capacities up to 10 t/h. The fruit pickup machine picked up oranges at 15 to 20 t/h at 97% efficiency and caused 3 to 7% split peels from handling.*
Keywords. *Canopy shakers, Citrus, Trunk shakers, Pickup machines.*

Citrus harvesting research and development efforts in Florida through 1994 have been reviewed by Whitney (1995). They were initiated in the late 1950s when the industry recognized the extent to which the high labor requirement and cost placed it in a precarious competitive position. These efforts continued into the 1980s, but the developed harvest aids or mechanical systems could only compete with conventional manual harvesting methods in a very limited set of conditions. During the decade of the 1980s, the industry experienced a succession of devastating freezes which reduced production to about one-half of the record 1979-1980 crop of 11.6 Mt. High fruit prices coupled with low production and adequate harvesting labor minimized interest in mechanical harvesting until 1991 when new citrus plantings in South Florida rapidly increased production and fruit prices dropped significantly. New harvesting research was initiated in 1992 and the effect of harvesting practices on fruit quality was investigated by Miller et al. (1995). They found that dropping citrus on the ground resulted in three times the decay as compared with citrus harvested directly into a picking bag. In 1993, Fruit Harvesters International (Alva, Fla.) initiated development of a mechanical harvesting system (trunk shake-catch).

The Florida citrus industry initiated a research and development program in 1994 which was administered by the Florida Department of Citrus (FDOC). The program goal was to develop harvesting methods to ensure the harvesting of future crops at a competitive cost. Harvesting machines, built under contract with the FDOC for development, were designed for oranges destined for processing. Some of the work for the 1995-1996 and 1996-1997 seasons has been reported by Brown (1997) and Peterson (1998). Whitney (1997) reported results from initial field tests during the 1995-1996 season with trunk shakers, a canopy shaker, and a machine incorporating a rectangular array of tubes with spring-loaded fingers.

During the 1996-1997 season, field tests continued on some of the machines. Factors considered in the evaluation of the machines were tree characteristics, fruit detachment strength, fruit removal, harvest efficiency, and fruit and tree damage. The objective of this article is to report on these factors in test results with the machines.

Equipment and Methods

USDA Canopy Shaker

The USDA canopy shaker (Kearneysville, W.Va.) tested during the 1996-1997 season has been described by Peterson (1998). The design was a larger shaker (fig. 1) than the one tested during the 1995-1996 season (Peterson, 1998; Whitney, 1997). It had a catchframe and conveyors attached to deliver the collected fruit to the rear of the catchframe (fig. 2). The canopy shaker had two shaker drums with eight sets of 3.2-cm-diameter nylon spokes

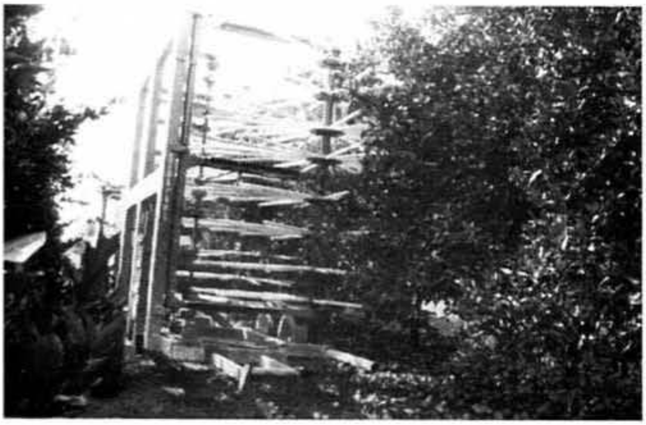

Figure 1—Rear view of USDA canopy shaker as operated in tests 1-4 without catchframe.

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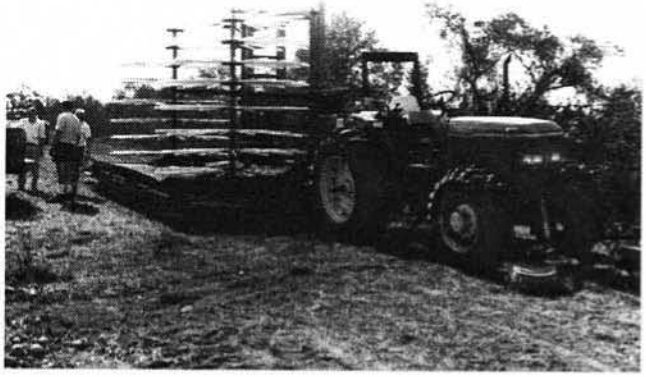

Figure 2—Front view of USDA canopy shaker with catchframe as operated in tests 5 and 6.

Figure 3—Rear view of Compton shake-catch harvester. Shake/deflector unit is at left of tree row and receiver unit is at right of tree row.

Figure 4—Rear view of Compton receiver unit. Dump pan is at left and longitudinal conveyor is at center.

mounted on each of the two vertical shaker shafts. Each set contained 16 spokes 1.5 m long beyond the shaft/hub to which they were bolted. The vertical spacing between spoke sets was 38 cm, and the top set was about 3.7 m aboveground. The left side of the tandem axle support could be hydraulically lifted up to 0.5 m above level so that when the canopy shaker was operated in the ditch of bedded citrus, the left side of the main frame of the harvester could be lifted to maintain a near level position as it moved down the tree row. Oranges were removed by the two shaker drums oscillating horizontally opposite each other as the spokes free-wheeled (some braking was applied) through the tree canopy.

Five field tests were conducted in early- and mid-season orange trees and one in late-season Valencia orange trees which had formed fairly uniform hedgerows. In each test, the canopy shaker was towed with a tractor at a constant ground speed down one side and then the opposite side of the tree row canopy. Ground speeds ranged between 1.2 to 2.4 km/h. Horizontal displacement of each vertical shaker shaft was 11.5 cm at 5 Hz, unless noted otherwise. Measurements (fruit removal, etc.) were made on four replications (two- or three-tree plots) in a tree row. The plot trees were representative of those in the row. Fruit removal, etc., were determined from weight measurements on fruit removed by the machine and fruit left (gleaned) on the trees.

Compton Shake-catch Harvester

The Compton shake-catch harvester (Compton Enterprises, Inc., Chico, Calif.) consisted of two self-propelled units (a shaker and a receiver unit). Whitney (1997) reported 1995-1996 field test results on the development of the shaker head mounted on the shaker unit. For harvesting, each unit moved down opposite sides of the tree row (fig. 3). Tree canopies were skirted to 1.2-m height at the dripline and 0.5 m at the trunk to accommodate the deflector and receiver catchframe units. The shaker was side-mounted on a four-wheel prime mover with hydraulically adjustable tread width and height on the two left wheels to accommodate the different ditch cross-sections in bedded groves. Fruit removed by the shaker was deflected to the receiver unit on the opposite side of the tree row by a flat, sloping surface mounted on top of the shaker prime mover. The receiver unit was mounted on three wheels (1 front steering, 2 rear) and had a flat dump pan 1.2 m wide × 6 m long on the tree trunk side (fig. 4) to receive the fruit from the shaker deflector. Fruit was moved off the pan into the receiver unit longitudinal conveyor by elevating the pan edge nearest the tree trunk and pivoting about its opposite edge, and side shifting laterally toward the longitudinal conveyor. Fruit in the longitudinal conveyor moved to the rear of the receiver unit to a container (tub) on a roller platform which could be hydraulically raised and lowered. As the fruit was discharged from the conveyor into the tub, a fan blew trash out of the fruit. Three workers operated the system (shaker operator, receiver operator, tub handler).

The side-mounted shaker head had a scissors-type clamp with cylindrically shaped pads filled with plastic particles. The head had two sets of unbalanced masses on the same shaft and were belt-driven with a hydraulic motor. The two sets of unbalanced masses totaled 125 kg, had an eccentricity of 22 cm, and were rotated in the same direction. One set rotated 10 to 15% faster than the other at 8 to 10 Hz.

Three field tests were conducted in early- and mid-season oranges and one in late-season Valencia orange. Measurements of fruit removal percentage, etc., were made on four replications of two-tree plots in a row and were determined by weighing the fruit removed and fruit left (gleaned) on the trees.

AMI Fruit Pickup Machine

This machine was built by Agricultural Machines, Inc. (AMI, Avon Park, Fla.) to pick up fruit after being dropped from the tree to the ground manually or by machine. It operated on one side of the trunkline so that two passes were required to pick up fruit from a tree row. Initially for the first field test, the pickup machine was mounted on a Rhino® prime mover (fig. 5). It was self-propelled with a pickup head and conveyors to move the fruit from the ground to a storage bin on the machine. A rod draper chain was used on the pickup head and conveyor system. As the machine moved forward, the pickup head chain moved laterally along the ground to pick up fruit in place to within 60 cm from the trunkline. The fruit was later transferred from the pickup head chain to other conveyors for delivery to the storage bin. The fruit was unloaded from the storage bin into a semi-tractor trailer with two vertical elevator conveyors mounted in one side of the storage bin.

For the second and third field tests, the pickup head was mounted on a Pixall Big Jack® (fig. 6). Fruit stored in the Big Jack® hi-lift storage bin was dumped into the semi-tractor trailer.

Three field tests were conducted on flat beds in south Florida. After the fruit had been dropped to the ground, one or two persons normally moved fruit away from the trunkline. No ground preparation (trash removal or smoothing) was performed. When picking up fruit, a ground speed of about 1 km/h was normally used. After fruit pickup, counts were made of fruit left on the ground in four areas and the percentage of split fruit in four fruit samples in the storage bin and/or semi-tractor trailer.

Figure 5—Front view of Agricultural Machines pickup machine as mounted on the Rhino® prime mover.

Figure 6—Front view of Agricultural Machines pickup machine as mounted on the Pixall Big Jack®.

RESULTS

USDA CANOPY SHAKER

In initial testing, the catchframe did not perform satisfactorily and was revised for later field tests (tests 5 and 6). There were also problems with the shaker in that the ends of the spokes whipped badly (near natural frequency) when the shaker was operated at or near 5 Hz as was done during the 1995-1996 season. To reduce the whipping, the 3.2-cm-diameter spokes were replaced with 3.8-cm-diameter spokes 1.5 m long. Spoke end whipping was still a problem and the spokes were shortened to 1.4 m to further reduce the whipping problem. Additional problems were encountered with bearing failures and fatigue in some of the linkages on the shaker, and they were replaced with stronger components or strengthened.

Harvesting results are summarized in table 1. For tests 1-5 in early- and mid-season oranges, the spokes were 3.8 cm diameter and extended 1.5 m from the center of the shaft. Figure 1 shows the canopy shaker as used in tests 1-4 without a catchframe. The mature trees in tests 1 and 2 were similar and were planted on two-row beds with a ditch between beds. Fruit removal averaged 54% in test 1 and 56% in test 2.

The grove situation for test 3 was considerably different than for tests 1 and 2. The trees were smaller, spaced closer together in the row, and planted on single row beds with gently sloping sides. Prior to conducting test 3, the shaker had been operating in the grove with the left side of the frame raised so that the tops of the two vertical shaker shafts were tilted towards the tree canopies, and the nylon spokes were being pressed into the canopies so that the spoke ends extended 30 cm beyond the trunkline. The canopy shaker was being operated this way to maximize fruit removal, but it was causing a considerable amount of limb damage from broken crotches in the outer canopy and limbs being broken off at the trunk. The brake pressure (rotation resistance) on the vertical shafts may have been excessive for these small trees and contributed to the limb breakage. In addition, some of the fruit removed by the shaker were split. Both the tree and fruit damage were a concern to the grower.

For the evaluation in test 3, the shaker was operated in two ways. In test 3a, the shaker continued to operate as described above at a frequency of 5 Hz with spoke ends 30 cm beyond trunkline. In an attempt to reduce fruit and tree damage, test 3b was conducted at a lower shaker

Table 1. Harvest test results with canopy shaker in oranges

Test	Cultivar	Bottom Tree Canopy Width (m)	Tree Canopy Height (m)	Orange Detachment Force (N)	Mean/Standard Error of Mean of Oranges Removed (%)
1	Hamlin	4.6	3.7-4.6	72	54/2.7
2	Hamlin	3.8	4.0-4.6	92	56/4.7
3a	Hamlin	3.7	1.8-3.0	62	95/0.8
3b	Hamlin	3.7	1.8-3.0	62	73/4.1
4	Pineapple	4.4	3.7-4.6	92	80/3.8
5	Pineapple	2.7	2.4	26	80/2.0
6a	Valencia	3.0	3.7	102	80/3.4
6b	Valencia	3.0	3.7	102	83/3.1

frequency of 4.5 Hz and the shaker was operated further away from the canopy so the spoke ends were at or near the trunkline. Operating the shaker at the higher frequency and closer to the trunkline (test 3a) increased fruit removal by 22 percentage points, but also resulted in increased fruit splits (2.5% vs 1% in test 3b) and substantially increased limb breakage. At the higher frequency, spoke end acceleration and displacement (being nearer the natural frequency) were probably higher and could have contributed to increased fruit removal and fruit splits from spoke-fruit collisions. These oranges were characteristic of thin-skin Hamlin which are more susceptible to fruit splitting than the thicker-skin Pineapple and Valencia as reported by Churchill et al. (1980).

Test 4 was conducted in mature trees on a flat bed with the canopies for the most part naturally formed with few hedging and topping cuts. The left side of the frame was raised to tilt the top spokes into the canopy. Fruit removal averaged 80% and tilting the top spokes into the canopies probably increased fruit removal. There was some limb breakage as a result of the shaker shafts (hubs) and spokes being pressed into the canopies. Split fruit averaged 3%. Because of the problem with split fruit in tests 3 and 4, fruit burst tests (similar to Churchill et al., 1980) were initiated to determine the force required to burst the peel between two parallel plates, and give an indication of the susceptibility of the fruit to peel splitting. In test 4, the fruit burst force averaged 321 N. Down-the-row fruit removal rates of the canopy shaker were up to 25 t/h in fruit yields of 50 t/ha.

Test 5 was conducted after a January 1997 freeze and the effects of the freeze were fairly obvious on the small, young trees. Defoliation and fruit drop were heavy, and the fruit detachment force was only 26 N. The catchframe had been revised and mounted on the canopy shaker for this test (see fig. 2). The outside edge of the catchframe was operated about 15 cm from the trunkline (right side of machine) and limited the maximum reach of the spokes into the canopy to 15 to 30 cm from the trunkline. The tree canopies had been skirted to a height of 60 cm at the dripline and 45 cm at the trunk to accommodate the catchframe. Shaker fruit removal averaged 80%, and 27% of the fruit missed the catchframe and fell on the ground. There were no split fruit and the fruit burst force averaged 444 N.

Test 6 was conducted in young Valencia orange trees on two-row beds. The canopy shaker had been changed from tests 1-5. The bottom four sets of 1.5-m-long (radius) spokes on each shaker shaft were replaced with four sets of 1.8-m-long spokes, which were formed by inserting the original nylon spokes into 76-cm-long steel tubes bolted to the shaft hubs. The purpose of the steel tube mounting was to stiffen the base of the 1.8 m spokes to minimize whipping problems encountered when operating near a 5 Hz frequency. To provide clearance for the 1.8 m spokes, the swing arms supporting the two vertical shaker shafts were extended 30 cm. This positioned the ends of the 1.8 m spokes 30 cm beyond the edge of the catchframe. In preliminary tests, the ends of the lowest set of 1.8 m spokes often hit the trunk and major scaffold limbs, causing extensive bark damage. Consequently, before test 6 was conducted, the lowest set of 1.8 m spokes was removed, leaving three sets.

The shaker frequencies in tests 6a and 6b were 4.7 and 5 Hz, respectively. On most trees, the end of the 1.8 m spokes penetrated the canopies beyond the trunkline. Mature fruit removal averaged 3 percentage points higher at 5 Hz than at 4.7 Hz, 83 versus 80%. While the higher frequency removed more mature fruit, it also removed more young fruit (next year's crop) which had a diameter range of 6 to 18 mm. The mature to young removal ratios were 8 and 5 at 4.7 and 5 Hz, respectively. Mature fruit missing the catchframe was 22 and 27% at 4.7 and 5 Hz, respectively. Bark removal and damage on the main scaffold limbs was evident as a result of the spokes engaging and disengaging the canopies.

Compton Shake-catch Harvester

In preparation for harvesting and the field tests, the harvester had several breakdowns and required several adjustments. The first test, test 7, was conducted on Parson Brown orange trees on two-row beds with each tree shaken for 10 s at 10 Hz and 5-cm shaker displacement. The average trunk circumference and shaker clamp height were 56 and 20 cm, respectively. Fruit removal averaged 84 and 4% of the fruit missed the catchframe (table 2). Down-the-row harvest rate in fruit yields of 65 t/ha was slightly more than 1 tree/min or 9 t/h, and the shaker prime mover was operated with three wheels (left front wheel lifted off the ground).

Test 8 was conducted in Hamlin orange trees on two-row beds. Preharvest fruit drop from a January 1997 freeze (also reported in test 5 above) was 10% and the fruit detachment force averaged 69 N. Each tree was shaken for 12 to 14 s at 8 Hz. Trunk circumference and clamp height averaged 56 and 38 cm, respectively. Fruit removal averaged 94%, and 3% of the fruit yield missed the catchframe. Counts of fruit in the top of the tubs indicated an average of 29% splits, which were much higher because of the pan dumping operation on the receiver unit. When the pan was shifted toward the longitudinal conveyor of the receiver unit and dumped, fruit were crushed between the belting at the inside edge of the sliding portion of the dumping pan and the nonsliding portion of the receiver unit.

Test 9 was conducted on Pineapple orange trees on two-row beds. With in-row tree spacing of 3 and 4.5 m, the 3-m spacing was not adequate to allow the receiver unit to be positioned properly between the trees. Each tree was shaken 8 to 10 s at 10 Hz with the trunk circumference and clamp height averaging 53 and 38 cm, respectively. Fruit removal averaged 94% with a detachment force of 115 N, and 7.9% of the fruit missed the catchframe. Some of the missed fruit was the result of the receiver/deflector units not sealing (overlapping) properly in the 3-m in-row spacing. Down-the-row harvest rate was 100 trees/h and 5 t/h in low yielding trees (30 t/ha). Removal of the belting attached to the pivoting (inside) edge of the dump pan on the receiver unit practically eliminated fruit splitting (1%) which had been experienced in test 8.

Table 2. Harvest test results with Compton shake-catch harvester

Test	Cultivar	Tree Canopy Height (m)	Orange Detachment Force (N)	Mean/Standard Error of Mean of Oranges Removed (%)	Fruit Missing Catchframe (%)
7	Parson Brown	5.2	115	84/2	4
8	Hamlin	4.6	69	94/1.4	3
9	Pineapple	3.7	115	94/2.1	8
10	Valencia	3.7	107	74/2.5	12

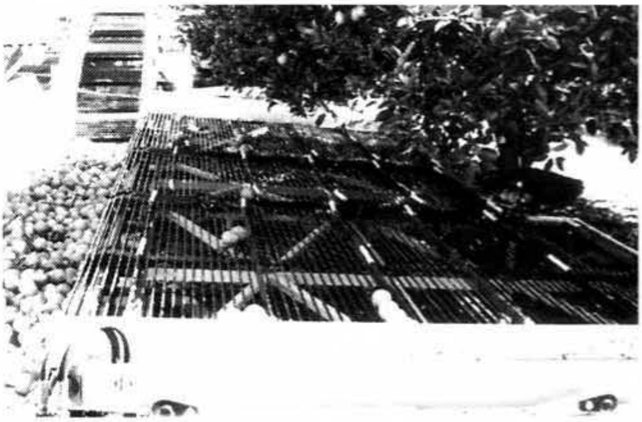

Figure 7—Front view of Compton rebuilt receiver unit showing cross conveyors at right which moved fruit to the longitudinal conveyor at left.

The dump pan on the receiver unit required frequent dumping during normal harvesting operations. Low canopy skirts, particularly near the trunkline, frequently required the prime mover of the receiver unit to be driven away from the trunkline so the outside edge of the dump pan could be elevated sufficiently to be dumped (operations which tended to slow harvesting).

Prior to test 10, the receiver unit was returned to California and completely redesigned and rebuilt. The newly designed receiver unit utilized continuously running rod cross conveyors to move the fruit from the trunkline to the longitudinal conveyor (see fig. 7). Test 10 was conducted on Valencia orange trees on one-row beds. Each tree was shaken 5 to 7 s at 8 Hz with trunk circumference and clamp height averaging 51 and 23 cm, respectively. Mature fruit removal was 74% and the mature fruit to young fruit removal ratio averaged two with young fruit diameters ranging from 15 to 38 mm. The percentage of mature fruit which missed the catchframe (12%) was greater than in previous tests because the shaker/deflector unit and receiver unit could not properly position to get a good row seal where the two units overlapped in the trunkline. Shaking caused trunk bark damage on some of the trees.

AMI Fruit Pickup Machine

Fruit densities were 20 to 30 fruit/m^2 of under-tree grove floor area for the three field tests. The first test with the Rhino prime mover was conducted in Pineapple oranges after the USDA canopy shaker had shaken off the fruit (see test 4). The down-the-row pickup capacity was 15 t/h and 3% of the fruit on the ground were missed. The unloading capacity of the two elevating conveyors into the fruit trailer was 75 t/h. Counts in the trailer averaged 7% split fruit with an average fruit burst force of 321 N. It should be noted from test 4 that the USDA canopy shaker caused 3% split fruit ahead of the pickup machine. It was felt that fruit damage on the pickup machine was caused by the pickup chain and unloading elevator conveyors.

For the second and third tests (Pixall Big Jack), Valencia oranges had been dropped to the ground by hand harvesters. The down-the-row pickup capacity in both tests was 20 t/h with 3 to 4% of the fruit missed on the ground. The split fruit in the storage bin and semi-tractor trailer averaged 3.6 and 5%, respectively (with most of the fruit damage apparently being caused by the pickup chain), and the average burst force of the fruit was 360 N.

Discussion

USDA Canopy Shaker

Matching the tree canopy dimensions to the canopy shaker and catchframe will be essential for this harvest system to remove and recover a high percentage of the fruit. This means limiting the canopy size so the spokes enter the entire canopy width and height. For the 1.8-m-long spokes, the canopy width should not exceed 3.6 m and the canopy height should not exceed the length of the shaker shafts. The tree canopies should be in a hedgerow with a low percentage of the fruit near a vertical plane in the trunk line. This harvest system will probably not be practical for many conventional groves because the tree canopies are too large and spaced too far apart. Catchframes will need to be on both sides of the row to minimize fruit collection losses.

This harvesting concept demonstrated a potentially high fruit removal rate (25 t/h down-the-row) and has a potential selectivity advantage in Valencia oranges. However, as stated above, smaller than conventional canopies will probably be necessary to achieve high harvest efficiencies. It must be determined if satisfactory fruit production levels can be maintained with smaller canopies. The concept needs to be more extensively investigated to determine the optimum tree and machine properties, and fruit production levels.

Compton Shake-catch Harvester

The large scissor-type shaker head effectively removed early- and mid-season oranges in trees 3.7 to 5.2 m high and trunks 53 to 56 cm in circumference. Shaking duration was 8 to 14 s at 8 to 10 Hz and a 5-cm displacement. In the Valencia harvest test which was conducted late in the season when the diameter of the young fruit (next year's crop) averaged 26 mm, the shaking duration was limited to 5 to 7 s to minimize the removal of the young fruit. Earlier in the harvest season when young fruit is smaller and their removal is affected less by shaking, the removal of mature Valencia in 8 to 14 s would likely be similar to that for the other varieties (84 to 94%).

The new rod conveyor receiver unit appeared to avoid delays caused by the dump pan receiver. Down-the-row harvest rates of 5 to 10 t/h were demonstrated. The trunk shake-catch harvest system needs to be more extensively developed and tested to determine its typical performance in conventional orange groves.

AMI Fruit Pickup Machine

The fruit pickup head was the key to this machine which operated differently than most of the fruit pickup devices that were developed during the 1960s and 1970s (Whitney, 1995). Without ground preparation (trash removal and smoothing) prior to dropping the fruit, 3 to 4% of the fruit were missed, which is about 1 to 2% more than what was missed by the earlier machines. However, the AMI machine did not retrieve fruit from between trunks in the trunkline as the earlier machines did. The down-the-row capacity of the AMI pickup head was similar to that of the earlier dripline pickup machines. Because the pickup machine is also used to transport the fruit to a truck outside the grove, the daily capacity of the present pickup machine is much lower than the tonne per hectare (t/h) rates observed in the tests. Additional development and testing should continue to refine the pickup head, reduce fruit splits, and work out a system that can continuously pickup fruit, store it on-board, and periodically discharge a load to a standard grove truck.

CONCLUSIONS

1. Orange removal by the USDA canopy shaker was 55 to 80% in mature trees to 95% in small trees with down-the-row capacities of 25 t/h in fruit yields of 50 t/ha.
2. Orange removal by the Compton shake-catch harvester ranged from 84 to 94% off the tree with a 3 to 12% fruit collection loss by the catchframe and a down-the-row capacity of 5 to 10 t/h in fruit yields of 30 to 65 t/ha.
3. The Agricultural Machines, Inc. pickup machine had a down-the-row capacity of 15 to 20 t/h in fruit yields of 40 to 60 t/ha, with losses on the ground of 3 to 4% and 3 to 5% split fruit at the semi-tractor trailer.
4. Development and testing of the above concepts should continue and be tested in grove conditions which will maximize their harvesting efficiencies.

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