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Evaluation of Impacts of Mechanically Harvesting High Density Semi-dwarf Citrus on Tree Health and Yield

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In the 1990s, Florida had 845,000 acres of citrus and was competitive with Brazil. That number has since reduced to approximately 531,500 acres due to hurricanes, canker eradication program, urban development, economic downturn, and finally the discovery and spread of Huanglongbing (HLB), which causes tree decline and death. Many of the factors affecting the Florida citrus industry also concern other citrus producing states—such as Texas, Arizona, and California. The national threat of HLB has set the stage for developing new approaches and technologies for citrus production and harvesting that secure a future means to thrive in the midst of various invasive diseases and pests. One approach being considered is Advanced Citrus Production and Harvesting Systems (ACPHS), which uses high density semi-dwarfed trees, and intensive fertigation with optimized nutrient and water availability that accelerates plant growth. Adopting ACPHS for citrus production could increase yield production per acre, while simultaneously shortening the time to return on investment, meaning that grove life can be shortened by disease pressure and still remain economically viable. However, this new grove architecture presents new engineering problems for managing production and harvest of citrus groves. Since ACPHS has smaller trees planted at high density with limited operational area, existing machines are not suitable. One reoccurring challenge to the adoption of mechanical harvesting technology is grower concerns about the impact of mechanical harvesting on tree health, next year's crop, and fruit damage. This concern has been amplified due to the presence of HLB, which weakens the tree and could have potential negative interaction with tree longevity when trees are vigorously shaken by the harvesting machine. In this paper, the authors introduce a new Over the ToP Citrus Harvester (OTPCH), which has been specifically designed for high density semi-dwarf trees, and a multi-year experimental trial that is being conducted to evaluate the impact of harvesting on tree health. The first results of a two-year study are presented. Tree health indicators are measured in the field before and after harvest.

The Florida citrus industry is currently facing an unprecedented combination of issues that threaten its existence. Among those factors are pests and diseases (e.g., canker and Huanglongbing), urban development, and global market competition. The combination of higher production costs and the reliance on manual labor to harvest fruit present significant challenges for Florida citrus. In the last decade, over 81,000 ha (200,000 acres) of citrus have been lost in Florida primarily because of the citrus canker eradication program and citrus greening (HLB). Citrus canker is a disease that causes defoliation, blemished fruit, premature fruit drop, twig dieback, and tree decline (Schubert et al., 2001). Citrus greening can lead to tree decline and tree death within five years after infection. Control of citrus greening is complicated by the fact that it is vectored by the Asian citrus psyllid. Long term management rests on finding resistant varieties and developing advanced management strategies that can control psyllid populations.

One promising approach is the Advanced Citrus Production and Harvesting Systems (ACPHS) concept based on higher planting density with size-controlling rootstocks and intensive fertigation to more intensively manage water and nutrient applications. This approach to citrus production has been pioneered in South Africa for over half a decade and has been field tested in Florida since 2006. The goal of ACPHS is to increase yield per acre, while simultaneously shortening the time to return on investment (Morgan et al., 2008; Kadyampakeni et al., 2014a). However, these new grove concepts will require new equipment systems to manage production and harvesting as well providing systems to better control pests and diseases. Recently emerging autonomous operations and equipment may be well suited to ACPHS, which, in tree crops, necessarily involve closely spaced smallish plants. Such trees have known efficiencies in their cultural and harvesting management and constitute ideal orchard systems for easy autonomous scouting, pruning, mowing, spraying, and harvesting. In 2011, a cooperative effort was begun between the University of Florida and a startup company named GeoSpider, Inc., to develop an over the top harvesting and production equipment system for high density citrus. In Summer 2013, their first prototype tests were conducted. Early harvesting results showed promise, but were substantially below expected harvesting removal efficiencies. In 2014, new harvesting trials began to demonstrate the potential of this new machine achieving harvesting efficiencies in the 93% or better range. In this

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*Corresponding author. Phone: 352-392-1864; e-mail: tburks@ufl.edu report we will update the progress of this effort by discussing the following experimental outcomes:

1. Design and implement an effective set of field trials to evaluate mechanical harvesting impacts on tree health using instrumentation approaches described for a field plot located near Felda, FL, which take into account machine operating parameters, and HLB symptomatic versus asymptomatic trees.
2. Design and implement a field trial at the University of Florida, Southwest Florida Research and Education Center (SWFREC) near Immokalee, which seeks to evaluate the optimization of harvester parameters over the 'Valencia' harvesting period. Trial will seek to confirm if harvesting performance is effected by natural abscission variation during critical period of 'Valencia' harvest from early April to mid-May.

A Historical Perspective of Florida Citrus Groves, Their Management and Mechanization

In the past, the majority of Florida's sweet orange acreage had been planted at densities between 120–170 trees/acre (45–70 trees/hectare) and with tree height over 20 ft (6 m) (Whitney & Harrel, 1989). Typically the maximum tree height was limited to ~20 ft (6 m) by regularly scheduled tree hedging and topping practices. The average between-row spacing in oranges had been relatively constant at 25 ft (8–9 m) prior to early 1980s when it dropped below 8 m. Experimental studies of average in-row spacing as low as 12–15 ft (4.5 m) have been conducted since 1986 with promising results as described below.

The Florida citrus industry has slowly transitioned to a modern era of somewhat more closely spaced trees, but not to truly higher planting densities. However, higher-density cropping systems have been under evaluation for some time in Florida and elsewhere (Wheaton et al., 1991, 1995a, 1995b; Williamson et al., 1997; Tucker & Wheaton, 1978; Peterson, 1984). Those studies indicated that a higher density orchard of genetically dwarfed trees can begin bearing earlier and produce more fruit per unit area than traditional orchards. Whitney et al. (1994, 1996) showed that after nine fruit producing seasons, higher density orchard citrus trees had superior cumulative fruit and soluble solid yields (6.0 m x 2.5 m spacing and 5.5 m height). Trees on a moderately vigorous rootstock developed smaller canopies with greater quantities of fruit per unit canopy volume. The smaller canopies allowed for a higher percentage of fruit to be harvested. The manual harvesting rate in shorter, high-yielding trees was greater than taller, low-yielding trees. They provided fruiting conditions that favored the use of picking aids or platforms and the use of shakers and robots.

In the past 50 years, there has been commercial and research interest in use and improvement of mechanical harvesting to offset the costs associated with hand-harvesting (Ebel et al., 2012). Although mechanical harvesting of citrus was introduced to Florida in the mid-1950s (Futch et al., 2009), it has not been widely accepted in commercial orchards due to: 1) loss of leaves and twigs and scuffing of the bark on trunk and branches; 2) limb breakage and removal of flowers and young green fruit; and 3) exposure of shallow roots at the soil surface (Li et al., 2005). The primary concern of most Florida citrus growers was the effect of mechanical harvesting on long-term citrus tree health and productivity. However, long-term studies have demonstrated little effect on fruit yield by mechanical harvesting methods compared with hand harvesting (Hedden et al., 1988). Past studies have been conducted on healthy, well maintained trees and indicated that citrus trees can sustain up to 25% defoliation without reducing canopy growth, fruit yield, and fruit quality (Yuan et al., 2005), in part because citrus can compensate for leaf loss by increasing photosynthesis of remaining leaves (Syvertsen, 1994).

Morgan et al. (2014) measured the effects of short-term drought on water use and stem water potential of trees not affected by HLB with three different subgroups of foliage density (from high density to low density) and found that stem water potential and water use was not affected by harvesting method. Mechanically harvesting resulted in loss of leaf mass for all three density categories in both years of the study. Mixed results were found for yield. The yield of mechanically harvested trees with low and moderate density trees increased the first year compared with the previous year's yield but decreased the second year.

Machinery for ACPHS mass harvesting. Although mass harvesting systems such as the shake and catch system developed by OXBO (OXBO International Corporation, Byron, NY) are available for traditional low-density citrus groves with fruit destined for the processed market, these systems are not easily adapted to higher density groves which have limited "free" space between rows.

In Fall 2003, Geo-Spider, Inc. (Gainesville, FL), filed a patent on an approach to citrus production in ACPHS groves, with the objective to develop an Over the Top Citrus Production and Harvesting system called the GroveMaster™ , which is specifically designed for higher density groves. The GroveMaster™ conceptualizes a multi-purpose equipment system which will operate in higher-density size-controlled groves much in the same way that a tractor and implements operate in traditional field agriculture. The prime mover will be an Over the Top Platform (OTP) which is sized for the ACPHS citrus grove. It will have the capability to be adapted with minimal change-over effort from one production task to another. Unlike current mass harvesting equipment systems, the GroveMaster™ will not only be utilized during harvesting but throughout the crop season. Conceptually, the GroveMaster™ OTP is very similar to other OTP systems being employed in grape, olive, and blueberry harvesting. Companies such as MacTeq (Santa Fe, Argentina), OXBO Corp., and BEI (BEI International, South Haven, MI) currently manufacture this type of system. Consequently many of the system concepts are already in the market place. For instance, OXBO manufactures a system for grape harvesting that is very similar to the GroveMaster™ multi-function concept with the major difference being in the harvesting approach and plant size. As a result, there is a fairly significant body of knowledge in the market place on building OTP platforms. There are companies like OXBO and MacTeq that have built canopy shaking machines that are appropriate for traditional citrus, but have not applied the technology to a higher density grove which introduces complexity due to the compactness of the platform footprint. These bulky harvesting systems require wider between row spacing for their shaking mechanisms, and more end of row space for efficient maneuverability. Thus, the limited row space in higher density groves prohibits the use of current citrus mass harvesting systems for processed fruit. In addition, the mass harvesting approaches are not appropriate for fresh market due to fruit damage.

Development of over-the-top systems. A framework was designed and built to form the OTP chassis and two small diesel

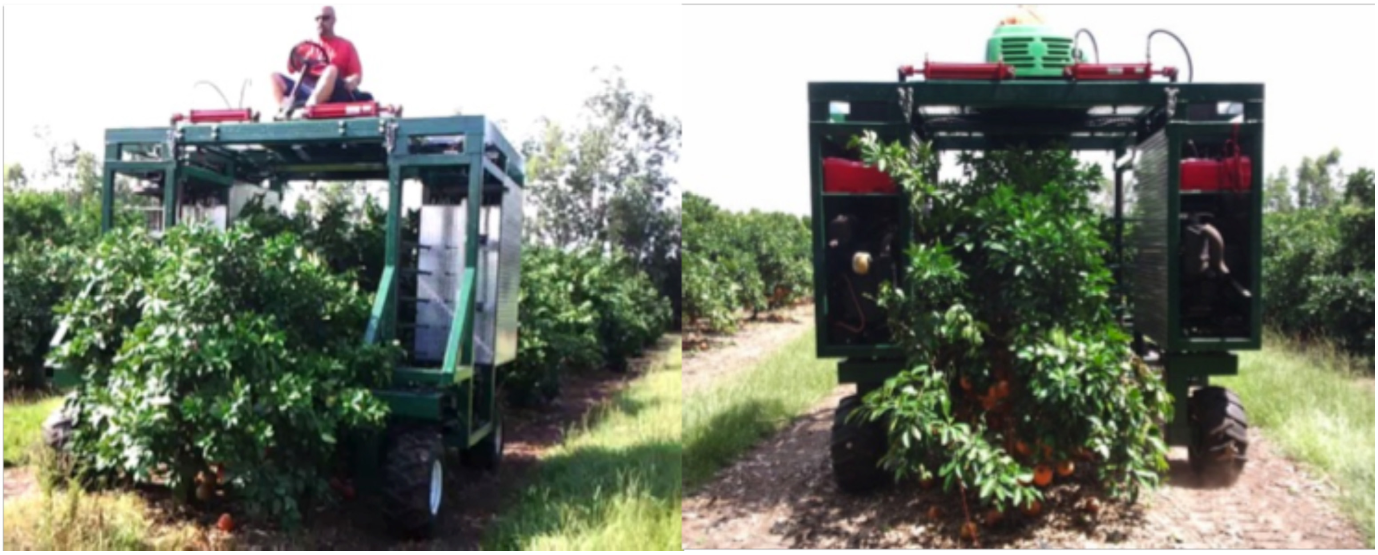

Fig. 1. The citrus canopy shaking machine during the Spring 2013 preliminary trial.

engines with hydraulic pumps were adapted to the OTP platform to provide power as shown in Fig. 1. Two separate hydraulic systems were developed on the platform: 1) 34 HP system to propel the vehicle and eventually power the material handling; and 2) 24 HP system to power the shakers and material handling. Although additional costs and complexity were created by having two engine/hydraulic systems, the prototype cost savings realized using salvage components offset these costs. However, our development time and costs increased as a result.

Development of canopy shaking systems. Prior research and development by GeoSpider, Inc., and the University of Florida had developed concepts for the shaker system, while a catch frame prototype had been developed and tested. We began our efforts with the physical Over the Top Platform Harvester (OTPH) design and later incorporated and enhanced those concepts through the use of SolidWorks™ . The basic functionality required in the shaking system is tree size adjustable shakers, which will allow for harvesting trees ranging from 5 ft to 9 ft tall (1.5–3 m). This flexibility enables harvesting trees as young as three to four years till maturity. In addition, a catch frame that uses a flexible closure design should be provided to eliminate damage to young trees. The conveyor systems will move the fruit toward the rear of the OTP, where the elevators will lift the fruit above the tree line for conveyance to trailing transport vehicles. Optional on-board storage can be added to allow for occasional delays in transport vehicles.

It was determined through past research efforts that the most effective harvesting approach would be canopy shaking. There is a large body of knowledge in citrus detachment forces, trunk and canopy shaking that were drawn upon to reduce development time. It was critical to develop a system that can operate at appropriate rotational and vibrational frequencies, with an appropriate rod penetration into the tree canopy and without excessive tree damage. Fortunately, in the ACPHS system the trees will be shorter and narrower than traditional trees, which will naturally reduce the shaker dimensions, particularly the finger size and length. The denser canopy of ACPHS systems will also be a factor in the design of the shaker. The shaker prototype was designed to enable us to test different shaking principles, such as, operating at different shaking strokes with variable shaking frequencies, and the appropriate combinations of stroke and finger dimension. Additionally, the shaker assembly was designed so that fingers can be easily interchanged, since it is likely that finger design modifications will be necessary. Ultimately, citrus fruit detachment will depend on the shaking parameters (frequency, canopy penetration, and finger design), vehicle speed, abscission status (natural vs. applied), and fruit load density of tree canopy.

Previous harvesting field trials. Trials were conducted in 2013 and 2014 at the University of Florida's model ACPHS grove, planted in 2007 in Citra, FL, at the Plant Science Research and Extension Unit (PSREU). The PSREU trial consisted of ruby red grapefruit, *Citrus* x*paradisi* scion with 'Flying Dragon' trifoliate orange rootstock combinations, selected to allow planting at densities higher than normal. All trees were spaced 20 ft apart between rows with spacing in row spacing of 8 ft, as shown in Fig. 2, A and B.

Preliminary trials were conducted to determine the proper machine operating parameters, in May and June 2013 (The ambient air temperatures were in the range of ~ 90 °F). Although this was later than normal harvest, it allowed us to tune the machine parameters. A final set of field experiments were conducted on the same 'Ruby Red' block, to determine the harvesting machine performance under normal field conditions on 6 Jan. 2014 (ambient air temperature was 51 °F). Before harvesting, the trees were skirted to simulate normal harvest conditions for a catch frame on the harvester. Skirting and pruning of the grapefruit tree's canopies were completed on 18 Nov. 2013, to establish the canopy height and width at the approximate internal dimensions of the harvesting machine (Fig. 1). A series of experiments were conducted to evaluate the interactions between the primary machine operation parameters; finger design and length, shaker frequency, rod penetration into canopy, shaker tunnel width, and ground speed. The data from these harvesting trials were used to optimize the machine operating parameters for the best harvesting efficiency. These results are shown in Table 1 during Winter 2014 harvest trials.

The critically important decision about which operating parameters to select was accomplished using interference analysis

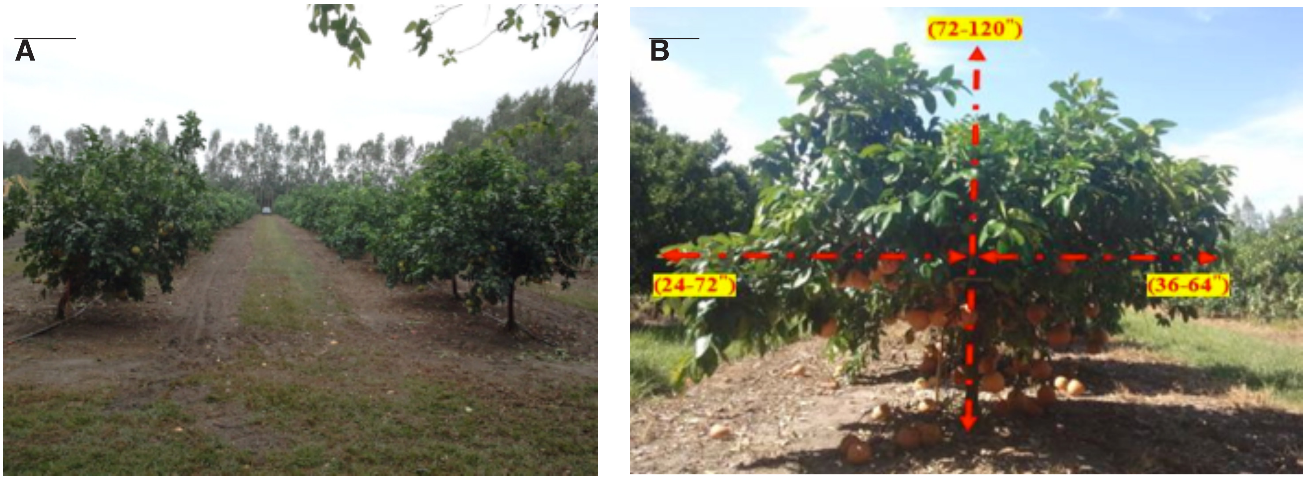

Fig. 2. Grove conditions (**A**) and pruned/skirted (**B**) 'Ruby Red' grapefruit *Citrus* x*paradisi* trees

Table 1. Average grapefruit *Citrus* x*paradisi* fruit detachment percentage for 2014 harvest trial.

	Harvester forward speed (mph)				
	0.62		1.42		
	Canopy Shakers Speed (inch/s)		Canopy Shakers Speed (inch/s)		
Turnbuckle length (inch)	56.50	73	56.50	73	Average
12	69.30 bcd	64.46 cd	60.24 ce	55.26 c	62.32
14	78.32 abde	89.94 a	67.14 bcd	81.58 ad	79.25
16	84.62 ab	93.56 a	80.17 abde	93.52 a	87.97
Average	77.41	82.65	69.18	76.79	–
Shakers speed	73.30	–	79.72	–	
Harvester speed	80.03	–	72.98	–	

Average values, which have been followed by the same letter in each row and column, do not have significant differences among them statistically at a 0.90 confidence level.

on of the following operating variables (two machine forward speeds, two beaters' shaking speeds, and three shaking beaters positions) for the percentage of harvested grapefruit. Table 1 shows the effect of the interference between the three operating variables (machine forward speed, beaters' shaking speed, and the harvester' beaters position) on the average fruit harvest percentage. The results of that interference reveal that the highest percentage of the harvested fruit is 93.56% as a result of interference between the second beaters' shaking speed of 73 inches per second (inch/s), the first machine forward speed of 0.62 miles per hour (mph), and the 16-inch turnbuckle length position (that controls canopy penetration). This high percentage of harvested fruit may have been a result of the lowest forward speed (0.62 mph) providing sufficient shaking time to shake the whole tree canopy synchronously with the appropriate shaker speed of 73 inch/s. The second highest percentage was 93.52% as a result of the interference between the second beaters' shaking speed of 73 inch/s, second machine forward speed of 1.42 mph, and the 16-inch turnbuckle length. This second fruit removal efficiency is similar to the first and may have resulted from the intersection of the highest shaking speed and the larger beater penetration into the canopy, which provided a deep enough beater penetration into the grapefruit tree canopy at the 73-inch/s shaker speed, to shake the whole tree canopy synchronously, regardless of the shaking time. Furthermore, data shows that the lowest percentage of dislodged grapefruit was 55.26%, which came as a result of interference between the second shaking speed of 73 inch/s, the second machine forward speed of 1.42 mph, and the 12-inch turnbuckle beater position.

Statistically, there were significant differences for the interference effects between the forward speed (0.62 mph), beaters' shaking speed (73 inch/s), and the 16-inch turnbuckle length (third beaters' position) from one side, and the interferences between the other harvester operation variables, which provided harvested grapefruit percentages of 69.3%, 67.1%, 64.5%, 60.2%, and 55.3%, respectively, from the other side on the harvested fruit percentage (at 10% level of significance). For more information on these studies please refer to Al-Dosary (2014).

In a subsequent trial, the length of the beater fingers was increased to observe a potential harvesting efficiency affect. By operating the harvesting machine with either the slow forward speed of 0.62 mph or the fast speed of 1.87 mph, the 63.7 inch/s shaker speed, beater penetration at the 16-inch turnbuckle length, and the extra long beaters resulted in an equivalent harvesting percentage as was realized by running the machine at a forward speed of either 0.62 mph or 1.62 mph, 73 inch/s shakers speed, 16 inch-turnbuckle length, and the short beaters (93.56% and 93.52%, respectively). Applying statistical analysis to the field

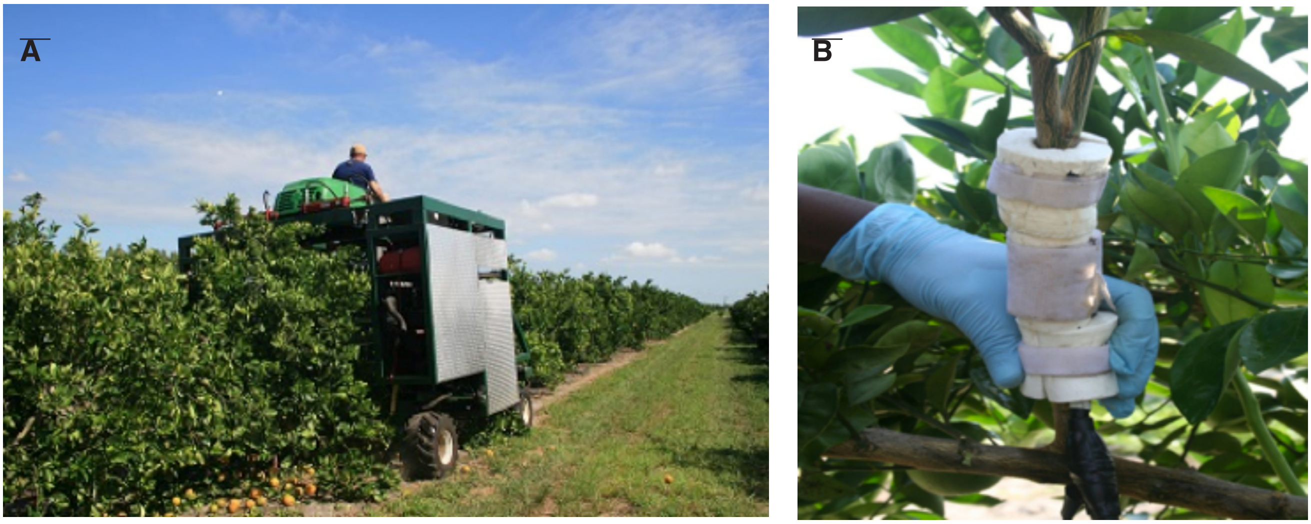

Fig. 3.Grove conditions and harvester (**A**), during field trial on 'Valencia' sweet orange (*Citrus sinensis*), located near Felda, FL, and (**B**) installed sap flow sensors on selected trees in trial block.

data at 10% level, there is no significant difference for the influence of harvesting machine forward speeds and the length of the new, longer beaters on the average harvest percentage. However, it should be noted, that the long beaters minimize the differences in harvesting efficiency caused by beater frequency and minimize the loss in efficiency due to increased travel speed, thus making it possible to harvest at a faster rate and still maintain high harvest efficiencies. It is possible to obtain an even higher harvesting percentage of more than 93.29% by eliminating replicated treatment outliers. Under both harvesting ground speeds, harvesting efficiency was influenced by oversized trees. In the case of replicate 3 at the slowest ground speed, the harvest efficiency was 73% for that tree, while the other four were above 97%. Similar conditions occurred at the fast ground speed for replicate 2. In both cases, this can be attributed to fact that the tree canopy size (width and height of canopy) was greater than dimensions of the internal harvesting tunnel of the shaking machine (69 x 104 inches). Almost all of the grapefruit remaining unharvested were found at the central top of the canopy or underneath the canopy skirt line. Since this prototype did not have a catch frame we went ahead and harvested trees with a lower skirt line then desired. However, in practice this would not be allowed.

Harvesting trials in Spring 2015. In Spring 2015, additional harvesting trials were conducted on 'Valencia' orange (*Citrus sinensis*) trees located on the Hickory Branch Grove (managed by CPI), near Felda, FL. This grove had not been previously hedged or skirted for mechanical harvesting. The trees set aside for the trial consisted on a small block of 'Valencia' on Carrizo rootstock, consisting of six rows of approximately 26 trees per row. Each harvest date would use one row for the control manual harvest and the second row for mechanical harvest. The primary purpose of this trial was to; 1) observe whether there was a natural abscission effect on harvest efficiency as the 'Valencia' harvest progressed from March to May; and 2) to observe whether there was evidence of differences in the water uptake between the trees harvested manually and those harvested mechanically. As mentioned previously, prior studies have demonstrated a correlation between harvesting induced tree stress and water uptake measured by sap flow sensors. In Fig. 3A, the harvester is shown harvesting 'Valencia' trees, while Fig. 3B shows a Steam Heat Balance (SHB) sensor installed in a tree (without the insulated blanket) during Winter 2014 harvest trials.

Three harvesting dates were planned to monitor harvest efficiency and water uptake at the Hickory Branch grove, in the Spring 2015 on 31 Mar., 14 Apr., and 7 May. It was determined prior to the trial that the harvesting efficiency aspect of this study would be kept simple by selecting the optimal harvesting settings from the 2014 grapefruit harvest trials. This would allow the entire harvest trial to focus on just one variable, being the harvest date. The machine was operated at a forward speed of approximately 1 mph, with a 73-inch/s shaker speed, 16-inch turnbuckle length, and a moderate beater length. During the offseason, the beater had been modified to a slightly shorter length from that previously studied. With these settings, the shaker machine would harvest on the three successive dates monitoring harvest efficiency.

One week prior to harvests on 31 Mar. and 14 Apr., four heat pulse sap flow sensors were installed on each of one HLB symptomatic (HLB+) and one non-symptomatic (HLB-) tree in each harvesting method trial (manual and mechanical) for a total of 4 trees and 16 sensors. The experimental approach was adapted for determining sap flow measurements from individual plants, which had been confirmed in citrus. Reasonably accurate plant water use has been observed with steam heat balance (SHB) sensors (Kadyampakeni et al., 2014b). The SHB technique is nonintrusive, responds quickly to plant water flow, and can be used over long periods of observations. They do, however, respond to drought and rainfall influences on plant water uptake

Sap flow was measured by the heat balance method using an automated Flow32-1K flow system (Dynamax Inc., Houston, TX). Stem heat balance gauges (Models SGA13, SGB16, SGB19, and SGB25, Dynamax, Houston, TX) were used to measure sap flow. Stem diameters were ranged from 0.53–0.93 inches (13.4–23.6 mm). Gauges were installed at least 48 inches (120 cm) above the soil surface. Gauges installation was performed as described by the Dynamax, the manufacturer. Stems were coated with silicone grease (Dow Corning 4, Dow Corning, Midland, MI) to improve thermal contact and prevent stem damage. Sap flow (g·h^{-1}) was analyzed by harvest method and disease symptomology by harvest date (31 Mar., Table 2; 14 Apr., Table 3). Interactions of harvest method, disease expression preharvest and postharvest was also determined.

Table 2. Sap flow measured on Huanglongbing symptomatic (HLB+) and non-symptomatic (HLB-) sweet orange, *Citrus sinensis*, trees mechanical or hand harvested on 31 Mar. 2015.

Factors	Variables	Mean^z (g·h^{-1})
Harvesting method	Hand	116 a
	Mechanical	87.3 b
HLB+		
	negative	153.3 a
	positive	50 b
HLB–		
Hand	Before harvest	190.33 a
	After harvest	182.24 a
Mech	Before harvest	124.57 b
	After harvest	116.23 b
HLB+		
Hand	Before harvest	42.98 a
	After harvest	48.72 a
Mech	Before harvest	55.12 a
	After harvest	54.19 a
Hand HLB–	Before harvest	190.33 a
HLB+	Before harvest	42.98 b
HLB–	After harvest	182.24 a
HLB+	After harvest	48.72 b
Mech HLB–	Before harvest	124.57 a
HLB+	Before harvest	42.98 b
HLB–	After harvest	116.23 a
HLB+	After harvest	54.19 b

^{z}Mean values with the same letter are not significantly different at $\alpha \leq 0.05$.

Table 3. Sap flow measured on Huanglongbing symptomatic (HLB+) and non-symptomatic (HLB-) sweet orange, *Citrus sinensis*, trees mechanical or hand harvested on 14 April 2015.

Factors	Variables	Mean^z (g·h^{-1})
Harvesting method	Hand	84.43 a
	Mechanical	93.1 a
HLB	negative	132.1 a
	positive	45.4 b
HLB		
Hand	Before harvest	95.3 b
	After harvest	164.7 a
Mech	Before harvest	109.4 b
	After harvest	160.1 a
HLB+		
Hand	Before harvest	31.6 b
	After harvest	47.6 ab
Mech	Before harvest	40.9 b
	After harvest	61.4 a
Hand HLB–	Before harvest	95.3 a
HLB+	Before harvest	31.6 b
HLB–	After harvest	164.7 a
HLB+	After harvest	47.6 b
Mech HLB–	Before harvest	109.4 a
HLB+	Before harvest	40.9 b
HLB–	After harvest	160.1 a
HLB+	After harvest	61.4 b

^{z}Mean values with the same letter are not significantly different at $\alpha \leq 0.05$.

Results and Discussion

In three successive harvest trials on 31 Mar., 14 Apr., and 7 May 2015, the harvesting performance was measured at 62%, 80%, and 76% (Table 4), respectively. These harvesting performance levels were significantly lower than the better performances of 93% observed in 2014. The lower efficiencies can be attributed to unskirted trees on all dates and an operator error on 31 Mar., where the shaker engine was only throttled to approximately 50% resulting in a much slower shaker frequency and lower power capacity. Also on the last harvest date, it was observed that the trees were 10% to 20% larger than in previous trials, and the machine got stuck in the sand, reducing the harvest effectiveness on several trees dramatically as the machine was driven out. It is expected that these numbers will improve dramatically once the trees are skirted to provide catch frame clearance. It was observed in many cases that the majority of the unharvested fruit was located below the skirt line, which does not receive direct shaker impact. This means that all branches under the 24-inch skirt line are dependent on second hand vibration resonated through the canopy rather than direct impact. Prior research had demonstrated that limbs below the skirt line experienced significantly lower accelerations (using tri-axial accelerometers) than limbs in the shaker zone above the skirt line. These trials were conducted under the most adverse conditions experienced by the machine to date. Harvesting was attempted on the side of the bed top on trees that were pushing 9–10 ft tall and unskirted. Nonetheless, even with unskirted trees, we were able to approach 80% harvesting efficiency on two of the three harvesting dates. However, the effect of natural abscission on harvesting efficiency was obscured by several external factors mentioned above.

Observations from sap flow measurements for both harvest dates indicated that tree water uptake was significantly reduced in HLB symptomatic trees (Tables 2 and 3). Symptomatic HLB trees had nearly three times less sap flow compared with non-symptomatic trees. Sap flow after harvest were not significantly lower than sap flow prior to harvest for either hand harvested trees or mechanically harvested trees (data not shown). These sap flow measurements would suggest great reduction in sap flow of trees symptomatic for HLB without lower sap flow after mechanical harvesting. The interactions of harvest method, disease expression, and measurement timing (pre- and postharvest) indicate sap flow reduction for disease symptomatic trees compared with non-symptomatic trees, no difference in sap flow after harvest was found.

Table 4. Average *Citrus sinensis* fruit detachment percentage for the three 2015 harvest trials.

Harvest date	Trees harvested	Harvested fruit (lb)	Gleaned fruit (lb)	Harvest efficiency
3/30/15	18	845.9	520.5	61.9%
4/14/15	23	1295.4	318.2	80.3%
5/7/15	23	1008.6	315.6	76.2%

Previous studies have found 20% to 30% reduction in sap flow for HLB symptomatic trees (Kadymapakni et al., 2014a and 2014b). However, the magnitude sap flow reductions in HLB symptomatic trees compared with non-symptomatic trees in the current study were not expected and have not been found in other studies. These results should be repeated to determine if the magnitude on sap flow reduction persists. Reduced sap flow in trees with reduced canopy density in Morgan et al. (2012) indicated a reduction in sap flow should have been expected. Therefore, the lack of reduced sap flow in mechanically harvested, HLB symptomatic trees after harvest was not expected and should be repeated. However, the mechanical harvester used in the previous study was not an over the top harvested and may have inflicted greater damage to the trees. For both harvest dates, tree water uptake was significantly reduced by HLB.

Conclusions

If preliminary results continue to hold true, this might indicate that the use of over the top mechanical harvesting does not negatively impact stress levels in HLB infected or non-infected trees. This would be a significant reinforcement of the potential for over the top production systems.

The effectiveness of harvesting trials were hindered on several fronts. In work performed in 2015, research objectives resulted in lower than expected harvesting efficiencies in the sub-80% range. There are clear opportunities to improve our planning and communication with the grower as well as the experimental design and execution. However, it was still very encouraging that on the last two trial dates the machine achieved nearly 80% fruit removal under adverse conditions. This speaks well to the fact that we are heading in the right direction. The potential improvement in harvesting efficiency for topped and skirted trees has been demonstrated in earlier 2014 trials, so plans to hedge and skirt trees for next year's trials are being made, which should result in a significant improvement in fruit removal.

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