Mechanical Harvesting Has Little Effect on Water Status and Leaf Gas Exchange in Citrus Trees

Kuo-Tan Li[1] and James P. Syvertsen
University of Florida, Institute of Food and Agricultural Sciences, Citrus Research and Education Center, Lake Alfred, FL 33850

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Abstract. **Mechanical harvesting of citrus trees can cause physical injuries, such as shedding of leaves, exposing roots, and scuffing bark. Although mechanical harvesting usually has not reduced yield, physiological consequences to the tree from these visible injuries have not been investigated. We hypothesized that physical injuries to tree canopies and root systems from a properly operated trunk shaker would not cause short-term physiological effects. Tree water status and leaf gas exchange of mature 'Hamlin' and 'Valencia' sweet orange [*Citrus sinensis* (L.) Osb.] trees that were harvested by a trunk shaker were compared to hand-harvested trees. A trunk shaker was operated with adequate duration to remove >90% of mature fruit or with excessive shaking time under various environmental conditions and drought stress treatments throughout the harvest season. Mid-day stem (Ψ_{stem}) and leaf (Ψ_{leaf}) water potentials along with leaf gas exchange were measured before and after harvest. Trees harvested by the trunk shaker did not develop altered water status under most conditions. Trees harvested with excessive shaking time and/or with limited soil water supply developed low Ψ_{stem} resembling Ψ_{stem} of drought-stressed trees. However, water potential of all treatments recovered to values of the well-irrigated, hand-harvested trees after rainfall. In addition, mechanical harvesting did not reduce CO_2 assimilation, transpiration, stomatal conductance, water use efficiency, or photosystem II efficiency as measured by chlorophyll fluorescence. Thus, despite visible injuries, a properly operated trunk shaker did not result in any measurable physiological stress.**

Mechanical harvesting of fruit crops gained its first major thrust in the1930s (O'Brien et al., 1983), and the principles of machinery-operated harvesting as well as its economical value have been developed ever since. Numerous types of harvest machines have been designed and commercially applied in various fruit industries including citrus in Florida (Hedden et al., 1983; Whitney, 1995). The major benefit of mechanical harvesting relies on its efficiency and lower costs in comparison to harvesting by hand, thereby increasing grower profit. However, the adoption of mechanical harvesting in Florida's citrus industry has been unexpectedly slow. By 2003 <3% of its 240,000 ha of processed orange groves were mechanically harvested (Brown, 2005).

Many factors contribute to the lack of widespread adoption of mechanical harvesting by the Florida citrus industry. Among these factors is the apparent violent shaking that trees experience during harvesting with trunk or canopy shakers. This is usually the grower's first impression of mechanical harvesting. Depending on the type of the harvest machines, the skill of the operators, the weather, the grove conditions, and the physiological status of the trees, a harvest machine can cause visible physical injuries to the trees. These include shedding of leaves, flowers, and young fruit, breaking branches, scuffing of bark, and exposing roots (Halderson, 1966). Nevertheless, long-term studies revealed that fruit yield of citrus trees was affected little by mechanical harvesting compared to trees that were hand harvested (Hedden et al., 1988). In cherry (*Prunus cerasus* L.) trees, however, mechanical harvesting hastened tree decline and cut their productive life in half (Burton et al., 1986). Although there is no evidence that visible injuries could seriously weaken citrus trees, tree health after mechanical harvesting remains a major concern to orange growers.

Previous studies have concentrated on finding the potential cause of mechanical injuries (Abdel-Fattah, et al., 2003; Gurusinghe and Shackel, 1995) as well as improving machinery design and harvest efficiency (Affeldt et al., 1989; Fridley, 1983; Peterson, 1998). It is apparent that currently available harvest machines have been greatly improved and tree injures caused by modern shaking machines are less severe than they once were. On the other hand, it also appears that unless a more sophisticated means of mechanical harvesting is employed, some visible tree injuries are unavoidable. This underscores the need to document the tree's physiological responses to injuries by mechanical harvesters.

Despite the fact that secondary infections after immediate injuries have been blamed for tree decline in mechanical harvested cherry, almond [*Prunus dulcis* (Mill.) Webb.] (De Vay et al., 1968), and peach [*Prunus persica* (L.) Batsch.] (Glenn, et al., 1995) trees, physiological reactions to physical injuries by harvest machines to these fruit trees or to citrus, have not been documented. In 2003, we initiated the first program dedicated to investigating the effects of mechanical harvesting on tree physiological activity in citrus trees. The objectives of this program were to 1) quantify the relationship between harvest machines and the potential of short and long-term physiologically important injuries, 2) examine the physiological effects of mechanical harvesting under different weather conditions and tree water status over the 6-month-long harvest season, and 3) develop safe operating conditions for mechanical harvesting to avoid tree injury in an effort to accelerate the adoption of mechanical harvesting in the Florida citrus industry.

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[1]To whom reprint requests should be addressed; e-mail ktli@ufl.edu.

We measured tree water status and leaf gas exchange characteristics after harvesting by a trunk shaker, one of the most popular harvest machine types in Florida. We hypothesized that the severity of injuries caused by a normally operating trunk shaker would not induce significant physiological stresses in well-managed citrus trees. In addition, if a tree that was under environmental stresses or was actively growing, it likely would be more vulnerable to any physiological stress induced from mechanical harvesting with an improperly operated shaker.

Materials and Methods

Three grove sites of 'Hamlin' or 'Valencia' sweet orange (*C. sinensis*) trees on Carrizo citrange [*C. sinensis* x *Poncirus trifoliate* (L.) Raf.] or Swingle citrumelo (*C. paradise* Macf. x *P. trifoliate*) rootstocks at the Univ. of Florida's Citrus Research and Education Center in Lake Alfred were used in this study. The soil type of these sites is Candler fine sand with low water holding capacity and low organic matter. Each site was subdivided by rows or sections to form a random block design. Trees received normal grove management, irrigation, pest control, and fertilization. During the dry season between late October and May, irrigation by microsprinklers was applied at the rate of 170 to 227 L/tree twice per week as needed. Harvest dates were the normal harvest period for either variety in Florida. 'Hamlin' is harvested between November and February, whereas 'Valencia' is harvested between February and June. Bloom time for both varieties is normally in mid-March (Davies and Albrigo, 1994)

Trunk shaker. A prototype (Dotan Ltd., Migdal Hae'mek, Israel) FMC linear-type trunk-shaking system (FMC Corp., Lakeland, Fla.) was used in this study. The padded clamp shaker head was equipped with 70.8 kg of unbalanced weight and connected by a power take off to a tractor engine operating at 2100 rpm. This weight and power combination was selected to generate a shaking frequency of 4 Hz with a maximum trunk displacement of 6.5 cm. The shaking frequency and force output were evaluated on adjacent trees with a set of accelerometers (PCB 35B33; PCB Piezotronics, Depew, N.Y.) and high-speed portable data acquisition systems (WavePort/PE8; Iotech, Cleveland). Trunk displacement was measured directly using a measuring tape.

Experiment 1. Grove site one contained forty-five 14-year-old 'Hamlin'/'Swingle' trees in an east-west oriented row. Trees were 3.5 m tall and spaced at 6.1 m between rows and 4.6 m within rows. The trunk diameter averaged 14 cm at 30 cm above ground. Thirty uniform trees were grouped into five blocks of six trees. Irrigation was withheld for 3 weeks before harvest and no rainfall was recorded during this period. On 7 Jan. 2004, two trees in each block were harvested by hand (Hd) and three trees were harvested by the trunk shaker. Hand harvesting removed 100% of the fruit whereas mechanically harvesting removed >90% of the fruit. Two trees harvested by the trunk shaker were subjected to 10 s shaking time (10S) and the other tree to 20 s (20S). The remaining tree in each block was not harvested and served as an un-harvested control (C). Irrigation was resumed in this grove the day after harvest except on one of the hand-harvested trees (HdD) and one of the 10 s mechanical harvested trees (10SD) in each block. To test effects of drought stress, irrigation was withheld from these trees for one additional month.

To characterize physiological responses of trees, mid-day stem water potential (Ψ_{stem}), leaf gas exchange, and leaf chlorophyll fluorescence were measured 1 d before harvest and every 1 to 3 d thereafter until 6 Feb. 2004. Details of physiological measurements are described below.

Experiment 2. Grove site two contained thirty-eight 12-year-old 'Hamlin'/'Carrizo' trees in five north-south oriented rows. Trees were 3.7 m tall and spaced at 4.5 to 9 m between rows and 3 m within rows. The trunk diameter averaged 12.6 cm at 30 cm above ground. Twenty-five uniform trees were grouped by rows into five blocks of five trees. Irrigation was withheld from this grove site for 2 weeks before harvest on 28 Jan., but 33.78 mm rain fell on 18 and 19 Jan. and another 13.46 mm on 27 Jan. Consequently, soil was well watered prior to harvest. Two trees in each block were harvested by hand (Hd) whereas three others were harvested using the trunk shaker as above. One mechanically harvested tree in each block was shaken for 10 s (10S) and the others for 30 s (30S) shaking time. After harvest, irrigation was resumed in this grove except on one of the hand harvested (HdD) and the 30S trees (30SD) in each block, in which irrigation was withheld for one additional week. Mid-day Ψ_{stem} and leaf gas exchange was measured on 23 and 29 Jan. and 5 Feb. as described below.

Experiment 3. Grove site three contained forty 15-year-old 'Valencia'/'Swingle' trees in a north-south oriented row. Trees were 3.5 m tall and spaced at 4.56 m between rows and 2.13 m within rows. The trunk diameter averaged 36.8 cm at 30 cm above ground. Twenty-five uniform trees in full bloom were grouped into five blocks of five trees. Soil was well watered since irrigation at the rate of 227 L/tree was applied daily to this grove site from 11 to 15 Mar. plus 36.07 mm rain fell on 15 Mar. and 55.12 mm on 16 Mar. Two trees in each block were harvested by the trunk shaker for 10 s on 17 Mar. One tree was hand harvested on 19 Mar. and another by the trunk shaker for 20 s. The remaining tree in each block was not harvested (C). After harvest, a portion of the bark was removed from the main trunk of one of the 10S trees in each block using a sharp knife to simulate severe bark injury (10SB) by the trunk clamp. An average of 7.5 × 21.2-cm bark area ≈20 to 40 cm above the soil surface on both the north and south side of the main trunk was removed. This corresponded to the area that was in contact with the shaker clamp pads. The total width of the removed bark equaled 42% of the trunk circumference. After 19 Mar., irrigation was withheld from trees that had been harvested until late April, while a regular irrigation schedule was continued on the un-harvested control trees. Mid-day Ψ_{stem} and leaf water potential (Ψ_{leaf}) were measured as described below every one to three days between 18 Mar. and 4 Apr., and again on 20 and 28 Apr.

Soil water content was measured gravimetrically immediately after Ψ measurements. Five soil samples from the root zone were collected at each measurement date at depths of 0 to 30 cm and 30 to 60 cm. Soil water content was calculated by the difference between fresh and oven-dried soil weight.

Leaf and stem water potential measurements. Mid-day Ψ_{stem} and Ψ_{leaf} were measured with a pressure chamber (Scholander et al., 1965) between 1330 and 1500 HR; Ψ_{stem} was measured on leaves that had been enclosed in plastic bags and covered by aluminum foil at least 3 h before measurement. Two exposed mature leaves from the last mature summer or spring flushes were used for each mid-day Ψ_{stem} measurement. Ψ_{leaf} was measured on uncovered, transpiring leaves immediately following Ψ_{stem} measurements on two similar adjacent leaves.

Leaf gas exchange measurements. Leaf gas exchange was measured with a portable photosynthesis system (LI-6200; LI-

COR, Lincoln, Nebr.) on selected clear days between 0930 and 1130 HR. Photosynthetic photon flux density (*PPFD*) was greater than 900 μmol·m^{-2}·s^{-1} during all measurements. Leaf temperature in the measurement cuvette was usually 2 to 3 °C above ambient air temperature. Relative humidity (RH) inside the cuvette was close to ambient RH. Measurements were made across all treatments in two 1-h blocks to allow testing for effects of changing environmental conditions over time. On each date measurements were taken on two to three healthy light-exposed mature leaves on the last summer or spring flushes on each tree. Net assimilation of CO_2 (A_{CO2}), stomata conductance (g_s), transpiration (E), and leaf water use efficiency [WUE (micromoles CO_2 per millimole H_2O)] was calculated.

Leaf chlorophyll fluorescence measurements. Chlorophyll fluorescence was measured with a pulse-modulated fluorometer (OS-1-FL; Opti-Science, Tyngsboro, Mass.) on selected days between 1300 and 1330 HR. Two leaves from each tree were dark-adapted with leaf clips for at least 2 h prior to measurement to ensure the photosystem II reaction centers were in an active open status. The minimal fluorescence emission from the dark-adapted leaf area (F_o, nomenclature from van Kooten and Snel, 1990) was excited by low intensity (<1 μmol·m^{-2}·s^{-1}) modulated 655-nm light and was detected in the 700- to 750-nm ranges. After F_o was recorded the photosystem was saturated by a high intensity (≈15,000 μmol·m^{-2}·s^{-1}), 350- to 690-nm light pulse for 1 s to induce the maximal fluorescence from the dark-adapted leaf area (F_m). Variable fluorescence from the dark-adapted leaf area (F_v) was calculated from ($F_m - F_o$) and maximum quantum efficiency of PSII photochemistry was derived from F_v/F_m (van Kooten and Snel, 1990). Measurements were taken on every tree in Expts. 1 and 2.

Environmental data and statistical analysis. Daily temperature, precipitation, and RH for the Lake Alfred site were obtained from Florida Automated Weather Network (Univ. of Florida/Institute of Food and Agricultural Sciences, 2005). Maximum daily vapor pressure deficit (VPD) was derived from maximum day temperature and minimum RH.

Data were subjected to analysis of variance (ANOVA). Each tree was an experiment unit. Measurements from each tree were averaged before analysis using general linear model or balanced model procedures. Data collected after harvest were also pooled and subjected to repeated measures ANOVA where appropriate. Mean values of treatments with or without standard error are presented. Significant differences were determined at $P \le 0.05$, 0.01, or 0.001 and separated by Dunn's or Duncan's multiple comparison tests where appropriate. Due to lack of interaction between treatment and blocks overtime, only treatment and block effects are reported.

Results

Tree water status

Experiment 1. A moderate drought stress occurred as the average mid-day Ψ_{stem} was below –1.5 MPa 5 d before harvest on 7 Jan. (data not shown). Mid-day Ψ_{stem} of trees re-watered on 8 Jan., 1 d after harvest, recovered immediately. Although C and Hd trees had slightly higher Ψ_{stem} (–1.23MPa) than that of 10S and 20S trees (–1.33 MPa), this difference was not significant. Mid-day Ψ_{stem} of trees un-irrigated after harvest (HdD and 10SD) remained below –1.41 MPa. A similar trend occurred the next day except for 20S trees, in which the mid-day Ψ_{stem} declined to the level of the continuously drought-stressed trees and that was significantly lower than that of C and Hd trees on 9 Jan. (Fig. 1). The 8.6-mm precipitation in the evening of 9 Jan. diminished any difference in Ψ_{stem} among treatments by 11 Jan. and thereafter. The regular irrigation and a total amount of 53.1 mm precipitation maintained all mid-day Ψ_{stem} above –1.2 MPa until 6 Feb.

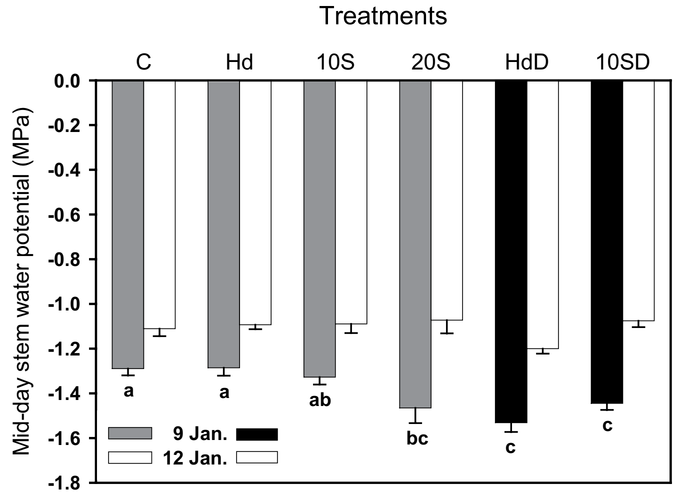

Fig. 1. Effect of mechanical harvesting and irrigation on mid-day (1330 to 1500 HR) stem water potential in 'Hamlin' citrus trees (Expt. 1); C = trees were not harvested, Hd = hand harvest, 10S = 10 s trunk shaking, 20S = 20 s trunk shaking, HdD = hand harvest and postharvest drought stress, 10SD = 10 s trunk shaking and postharvest drought stress. Trees were harvested on 7 Jan. 2004. Trees did not received water 3 weeks prior to harvest. Trees other than postharvest drought treatments received irrigation on 8 Jan.; 8.6 mm rainfall was recorded after 9 Jan. measurements. Date represents mean values of 10 replicated leaves. Vertical bars represent standard errors. Mean separation by Duncan's multiple comparison ($P \le 0.05$).

Expt. 2. The rainfall before and after harvest also ensured a high water status with mid-day Ψ_{stem} at –1.16 MPa in all trees regardless of the harvest and irrigation treatments (data not shown). However, on 5 Feb, a dry hot day when the temperature exceeded 29 °C, trees harvested by hand with or without postharvest irrigation, had lower mid-day Ψ_{stem} (–1.41 Mpa) than trees harvested with the trunk shaker (–1.3 MPa, $P = 0.003$).

Expt. 3. The 5 d of preharvest irrigation plus 36 mm precipitation prior to harvest on 17 Mar., resulted in a high Ψ_{stem} of –0.79 in all trees (Fig. 2A) and high soil water content (Fig. 2B). Since there was no rainfall until 3 weeks after harvest, the mid-day Ψ_{stem} and soil water content gradually declined. The initially high soil water content, however, apparently resulted in no drought symptoms on trees regardless of irrigation, harvest treatments, or bark removal. The only exception was on 29 Mar. after several clear days with high maximum temperature and VPD (Fig. 2C). On this day, trees without irrigation, regardless of harvest methods and bark removal, had lower mid-day Ψ_{stem} than C trees that had been irrigated regularly ($P = 0.017$). Irrigation was resumed on all trees on 3 Apr. and Ψ_{stem} began to increase 2 d later. There was no significant difference in Ψ_{stem} among treatments through late April.

Similar results in mid-day Ψ_{leaf} were obtained as values were generally 0.1 to 0.3 MPa lower than Ψ_{stem} measured at the same time of day (data not shown). Sample variations, however, resulted in no difference in Ψ_{leaf} among treatments.

Leaf gas exchange. Overall, there was no significant difference in A_{CO2}, g_s, E, and WUE between hand and mechanical harvested trees in Expt. 1 before and after harvest (Table 1). Mean gas exchange values on 6 Jan. were relatively high during the

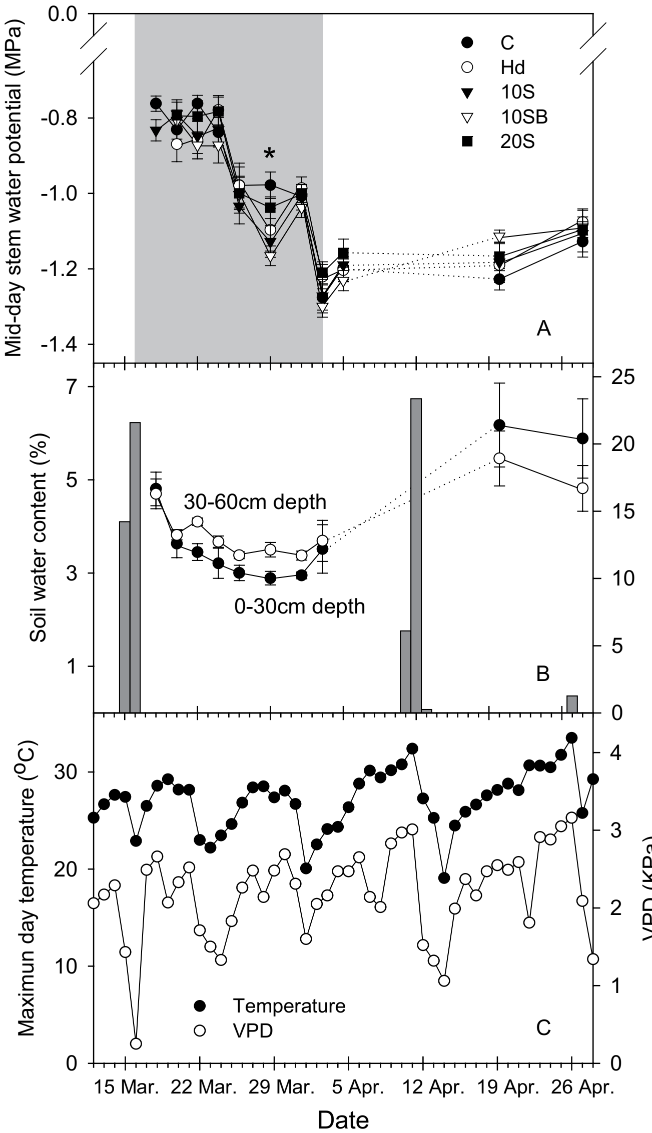

Fig. 2. (**A**) Effect of mechanical harvesting and irrigation on mid-day stem water potential in 'Valencia' citrus trees in full bloom (Expt. 3); C = Trees were not harvested, Hd = hand harvest, 10S = 10 s trunk shaking, 10SB = 10 s trunk shaking and partial bark removal, 20S = 20 s trunk shaking. Trees were harvested on 17 or 19 Mar. 2004. Irrigation was withheld from all trees except C trees between 16 Mar. and 3 Apr. (shaded area). The asterisk indicates statistical significance ($P = 0.017$). (**B**) Soil water content (lines) and precipitation (bars), and (**C**) maximum day temperature (T) and vapor pressure deficit (VPD) during experiment dates. Vertical bars represent standard errors.

winter in spite of the moderate drought stress imposed before trees were harvested on 7 Jan. After harvest, gas exchange readings in all trees were significant lower on 8 Jan and thereafter. Trees that were mechanically harvested and that were continuously not irrigated had lower A_{CO2}, g_s, and E than C and Hd trees. The unharvested C trees had consistently higher A_{CO2} than all harvested trees as shown by the postharvest means across 8 to 22 Jan. The differences, however, were not significant within individual measurement dates. Gas exchange rates remained relatively low after the harvest date until 22 Jan. There was little treatment effect on WUE, although after harvest, C trees with fruit had higher WUE than harvested trees, especially the 20S and HdD trees. Due to the greater reductions in E than in A_{CO2}, WUE after harvest was higher than before harvest in all trees.

Table 1. The effect of harvesting and irrigation on leaf gas exchange in 'Hamlin' citrus trees (Expt. 1). Trees were harvested on 7 Jan. 2004.

	Date of measurements					Mean after
Treatments[z]	6 Jan.	8 Jan.	12 Jan.	15 Jan.	22 Jan.	harvest
Assimilation of CO_2 (μmol·m^{-2}·s^{-1})						
C	10.7	5.4	4.9	8.7	5.0	6 a
Hd	11.7	5.4	3.1	7.4	4.2	5.01 ab
10S	9.2	3.9	3.0	8.9	4.1	4.98 ab
20S	8.2	3.7	2.5	5.0	3.2	3.6 b
HdD	9.8	3.5	2.9	6.6	2.8	3.95 b
10SD	10.4	3.7	3.1	6.1	4.5	4.3 b
Significance						
Treatment	NS	NS	NS	NS	NS	**
Block	*	NS	*	NS	NS	*
Stomatal conductance (mol·m^{-2}·s^{-1})						
C	0.306	0.054	0.063	0.121	0.069	0.077
Hd	0.3	0.062	0.047	0.106	0.062	0.069
10S	0.214	0.053	0.048	0.144	0.062	0.077
20S	0.267	0.047	0.041	0.092	0.06	0.06
HdD	0.209	0.037	0.037	0.097	0.052	0.056
10SD	0.267	0.034	0.051	0.097	0.064	0.062
Significance						
Treatment	NS	NS	NS	NS	NS	NS
Block	NS	NS	NS	NS	NS	NS
Transpiration (mmol·m^{-2}·s^{-1})						
C	7.82	1.62 ab	1.25	2.13	1.31	1.58
Hd	8.77	1.9 a	0.95	1.9	1.3	1.51
10S	8.23	1.25 b	1.03	2.2	1.29	1.44
20S	7.61	1.27 b	1	1.6	1.28	1.29
HdD	7.74	1.38 ab	1.05	1.87	1.31	1.40
10SD	8.32	1.45 ab	1.27	1.75	1.41	1.47
Significance						
Treatment	NS	*	NS	NS	NS	NS
Block	NS	NS	NS	NS	NS	*
Water use efficiency (μmol CO_2 per mmol H_2O)						
C	1.34	3.2	3.59 a	3.97	3.7	3.71 a
Hd	1.34	2.8	3.03 ab	3.68	3.03	3.14 ab
10S	1.1	2.97	2.73 b	4	3.02	3.18 ab
20S	1.09	2.68	2.37 b	2.94	2.28	2.57 b
HdD	1.24	2.5	2.66 b	3.46	1.94	2.66 b
10SD	1.29	2.41	2.47 b	3.28	3.13	2.82 b
Significance						
Treatment	NS	NS	**	NS	NS	**
Block	*	NS	***	NS	NS	*

[z]C = trees were not harvested, Hd = hand harvest, 10S = 10 s trunk shaking, 20S = 20 s trunk shaking, HdD = hand harvest and postharvest drought stress, 10SD = 10 s trunk shaking and postharvest drought stress.
[NS, *, **, ***]Nonsignificant or significant difference at $P \le 0.05, 0.01, 0.001$, respectively. Letters within rows indicate treatment mean separation by Duncan's multiple comparison test at $P \le 0.05$.

There were few significant differences in gas exchange among treatments in Expt. 2. Mean A_{CO2} before harvest was 5.8 to 7.5 μmol·m^{-2}·s^{-1}, g_s was 0.07 to 0.08 mol·m^{-2}·s^{-1}, and E was 1.5 to 2.5 mmol·m^{-2}·s^{-1}. Mean A_{CO2} after harvest was 4.5 to 5.5 μmol·m^{-2}·s^{-1}, g_s was 0.05 to 0.08 mol·m^{-2}·s^{-1}, and E was 1.3 to 1.8 mmol·m^{-2}·s^{-1}.

Leaf chlorophyll fluorescence. Similar to leaf gas exchange, there was no significant treatment effects on photosystem II efficiency as indicated by chlorophyll fluorescence F_v/F_m of leaves from all trees (Table 2). Uniformly high values of F_v/F_m

Table 2. The effect of harvesting and irrigation on leaf photosystem II efficiency as indicated by leaf chlorophyll fluorescence (F_v/F_m) in 'Hamlin' citrus tree (Expt. 1). Trees were harvested on 7 Jan. 2004.

	Photosystem II efficiency (F_v/F_m)						Mean after
Treatments[z]	5 Jan.	8 Jan.	9 Jan.	12 Jan.	15 Jan.	22 Jan.	harvest
C	0.81	0.78	0.80	0.78 ab	0.77	0.78 a	0.78
Hd	0.80	0.76	0.81	0.79 ab	0.76	0.73 ab	0.77
10S	0.80	0.77	0.79	0.79 a	0.77	0.73 ab	0.77
20S	0.81	0.79	0.80	0.73 ab	0.75	0.72 b	0.76
HdD	0.80	0.77	0.79	0.74 ab	0.71	0.75 ab	0.75
10SD	0.81	0.73	0.78	0.72 b	0.75	0.74 ab	0.74
Significance	NS	NS	NS	*	NS	*	NS

[z]C = trees were not harvested, Hd = hand harvest, 10S = 10 s trunk shaking, 20S = 20 s trunk shaking, HdD = hand harvest and postharvest drought stress, 10SD = 10 s trunk shaking and postharvest drought stress.
[NS, *]Nonsignificant or significant difference at $P \leq 0.05$, respectively. Letters within rows indicate treatment mean separation by Duncan's multiple comparison test at $P \leq 0.05$.

(0.8 to 0.81) were recorded before harvest. The F_v/F_m readings decreased on 8 Jan. and thereafter. After harvest, C trees had a slightly higher F_v/F_m than the others, and continuously drought stressed-trees (HdD and 10SD) had lower F_v/F_m.

Discussion

Using the commercial range of shaking time of about 10 s, trees harvested by the trunk shaker maintained water status and gas exchange rates similar to trees harvested by hand under most conditions during the harvest season. Even after an excessive shaking time of ≥20 s that was expected to cause damage to roots and trunk bark of actively growing trees, mechanically harvested trees did not develop water stress symptoms when the grove was well watered (Expts. 2 and 3). When soil was semi-dry, however, there was a rapid reduction in Ψ_{stem} of mechanical harvested trees, especially of 20S trees that developed stress similar to that of nonirrigated trees (Fig. 1). Similar to drought stress from root damage that occurs when transplanting mature trees (Castle, 1993) and, root pruning studies (Moreshet et al., 1988), the shaker-induced drought stress was ephemeral and disappeared once the grove was fully watered. The common practice of ceasing irrigation before and after mechanical harvesting to facilitate machine access might not be advisable if the grove has experienced any drought stress.

An average of 12% of total leaf area was removed by the trunk shaker in this study compared to <2% by hand harvest (Li and Syvertsen, 2004a, 2004b). Since canopy E is proportional to canopy leaf area (Atkinson, 1978; Li et al., 2003), this amount of leaf loss should have decreased canopy E. It is not surprising, therefore, trees harvested by the trunk shaker had temporarily higher mid-day Ψ_{stem} than trees harvested by hand in dry, hot days when water uptake from the soil was not limited such as on 5 Feb. in Expt. 2.

Chronic water stress induced by xylem embolism and reduced trunk hydraulic conductance after severe wind and shaking damage by large typhoons, resulted in decline and dieback of tall hinoki cypress trees [*Chamaecyparis obtuse* (Siebold & Zucc.) Endl.] several years after the damage (Ueda and Shibata, 2004). It is not clear whether the short-term trunk shaking that occurred during mechanical harvesting would cause similar results. However, the rapid recovery of stem water potential in 20S trees and the insignificant differences in water status between hand and mechanical harvested trees indicated that any physical injuries caused by the trunk shaker did not affect the overall water relations. Thus, canopy transpiration, xylem transport, and root uptake of water apparently were unaffected.

Leaf gas exchange was not affected by defoliation or putative root injuries caused by the trunk shaker. Although photosynthesis gradually decreases when citrus trees suffer drought (Mataa et al., 1998), the mild drought stress and the rainfall after harvest in Expt. 1, resulted in water potentials that were apparently not low enough to reduce gas exchange. Partial defoliation has been reported to increase leaf photosynthetic ability in remaining leaves of citrus seedlings, which supports the increased carbohydrate demand for regrowth (Syvertsen, 1994). Manually removing up to 25% canopy leaf area in mature citrus trees, however, did not induce photosynthetic compensation in remaining light-exposed leaves (Garcia-Sanchez, unpublished). Similarly, the mild defoliation caused by mechanical harvesting in this study, appeared incapable of inducing any photosynthetic compensation mechanism in light-exposed leaves. In addition, citrus trees have a very high canopy density with leaf area indexes approaching 11 (Jahn, 1979). The severity of leaf loss in trees after mechanical harvesting was not expected to remarkably reduce total canopy light interception. Since citrus leaves are capable of acclimating to a wide range of changing light environments even after fully mature (Syvertsen and Smith, 1984), preshaded leaves in the canopy might have partially restored their gas exchange ability in response to the increasing light exposure after mechanical harvesting. Therefore, the small reduction in leaf area after mechanical harvesting might be expected to have little effect on whole-canopy photosynthesis.

The low leaf gas exchange after harvest in Expt. 1, appeared to be directly related to the low temperature (Guo et al., 2003; Syvertsen and Lloyd, 1994). Before harvest, the day/night temperature had averaged at 27/12 °C for 1 week and moderate gas exchange readings were recorded on 6 Jan. The day/night temperature decreased to 15/5 °C 1 d after harvest and to 17.5/2.5 °C on 10 and 11 Jan. Until the end of January the temperature remained relative low as did the leaf gas exchange rate. The variations in gas exchange data can be attributed to the variations due to leaf age and to block effects, which reflects the time-related changes in temperature and VPD during measurements especially during the cool winter days.

Although chlorophyll fluorescence has been used to investigate plant photosynthetic responses to various types of environmental stresses, the feasibility of fluorescence indexes depends on the type and the magnitude of the stress (van Kooten and Snel, 1990). In general, chlorophyll fluorescence was not sensitive to mild or moderate drought stress, as F_v/F_m was not affected in many crops with imposed drought stress (Baker and Rosenqvist, 2004). Salinity induced drought stress also did not affect chlorophyll fluorescence emission in citrus (Lloyd et al., 1987). F_v/F_m decreased only after long-term drought stress in apple (*Malus* ×*domestica* Borkh.) leaves (Massacci and Jones, 1990). In contrast, F_v/F_m is a powerful probe for detecting photoinhibition caused by chilling temperature in citrus (Guo et al., 2003) and other tropical fruit trees (Nir et al., 1997). Similar to gas exchange measurements, we measured low F_v/F_m readings after harvest in all trees regardless of treatments, suggesting that the reduction in photosystem II efficiency after harvest was the result of cool temperature.

Crop load can increase photosynthesis and chlorophyll fluorescence in citrus (Syvertsen et al., 2003), apple (Tartachnyk and Blanke, 2004; Wünsche et al., 2000), and many other fruit trees

(Urban, et al., 2003). In Expt. 1 the un-harvested control trees had consistently higher gas exchange and photosystem efficiency but this crop load effect was not significant. It is possible that the low temperature after harvest obscured significant crop load effects on A_{CO2}. On the other hand, any low-temperature effect in Expt. 2 was eliminated because the weather remained warm before and after harvest. The slightly lower gas exchange in all treatments after harvest might therefore, be attributable to the loss of a crop effect.

Conclusions

Healthy, well-managed citrus trees were capable of tolerating the defoliation as well as any potential root and bark injury caused by the mechanical harvesting trunk shaker. Mechanical harvested trees did not develop any physiological stress as measured by stem water potential, leaf gas exchange, and photosystem efficiency. Trees that were shaken for an excessive duration might have had more severe root damage and thus developed temporary drought stress when soil moisture was relatively low. This drought stress can be avoided by limiting shaking time to <10 s and with proper grove irrigation. However, any impact of mechanical harvesting on whole-canopy light interception and gas exchange has yet to be determined. Potential effects of repeated mechanical harvesting on tree vigor, direct root injury by trunk shaking, and the growth of fine roots in relation to potential phloem injury warrant investigation.

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