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Measuring Performance of Citrus Harvesting Systems

Fritz Roka
Southwest Florida Research and Education Center, IFAS, University of Florida, 2686 State Road 29 North, Immokalee, FL 34142

Galen Brown
Florida Department of Citrus, 700 Experiment Station Road, Lake Alfred, FL 33850-2299

Ronald Muraro
Citrus Research and Education Center, IFAS Extension, University of Florida, 700 Experiment Station Road, Lake Alfred, FL 33850-2299

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Abstract. **A research project, coordinated jointly by the University of Florida/IFAS and the Florida Department of Citrus, collected field data to evaluate the harvesting performance of the trunk-shake and catch (TSC) systems. The objective of the study was to analyze machine performance and evaluate how performance was affected by grove conditions. Performance measures include, labor productivity, fruit recovery, harvest speeds, and incidence of tree damage. Data from each study block recorded tree density, tree age, irrigation system, and overall yields. In addition, data on tree size, clear trunk height, and skirting practices were collected and correlated with estimates of per tree harvest volumes, measurements of harvesting speeds, fruit removal percentages, and overall fruit recovery percentages. Crew size and total labor hours were collected on a daily basis and tabulated by block. This paper summarizes one year of data from more than 70 citrus blocks in central and southwest Florida.**

Ever since Spanish explorers introduced citrus to the Florida landscape, the technology of removing fruit from the tree has remained unchanged. Human hands clasp and snap each piece of fruit from its tree limb. At the dawn of the 21st century, mechanical harvesting finally may be coming of age, effectively and economically recovering the crop. The purpose of this paper is twofold. First, to outline performance criteria mechanical harvesting systems have to meet to be successful in the Florida citrus industry. Second, to present initial estimates of performance measures on one harvesting system currently operating in Florida groves.

The effort to develop commercially viable, citrus mechanical-harvesting systems in Florida is driven by concerns over labor availability and global competitiveness. Using hand crews, the Florida citrus industry needs at least 20,000 people annually to harvest its crop. Seasonal farmworkers provide nearly all the harvesting labor in Florida and there is growing concern that in the near future, the available labor supply of harvesters will not be sufficient. A strong U.S. economy is luring seasonal farmworkers away from agriculture with better year-round income opportunities. Further concerns about labor availability have arisen out of the significant shift in the demographics of citrus harvesters. Over the last 20 years, the average age and years of harvesting experience among farmworkers have decreased. The percentage of single men, or men who are working in Florida while separated from their families, has significantly increased. These workers are highly mobile and have few social anchors to Florida. More than 80% of the seasonal farmworkers migrate into and out of the state. More importantly, the harvesting work force is predominately foreign-born and working in the United States without legal documentation (Gabbard, 1998; Roka and Emerson, 1999). A change in U.S. policy to effectively enforce immigration laws would produce immediate shortages within the farm labor work force.

Concerns about labor availability have plagued the Florida industry for many years. During the 1970s, a tight farm labor market initiated interest into mechanical harvesting systems. Once the tight labor market eased, interest in the mechanical harvesting program subsided. What makes the current effort into mechanical harvesting more compelling is the recognition that the Florida citrus industry needs to become more cost efficient. Brazil, Florida's most significant orange juice competitor, can produce, process, and ship to the port of Tampa one metric ton of 65 °Brix frozen concentrate orange juice FCOJ at a cost of $275 less than a Florida grower (Spreen and Muraro, 1999). Florida growers spend from $1.50 to $2.00 per box (40.8 kg) to hand harvest and delivery fruit to a bulk fruit trailer. The goal of the current mechanical harvesting program is to reduce these harvesting costs by at least 50 cents, if not $1.00 per box.

While many growers recognize that mechanical harvesting systems have the potential to achieve net cost reductions, the shift away from hand harvesting will not come easily. A hand harvest system offers three benefits to a citrus grower—flexibility, complete (100%) fruit recovery, and minimal damage to the tree. The ability of hand harvesters to harvest trees of any shape and size allows growers to make planting and grove management decisions independent of harvesting considerations. The fact that hand crews are contracted on a daily basis offer growers an additional aspect of financial flexibility. Harvesting costs accrue at the moment of harvest. If, for whatever reason (freeze damage, low market prices, etc.), a grower chooses not to harvest his/her fruit, hand crews are not hired and harvest costs are zero.

To varying degrees, mechanical harvesting will fall short in providing growers with flexibility, complete fruit recovery, and minimal tree damage. Adopting mechanical systems will limit some of a grower's horticultural flexibility, as he/she will have to modify grove architecture and tree shape to accommodate mechanical harvesting requirements. A financial commitment to a mechanical system will generate overhead expenses (i.e., depreciation, interest, etc.) that will have to be paid regardless of whether a crop is harvested.

Five conditions must be satisfied if mechanical harvesting systems are to be commercially successful as the dominant harvesting method. First, mechanical systems will have to remove and recover a sufficient percentage of the crop. A "sufficient" recovery will be such that the economic value of the remaining fruit will be insignificant. Fruit prices, harvest costs of machine systems, and the labor costs of gleaning crews will dictate the acceptable threshold of "sufficient" recovery. Second, labor productivity must be improved to a point where a smaller available labor force can complete the harvest. Third, mechanical systems must reduce unit-harvesting costs to maintain a global competitive edge. Fourth, mechanical systems must not adversely affect a tree's expected productive life. Some tree damage from mechanical harvesting could be tolerated if yield and productive life were not diminished. Lower yields or fewer productive years would increase overall production costs. Fifth, harvesters and grove owners who purchase mechanical harvesting equipment must earn a profit on their machinery investment.

Based on the insight that one man's cost is another man's income, it might appear that the fifth condition poses a paradox. The harvester's income is what he/she charges the grower to harvest her/his crop. How can a harvester with mechanical equipment earn a profit when the very definition of a mechanical system's success is to lower unit-harvesting costs? The paradox is solved by labor productivity. The gains in labor productivity must be great enough, not only to offset the investment into the equipment, but also to compensate growers for less than 100% fruit recovery and any increases in grove production costs which may result from mechanical harvesting activities.

Materials and Methods

During the 1999–2000 season, data were collected from citrus blocks being mechanically harvested to evaluate productivity and other performance measures of the mechanical systems. In addition to labor productivity, other performance measures included machine productivity, harvest speed, and fruit removal and recovery percentages. Machine productivity and harvest speeds are important to assess equipment capacities, overall equipment demand, and how capital costs will be spread over production units. Mechanical systems will change the speed at which citrus harvesting occurs, and most likely affect harvest schedules between a grower and a processing plant. Fruit recovery results are important in calculating overall unit costs of harvesting and determining the value of gleaning crews.

Florida citrus is produced under a highly diverse set of grove conditions. Differences in soils, tree densities, variety/rootstock combinations, hedging, and general management strategies, define very specific grove and tree conditions. How a mechanical harvesting system performs in one block may be significantly different from its performance in a second block with different production conditions. During the course of this study, data were collected on grove and harvester characteristics to develop some insights into how grove characteristics could affect harvesting performance.

Performance measures were developed through a cross-sectional analysis of blocks harvested by trunk-shake and catch (TSC) systems. Data records were assembled from three sources of information—grower records, harvester records, and IFAS field measurements. Grower records provided descriptive information about the block, including scion cultivar and rootstock combination, tree age, planting density, irrigation system, net tree ha, and an estimate of total bearing tree spaces within the block. Growers provided a 5-year yield history of the block, whether the block had been previously mechanically harvested, and the daily weight tickets of harvested fruit during the 1999–2000 season.

Harvesting companies provided information about the labor and machine use. Important data included daily crew size and hours worked per day. Ideally, a daily log of machine hours with notes of machine downtime periods would provide the necessary information to estimate total machine hours per harvested block. Unfortunately, keeping a daily log of machine hours proved difficult for some harvesting cooperators. As an alternative to machine logs, payroll time sheets, which separated equipment operators from ground personnel, were used to estimate machine hours.

IFAS personnel collected data on tree measurements, percentage of harvested tree spaces, harvesting speeds, and volume of available fruit not harvested by the mechanical systems. Tree measurements included trunk circumference, clear trunk, skirt height (prior to harvest), and overall tree height. Equipment times were recorded for various harvesting operations including shaking time, movement between trees, and transfer of fruit from storage bins to field goats. From a sample of trees, the weight and number of fruit pieces not recovered by the TSC system, both in the tree and on the ground, were recorded.

Of the 56 blocks from which data were collected, 39 blocks were early/mid cultivars and 17 blocks were late season, 'Valencia'. Table 1 provides some descriptive statistics about tree density, age, and yield of the blocks harvested by TSC systems. Tree density and age were fairly similar between early/mid and late season cultivars. Trees in TSC blocks averaged 400 trees per ha and were 10 years old. As expected,

Table 1. Average tree density, age, and yield for the 1999-2000 TSC data blocks by cultivar and machine type. Standard deviation (SD) and sample size (no.) given in parentheses.

		Units	Early/mids	Valencia
Tree density				
	Average	tree/ha	400	419
	(SD, number)		(18, 39)	(3, 15)
Tree age				
	Average	yr	11	10
	(SD, number)		(4, 39)	(3, 15)
Acre Yield				
	Average	bx/ha	1,162	818
	(SD, number)		(121, 38)	(86, 12)
Tree Yield				
	Average	bx/tree	3.0	2.1
	(SD, number)		(0.9, 38)	(0.6, 12)

Table 2. Summary of performance measures of TSC system during 1999-2000 on early/mid blocks. Average performance value calculated for all blocks, range of 95% of blocks, and number of blocks from which data were used.

		Units	Early/mid
Fruit removal			
	Average	%	95%
	95% interval		93-97%
	Number of blocks		27
Fruit recovery			
	Average	%	91%
	95% interval		89-93%
	Number of blocks		27
Labor productivity			
	Average	box/h	24
	95% interval		21-27
	Number of blocks		30
Machine productivity			
	Average	box/h	192
	95% interval		175-209
	Number of blocks		16
Harvest (machine) Speed [z]		s/tree	53
	Average	tree/h	68
	95% interval		62-74
	Number of blocks		16

[z]Speed represents time harvesting one tree plus moving to second tree.

early/mid blocks generally yielded both more boxes per tree and mor boxes per ha than 'Valencia' blocks.

A TSC system is two operations that work in parallel. On one sid of a tree, a trunk shaker operates to remove fruit. At the same time an on the opposite side of the tree, a receiving unit catches the falling fru and conveys it back to a trailing bin. Fruit from the bin is off-loaded t a field truck (goat), which in turn delivers the fruit to a bulk fruit traile Table 2 summarizes fruit removal and recovery percentages, labc productivity, machine productivity, and harvest speed for all block harvested by TSC systems. Separate performance measures wer estimated for early/mid- and late-season blocks.

Results

Fruit removal measures indicate the percentage of available fru removed from the tree during the shaking action. Fruit recover represents the total percentage of available fruit in the tree that removed, caught, and delivered to the road trailer. For TSC systems, th fruit recovery percentage must be less than fruit removal percentag

Table 3. Fruit removal percentages from TSC harvested early/mid blocks, tree characteristics, and details of blocks with removal percentages outside the majority range.

Block ID	Majority of blocks		46	58	45	34	24
Avg Removal	96%	%	83%	88%	90%	91%	99%
Range	93-98%	%					
Number of blocks	22	#					
Yield-tree	2.99	bx/tree[z]	4.58	2.55	3.19	2.68	3.22
Tree age	11	yr	14	12	13	10	7
Tree density	400	trees/ha	363	363	363	435	450
Clear trunk	38	cm	33	39	34	40	46
Trunk circum	47	cm	49	55	45	37	80
Skirt height	86	cm	89	97	86	81	92
Tree height	4.8	m	5.2	5.6	5.6	4.4	4.8
Harvest dates		mo/day	11/23-1/17	1/21-2/3	1/25-2/17	1/18-2/4	1/8-2/1
Trees sampled		#	18	15	24	12	12
Harvester		code	1	1	5	6	4

[z] A box weighs 40.8 kg.

because some pieces of fruit will simply miss the catch frame or drop through the tree seal of the receiving unit. Sufficient clear trunk space and skirting are necessary for a TSC system to operate.

During the early/mid harvesting period, 95% of the blocks harvested by a TSC system achieved fruit removal percentages between 93% and 97%. Average fruit removal was 95%. During the late-season period, fruit removal percentages ranged between 93% and 95% with an overall average of 94%. On average, 91% of available fruit in early/mid blocks were recovered and delivered to the bulk trailer. For most of the early/mid blocks, fruit recovery ranged between 89% and 93%. The difference between 100% and the TSC recovery percentage was the crop percentage available to gleaning crews.

Harvest labor productivity was measured for each block by dividing the total net weight boxes harvested by the total number of harvesting hours. Work by Polopolus et al. (1997) established that in blocks yielding between 1000 and 1250 boxes per ha average harvest productivity of hand crews is ten, 40.8-kg boxes per hour. This average rate only includes the hours of pickers during harvesting. They do not include the paid hours of goat drivers, crew leaders, and other supervisory personnel.

Labor productivity rates for TSC systems averaged 24 boxes per hour during early/mid season. For 95% of the blocks, labor productivity ranged between 21 and 27 boxes per hour, at least a 2-fold increase in productivity over hand crews. These estimates were based on data from 30 blocks and included all personnel hired to glean and collect fruit not recovered during the mechanical operation. If labor productivity was based only the core TSC system, which includes two equipment operators and two ground workers immediately behind the harvesters, between 40 and 45 boxes were harvested per labor hour.

Machine productivity. Machine productivity measures the harvesting capacity of the harvesting equipment. Ideally, this estimate would be based on daily records of machine hours. Unfortunately, most harvesters did not record machine hours on a daily basis. In some cases, payroll records of equipment operators and field notes of equipment breakdowns were used to estimate machine hours. In other cases, even payroll information was not available to estimate machine hours.

Only 16 of the previous 30 early/mid-season blocks had sufficient data to estimate machine productivity. On the early/mid-season blocks, machine productivity averaged 192 boxes per hour with a range between 175 and 209 boxes per hour. Machine productivity estimates were based on recovering only 91% of the available fruit.

Harvest speed. Harvest speed was closely linked to machine productivity. Harvest speed was estimated by dividing total number of harvested trees by the number of machine hours. The reciprocal, or inverse, of this number indicates the number of seconds spent harvesting each tree. Estimates of harvest speed include shake time and time spent moving equipment between trees and to different rows. During the early/mid-season, on average, 53 s per tree were required to complete the shaking of one tree and reposition to another tree. This harvest speed translated to harvesting 68 trees per hour.

Effect of grove and tree characteristics on TSC performance. Averages and ranges of performance measures provide some indication of how mechanical harvesting systems are evolving. However, growers need more specific information on how these systems will perform in their groves. Insights as to how grove and harvester attributes affect system performance may be gleaned by comparing grove and harvester characteristics of blocks with extreme performance values against the same grove attributes found within the "majority" blocks. Tables 3–6 present revised estimates of average performance measures on early/mid blocks by identifying and separating blocks with extreme performance values. Blocks with extreme values for each performance measure were segregated from the remaining "majority" blocks and performance averages were recalculated for only the majority blocks. Average tree yield, tree density, and tree configuration are presented for the majority blocks. Performance estimates and grove characteristics for each "extreme" block are listed in adjacent columns. In addition, harvest date and a harvester identification code are listed for the extreme blocks.

Fruit removal percentage averaged 96% for 22 blocks that fell within a range from 93% to 98% (Table 3). Four blocks had lower removal percentages and one block achieved 99% removal. Among the blocks that experienced low fruit removal percentage, harvest dates tended to be early. Block ID numbers 46 and 34 were the first blocks harvested by Harvester #1 and 6, respectively. Harvester #1, in particular, experienced several personnel disruptions and equipment breakdowns early in the season. The block that experienced the highest fruit removal percentage (Block ID# 24, 99%) had higher clear trunk and skirt heights than the averages for the trees in the majority blocks.

For the majority blocks, labor productivity on early/mid blocks increased to 27 boxes per labor hour (Table 4). For five of the six blocks that were below the majority range, the most important similarity among these blocks was Harvester #6. Harvester #6, responsible for Block IDs 77, 35, 34, 33, and 78, employed the largest number of gleaners of any TSC system in 1999–2000. Up to 10 people followed Harvester #6, collecting unharvested ground and tree fruit.

Machine productivity on 12 early/mid blocks averaged 193 boxes per hour (Table 5). Four blocks (Block IDs 33, 24, 53, and 35) achieved between 15% and 43% higher productivity. Other than for tree density, which was generally higher on the "extreme" blocks (435 and 450 vs. 400 trees per ha), the data of tree/grove characteristics presented in Table 5 do not present any strong evidence to explain the differences in machine productivity on the latter four blocks. In all likelihood, machine hour data on the blocks with extreme values were not accurate.

On twelve early/mid-season blocks, harvest speeds averaged 66 trees per hour, or 55 s per tree (Table 6). One block (ID# 49) harvested at a slower speed, 44 trees per hour (81 s/tree). Three blocks (ID#s 45, 33, and 35) harvested at faster speeds. Two general trends are identified from the exceptions. First, harvesting speeds increased during the

Table 4. Labor productivity rates from TSC harvested early/mid blocks, tree characteristics, and details of blocks with labor productivity outside the majority range.

Block ID	Majority of blocks		77	35	34	33	78	52	44
Avg Labor Productivity	27	bx/h	8	10	10	12	12	15	44
Range	19-36	bx/h							
Number of blocks	23	#							
Yield- tree	3.17	bx/tree	2.20	2.55	2.68	2.36	2.54	2.04	1.62
Yield-ha	1202	bx/ha	950	1088	1163	1020	1098	573	695
Tree age	11	yr	10	10	10	10	10	14	13
Tree density	400	trees/ha	435	435	435	435	435	378	378
Clear trunk	38	cm	Na	34	40	35	Na	40	32
Trunk circum	47	cm	Na	39	37	32	Na	49	55
Skirt height	86	cm	Na	81	81	74	Na	74	91
Tree height	4.8	m	Na	4.4	4.4	3.7	Na	5.9	5.2
Harvest dates		mo/day	12/1-12/20	2/5-2/14	1/18-2/4	1/6-1/18	12/20-1/5	2/9-2/13	12/15-1/6
Trees sampled		#	0	11	12	12	0	6	18
Harvester		code	6	6	6	6	6	5	4

Table 5. Machine productivity (bx/h) from TSC harvested early/mid blocks, tree characteristics, and details of blocks with machine productivity outside the majority range.

Block ID	Majority of blocks		33	24	53	35
Avg Production	193	bx/h	222	229	250	276
Range	152-220	bx/h				
Number of blocks	12	#				
Yield- tree	2.95	bx/tree	2.36	3.22	4.81	2.55
Yield- hectare	1115	bx/ha	1020	1445	1723	1088
Tree age	10	yr	10	7	11	10
Tree density	398	trees/ha	435	450	378	435
Clear trunk	39	cm	34	45	42	34
Trunk circum	46	cm	32	43	52	39
Skirt height	91	cm	91	92	92	81
Tree height	4.9	m	4.9	4.6	4.8	4.4
Harvest dates		mo/day	1/6-1/18	1/18-2/1	1/22-2/4	2/5-2/14
Trees sampled		#	12	12	12	11
Harvester		code	6	4	5	6

Table 6. Harvesting speeds (trees/h) from TSC harvested early/mid blocks, tree characteristics, and details of blocks with harvesting speeds outside the majority range.

Block ID	Majority of blocks		49	45	33	35
Avg Speed	66	trees/h	44	85	94	108
Range	52-79	trees/h				
Number of blocks	12	#				
Yield-tree	3.04	Bx/tree	4.03	3.19	2.36	2.55
Yield-ha	1180	bx/ha	1473	1122	1020	1088
Tree age	9.5	yr	13	13	10	10
Tree density	405	trees/ha	378	363	435	435
Clear trunk	38	cm	33	34	35	34
Trunk circum.	45	cm	50	45	32	39
Skirt height	91	cm	91	86	74	81
Tree height	4.7	m	5.2	5.6	3.7	4.4
Harvest dates		mo/day	12/29-2/17	1/25-2/17	1/6-1/18	2/5-2/14
Trees sampled		#	24	24	12	11
Harvester		code	5	5	6	6

season, which can be explained by improvements of equipment operators and overall coordination within a given harvesting team. Second, harvesting speed was inversely correlated with tree yield. The higher the tree yields, the slower the harvest speed.

Performance values of individual blocks were plotted against specific grove or tree characteristics sorted from lowest to highest observation. For example, fruit removal percentages were plotted against clear trunk heights that ranged from 28.7 to 45.5 cm. If clear trunk height had an affect on fruit removal, then a "trendline" would be observed through the data. An upward slope would suggest that higher clear trunk heights increase fruit removal percentages. It is important to realize that trendline conclusions are limited to the range of data collected.

The plots did not indicate clear trendlines, reflecting no observable influence by the selected grove variables (listed in Tables 3–6) on a given performance value. Three reasons suggest why few clear insights were found. First, there may be no effect to be observed. For instance, why should tree density affect fruit removal of a TSC system? Second, the range of observed data may not be great enough to detect trends. Third, several factors may be combining in ways that make it difficult to isolate the effect of a single grove or tree attribute on harvesting performance.

Conclusions

If a significant amount of Florida's citrus production area converts to mechanical harvesting systems, it will be because the mechanical systems have achieved a sizable reduction in unit-harvesting costs. A portion of these cost savings have to accrue to grove owners in order to compensate them for the loss of grove management flexibility and incomplete fruit harvest which hand harvest crews currently offer. If harvesters are to earn a sufficient profit with mechanical harvesting systems, the systems will have to attain sufficient gains in labor productivity to afford the capital outlays while at the same time lowering harvesting costs to the grower.

Data collecting during the 1999–2000 season provided an initial reference point with respect to performance measures of a TSC system. Currently, TSC systems are the most widely used mechanical system. With grove and tree characteristics defined by values in Table 4, labor productivity with gleaning increased to 27 boxes per labor hour, a 170% increase in productivity over an average hand crew. Labor productivity increased to more than 40 boxes per hour if separate gleaning crews are not used to harvest fruit not collected by the TSC system. More than 95% of the available fruit was removed from the tree. On average, a TSC system delivered 91% of the crop to the bulk fruit trailer.

Observed tree and grove characteristics did not provide clear insights as to how tree and grove conditions affect harvesting performance. The FDOC Harvesting Research Advisory Council has funded the study for a second year. Data collection efforts will continue on blocks harvested by TSC systems with the goal of refining how grove and tree characteristics affect harvesting performance.

Acknowledgments

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