EFFECTS OF FOLIAGE DENSITY AND GROUND SPEED ON ULTRASONIC MEASUREMENT OF CITRUS TREE VOLUME

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ABSTRACT. *Ultrasonic sensors can be used to quantify and map tree canopy volume, which is useful for planning site-specific management practices within a grove and estimating crop yield. An experiment was conducted to examine the effects of the canopy foliage density and ground speed on the performance of the Durand-Wayland ultrasonic system in tree volume measurement. Fifteen densely foliated (dense) and 15 partially defoliated (light) citrus trees were scanned from both sides at three ground speeds in three replications. The measurements were compared to those calculated from manual measurements of the tree dimensions. The difference between ultrasonic and manual volumes was used to evaluate the performance of the ultrasonic system.*

The difference between ultrasonic and manual volumes ranged from –17.3% to 28.71% at the 95% confidence level. Ninety five percent of the ultrasonic measurements were repeatable within –12.7% to 30.9% of the manual volume. Canopy foliage density had significant effect on ultrasonic measurements of canopy volume. The volume difference was higher in light than dense trees. There was no significant effect of ground speed (1.6 to 4.7 km/h) on ultrasonic volume measurements. Variability of the measurements in partially defoliated canopies increased as ground speed increased. There was a significant difference between the volumes of two sides of the trees.

Keywords. *Ultrasonic sensors, Site-specific management, Citrus, Canopy volume, Canopy foliage density.*

Traditionally, management decisions for Florida citrus groves are made on average basis, i.e. considering the entire block as one homogeneous unit. But, generally, soil and tree characteristics are not uniform within a given grove (Whitney et al., 1999). Thus uniform application of agrochemicals may not match with the demands of individual tree and result in over- or under-application. The presence of dead, declining, and reset trees and the gaps between adjacent trees demand more accurate applications to maximize profit margins and reduce environmental contamination.

Precision farming facilitates the division and management of large blocks into smaller areas or nearly homogeneous units (Righetti and Halbleib, 2000; Whitney et al., 2001). Several studies have concentrated on yield mapping (Miller and Whitney, 1999; Crews et al., 2001) and nutritional aspects (Schumann, 2001) of precision farming in citrus. Wheaton et al. (1995) and Whitney et al. (1999) have correlated tree volume to citrus crop yield. Although tree canopy characteristics (volume, height, density, etc.) are known to be important factors in providing a quantitative basis for variable management of orchards (Schumann et al., 2003) in practice it is very difficult to obtain such information. Manual measurement of tree size (height, cross-sectional area, volume) is laborious and time consuming. Albrigo et al. (1975) computed the canopy volume using the prolate spheroid volume formula based on canopy diameter parallel to the row, maximum canopy height above ground, skirt height, and height to the point of maximum canopy diameter. Wheaton et al. (1995) used a formula to compute the canopy volume based on one-half of an ellipsoid considering canopy diameters parallel and perpendicular to the row (near ground level) and maximum canopy height. These formulae were based on some tree shape assumptions that sometimes might be questionable.

Recent advances in computer hardware and software, global positioning system (GPS), remote sensing, and plant canopy sensors offer opportunities for fast and inexpensive measurement of the tree canopy characteristics for variable rate application of the grove production and protection inputs. One possible method is ultrasonic measurement of tree volume. The information could enhance interpretation of plant growth and improve planning for site-specific management of a grove.

Giles et al. (1988) developed a system for to electronically measure canopy volume. The system was based on ultrasonic range transducers and was mounted on an orchard air-blast sprayer. Ultrasonic transducers measured the distance to the canopy foliage and their performance was not affected by ground speeds of 2, 4, and 6 km/h. Roper (1988) described a sprayer equipped with ultrasonic foliage sensors. These sensors actuated spray nozzles when foliage was detected. Giles et al. (1989) reported an electronic system and method for orchard tree foliage sensing, grove mapping, and varying application rate of materials. The system could measure the amount and vertical distribution of foliage at a given height

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of orchard trees. The data could be used to generate foliage map of the orchard. Moltü et al. (2001) developed an automatic spray system using a micro-controller to receive tree shape information from two ultrasonic sensors and to actuate electro-hydraulic valves mounted on a hydraulic circuit. The system allowed spraying higher doses on the central part of the tree where there is more foliage. This method could save up to 37% of the product while maintaining the quality of the treatment.

Kataoka et al. (2002) evaluated the performance of ultrasonic and laser beam sensors in crop height measurements. Average ultrasonic measurements of soybean height showed less than 30-mm error based on manual measurements. Solanelles et al. (2002) compared a conventional sprayer with an air-assisted sprayer using a prototype electronic control system. The system consisted of two ultrasonic sensors and solenoid valves for variable rate application of the spray to the tree canopy. The arrangement could save 30% and 65% of spray liquid in pear and olive orchards, respectively. Tumbo et al. (2002) compared laser and ultrasonic measurements of citrus canopy volume with manual methods. Ultrasonic and laser measurements showed good agreement with manual methods, however, the study did not consider different operating conditions.

The potential application of ultrasonic sensor includes orchard management based on rapid quantification of tree volume. The information could also be used in variable rate application of agrochemicals within a grove. This study was designed to:

- evaluate the repeatability of ultrasonic measurements of tree volume,
- determine the effects of ground speed and foliage density on the ultrasonic measurements,
- quantify the difference between volumes of the North and South canopy halves of citrus trees.

Materials and Methods

Fifteen densely foliated (dense) and 15 partially defoliated (light) citrus trees were selected for canopy volume measurement. The dense trees were 10-year-old Hamlin orange on Swingle rootstock at 6.1- × 4-m spacing while the light trees were 15-year-old Hamlin on sour orange rootstock at 6.7- × 4.6-m spacing. These trees were located at the Citrus Research and Education Center, Lake Alfred, Florida. The tree densities were categorized based on visual assessment of the foliage. On scale of 1 to 5, light trees were rated as 2 to 3 and dense trees as 4 to 5. Tree canopies were not topped or hedged at the time of the measurement. The canopies of the selected trees did not touch adjacent trees.

Manual Tree Volume Computation

A digital pole (Senshin Industry Co., Ltd. Japan) and measuring tape were used to measure the heights and diameters of the selected trees. The measured dimensions were used to compute manual canopy volume of individual trees from the following equation 1. The equation uses six diameters and four heights (fig. 1). It assumes nearly cylindrical and spherical segment geometries for the lower and upper parts of the canopy, respectively. Equation 1 could provide a better estimate of the canopy volume compared to other formulae with fewer dimensions that have been used in previous studies (Albrigo et al., 1975; Wheaton et al., 1995).

$$V = \frac{\pi}{4}\left[\left\{D_{1c}\,D_{2c}\left(H_b - H_d\right)\right\} + \frac{1}{2}\left(H_a - H_b\right)\left\{\left(D_{1b}D_{2b}\right) + \left(D_{1a}D_{2a}\right) + \frac{4}{3}\left(H_a - H_b\right)^2\right\}\right] \quad (1)$$

where

- V = canopy volume (m^3)
- H_a = maximum canopy height above ground level (m)
- $(H_a - H_b)$ = canopy height at tree crown (m)
- $(H_b - H_d)$ = height of maximum canopy diameter (m)
- H_c = height to the point of maximum canopy diameter (m)
- H_d = height from ground to canopy skirt (m)
- H_i = height of intercept between two adjacent trees (m)
- D_{1a} = canopy apex diameter parallel to row (m)
- D_{2a} = canopy apex diameter perpendicular to row (m)
- D_{1b} = tree crown canopy diameter parallel to row (m)
- D_{2b} = tree crown canopy diameter perpendicular to row (m)
- D_{1c} = maximum canopy diameter parallel to row (m)
- D_{2c} = maximum canopy diameter perpendicular to row (m)

The differences between pairs of parallel (D_{1a}, D_{1b}, D_{1c}) and perpendicular (D_{2a}, D_{2b}, D_{2c}) diameters accounted for non-circularity of the canopy to some extent.

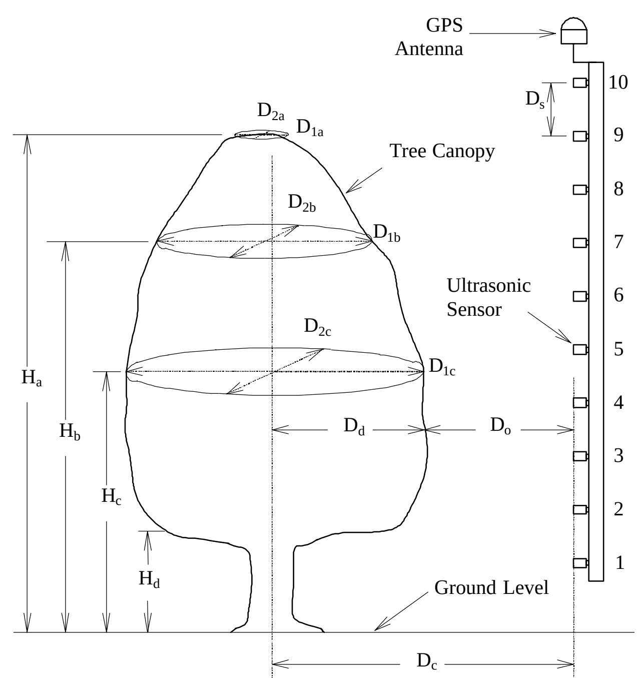

Figure 1. Schematic view of tree, ultrasonic sensors, and dimensions used to compute canopy volume manually and with ultrasonic measurements.

ULTRASONIC MEASUREMENTS AND VOLUME COMPUTATION

A Durand Wayland, Inc. (LaGrange, Ga.) ultrasonic system, reported earlier by Tumbo et al. (2002), was used to measure canopy volumes of the selected (15 dense and 15 light) citrus trees. It consisted of a microprocessor and 10 ultrasonic sensors (transducers or ranging units) that were mounted on a vertical mast. The sensors pulsed at 40 kHz and the signals had a divergence angle of 6 degrees. They were fired sequentially in groups of (1-5-9), (3-7), (2-6-10), and (4-8), respectively. With this firing order and a sensor spacing of 0.46 m, the distance between simultaneously firing sensors was 1.84 m. This sequential firing order was designed to prevent the signal interference between adjacent sensors. Ultrasonic readings (8-bit digital counts) were downloaded continuously for checking the function of the sensors. Each sensor individually measured the distance to the foliage (fig. 1). The system was hauled with a tractor. During data acquisition, the sensors were aligned with the center line between the rows.

The system was moved at three ground speeds of 1.6, 3.4, and 4.7 km/h to quantify half canopy volumes of the selected trees on the North and South sides of the tree rows. The measurements were replicated three times within each ground speed. Tractor engine rpm setting and gear selection controlled the speeds. These parameters were determined by prior measurements of travel time on a 30-m distance in the field conditions (six replications).

A laptop computer acquired the readings from the ultrasonic system through RS 232 communication ports. A DGPS receiver (Trimble 132 AgGPS) was used to match the ultrasonic data with locations of the measurements. Data were sent to communication port at approximately 5.1 samples per second (each sample consisted of readings from 10 sensors). The rate was verified experimentally. The sensors' 8-bit digital counts represented distances from the sensors to the canopy (D_o, fig. 1). These readings (0-255) were converted to distances from periphery of canopy to the center of the tree (D_d) in 2.5-mm resolution. The distances could be affected slightly by the mast vibration as well as roll and yaw of the sensors during travel. The mast was tide up with ropes in four sides to minimize the sensor vibration and the error in ultrasonic distance measurements. Using, the tractor speed, distance from the periphery of canopy to tree row line ($D_{d,}$ fig. 1), sampling rate, and sensor spacing canopy volume of each side of a tree was computed from the following equation (Tumbo et al., 2002):

$$U = \sum_{1}^{n} \frac{SD_d D_s}{S_r} \tag{2}$$

where

U = ultrasonic canopy volume of one side of a tree (m^3)
S = tractor ground speed (m/s)
D_d = distance from the periphery of canopy to tree row line (m)
D_s = sensor vertical spacing (m)
S_r = ultrasonic sensor sampling rate (5.1 samples/s)
n = number of scans (samples) per tree

D_d was obtained by subtracting D_o (distance from sensor to the periphery of the foliage, i.e., ultrasonic readings) from D_c (distance between sensor and tree row line). In equation 2, D_d represents summation of all D_d values in one scan (sample). D_c was assumed to be 3 m. In preliminary studies, D_o was "ground truthed" by comparing ultrasonic distances of each sensor with manual measurements. The total volume of a tree was obtained by summing up the volume of north and south sides of the tree. The measurements were not corrected for temperature effect.

DATA ANALYSIS

The difference between ultrasonic and manual volumes was used to characterize the performance of the ultrasonic system. This difference could be influenced by the accuracies of both ultrasonic and manual measurements. Repeatability of tree volume measurement was examined by the range of the differences among three replications of each tree. Manual tree canopy volumes, computed with equation 1, were used as the basis for evaluating ultrasonic volumes. The following equation was used to calculate the difference between ultrasonic and manual volumes. This difference includes errors in both measurements.

$$\text{VD} = \frac{U_v - M_v}{M_v} \times 100 \tag{3}$$

where

VD = difference between ultrasonic and manual volumes (%)
U_v = ultrasonic volume (m^3)
M_v = manual volume (m^3)

The mixed procedure (PROC MIXED) was used to analyze the data and means were compared using PDIFF option of LSMEANS statement. Matching means were separated by the t-test at 5% level of significance and variability in data was expressed with standard error (SE). The correlation procedure (PROC CORR) (SAS Institute, 1990) was used to find the relationship between ultrasonic volume difference and manual tree volume, maximum height, and diameter of trees.

RESULTS AND DISCUSSION

REPEATABILITY OF ULTRASONIC MEASUREMENTS

Results indicated that the difference between ultrasonic and manual volumes of individual trees ranged from –17.37% to 28.71%, at the 95% confidence level. Ninety five percent of the ultrasonic measurements were repeatable within –12.7% to 30.9% of the manual volume. The range of the difference varied for dense and light trees as explained in the following section. It should be noted the assumption of a constant distance of 3 m between the sensors and tree row line (D_c) may introduce some error. This is because in field conditions some deviation from the straight path as well as the roll and yaw of the sensors (due to rough terrain) could affect the distance measurements. Nonetheless, these effects are partially accounted for by three replications.

EFFECT OF CANOPY DENSITY

Dense trees were more uniform in size (height, diameter, and volume) than light trees (fig. 2). The variation in size of light trees might be attributed to poor health and partial defoliation of the trees. The dense and light trees had significantly different VDs (difference between ultrasonic

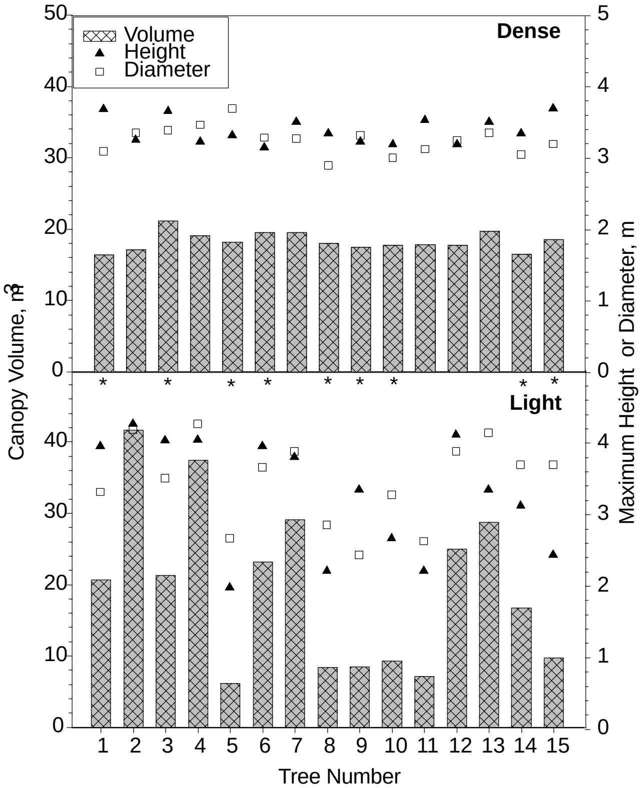

Figure 2. Manual canopy volume and maximum height and diameter of the selected dense and light trees. Dense trees identified by * indicate more missing canopy foliage on south side than north side of the trees.

and manual volumes) at 1.6 and 3.4 km/h speeds, but not at 4.7 km/h (fig. 3). Overall the difference (VD) was significantly higher (7.1% vs. 4.3%) for light trees (fig. 4). Ultrasonic volumes expressed as percentage of manual volumes also showed higher ranges in light trees (table 1). This increase in the range might, in part, be due to the large variation in tree height, diameter, and volume of light trees. The difference between ultrasonic and manual volumes (VD) showed some negative correlation with maximum height, maximum diameter, and manual volume in light trees (fig. 5). The

Table 1. Ultrasonic volume as percentage of manual volume.

Foliage Density	Speed (km/h)	Min.-Max. (%)	Mean (%)	Std Error (%)
Dense	1.6	89.38 - 118.32	103.74	1.09
	3.4	87.27 - 118.97	103.04	0.97
	4.7	89.13 - 119.30	105.97	0.99
Light	1.6	93.23 - 135.45	107.64	1.46
	3.4	89.44 - 148.11	107.88	1.85
	4.7	79.80 - 154.48	105.75	2.98

results indicate that groves containing light trees and replants have lager VDs in ultrasonic measurements.

Effect of Ground Speed

Within each density, mean difference between ultrasonic and manual volumes were not significantly different for three ground speeds (fig. 4). However, increasing ground speed could affect variability of the measurements. This affect was evident in light trees (fig. 4, table1). The reason might be attributed to reduced number of scans per tree and more openings in the canopies. The openings in the canopy and light density of foliage could weaken the signal echo and adversely affect the measurements. This result does not fully agree with that of Giles et al. (1988) who reported no effect of ground speed (2 to 6 km/h) on performance of ultrasonic sensors. The discrepancy might be related to the canopy density of the scanned trees. At any rate, in groves containing light trees or replants, it might be prudent to reduce ground speed (increase number of scans per tree) to obtain more accurate measurements. Even at very slow speed, ultrasonic measurement of canopy volume could be substantially faster than manual measurement. The latter requires an estimated time of 18 to 26 day/ha.

Effect of Tree Sides

The results showed differences in ultrasonic volumes of two sides (north and south) of the tree in both dense and light density canopies (fig. 6). The differences between volumes the two sides were 0.45% to 15.45% and 0.63% to 62.40% in dense and light trees, respectively. Corresponding differences among replications were 0.23% to 21.12% and 10.80% to 20.12%. According to Syvertsen and Smith (1984) higher

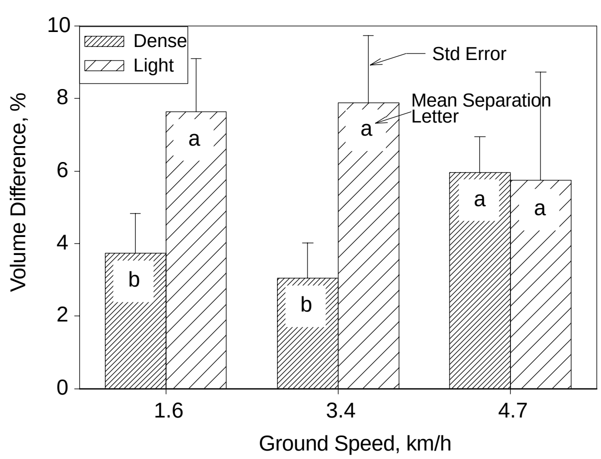

Figure 3. Effect of canopy density on the difference between ultrasonic and manual volumes at three ground speeds.

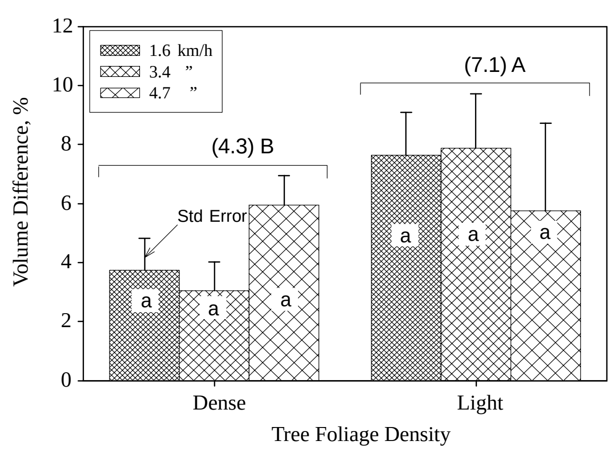

Figure 4. Effect of ground speeds on the difference between ultrasonic and manual volumes. Upper case and lower case letters represent mean separation between densities and speeds, respectively (at the 5% level).

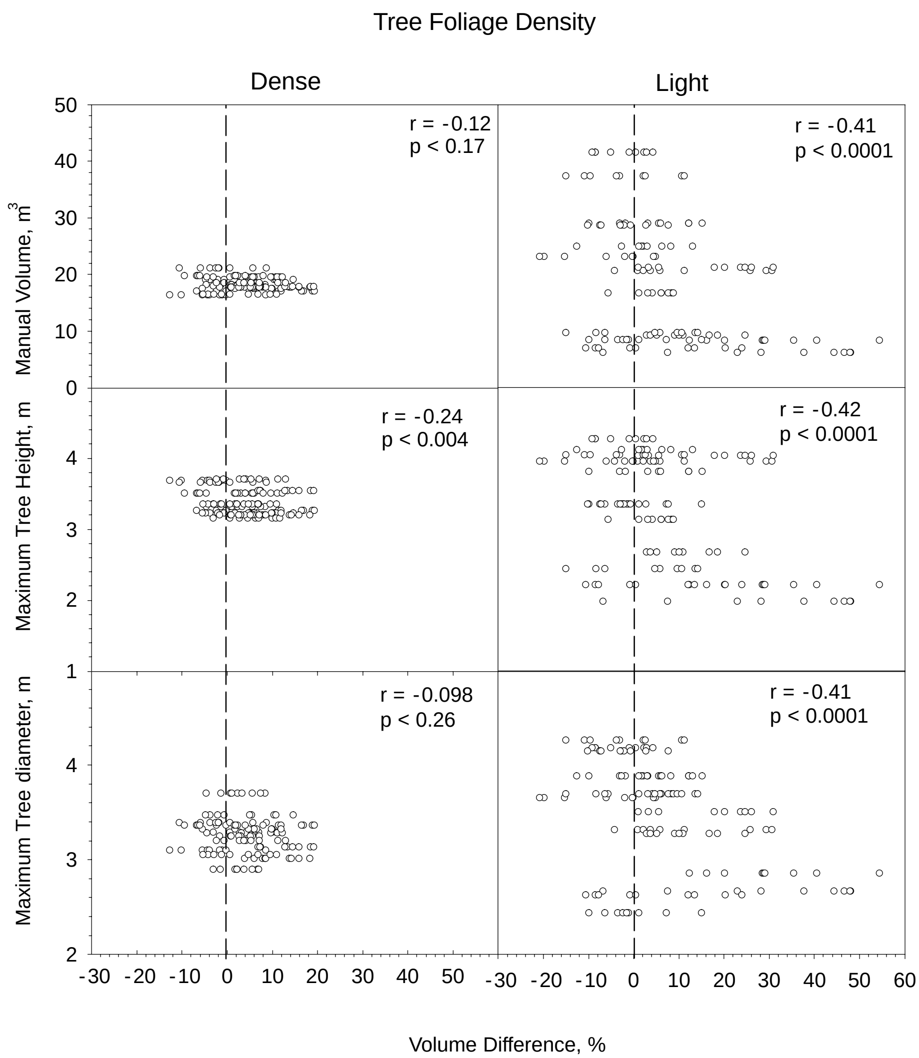

Figure 5. Relationship between tree parameters (volume, height, and diameter) and the difference between ultrasonic and manual volumes (VD).

exposure of the south side of the tree to sunshine (higher interception of photosynthetically active radiation) could increase the foliage volume of the south side. However, while the volume of the south side was higher than the north side in light trees the trend was reverse in dense trees (fig. 6). Nevertheless, the difference between north and south side volumes was significantly different in both groves (fig. 7). This trend reversal could, in part, be due to some deviation from the intended driving path (change in distance between the sensors and tree row line), as the scanned rows were located at opposing edges of two groves. Another explanation might be the presence of missing foliage on the south sides of few dense trees as identified in figure 2.

In earlier studies (Li et al., 2002; Tumbo et al., 2002; Giles et al., 1988), tree canopies have been assumed as symmetrical and canopy volume of the entire tree has been computed from ultrasonic measurement of one side only. However, in light of the above results, it appears that the canopies are generally asymmetrical; therefore the trees should be scanned from two sides to obtain more accurate results. Furthermore, when the system is used in bedded groves (with alternating bed and ditch rows) it should be ensured that the sensors would scan the entire height of the tree in the ditch side. In this grove condition, the distance from the sensor to the center of canopy should also be corrected for alternate row spacings.

CONCLUSION

- The difference between ultrasonic and manual volumes ranged from –17.37% to 28.71%, at the 95% confidence level. Ninety five percent of the ultrasonic measurements were repeatable within –12.7% to 30.9% of the manual volume.
- The groves containing light trees and replants had higher difference between ultrasonic and manual volumes than groves with dense trees.
- There was no significant effect of ground speed (1.6, 3.4, and 4.7 km/h) on the difference between ultrasonic and manual volumes. However, in light trees, variability of the measurements increased with ground speed.
- The two halves (north, south) of the trees had different volumes, therefore, trees should be scanned from two sides.

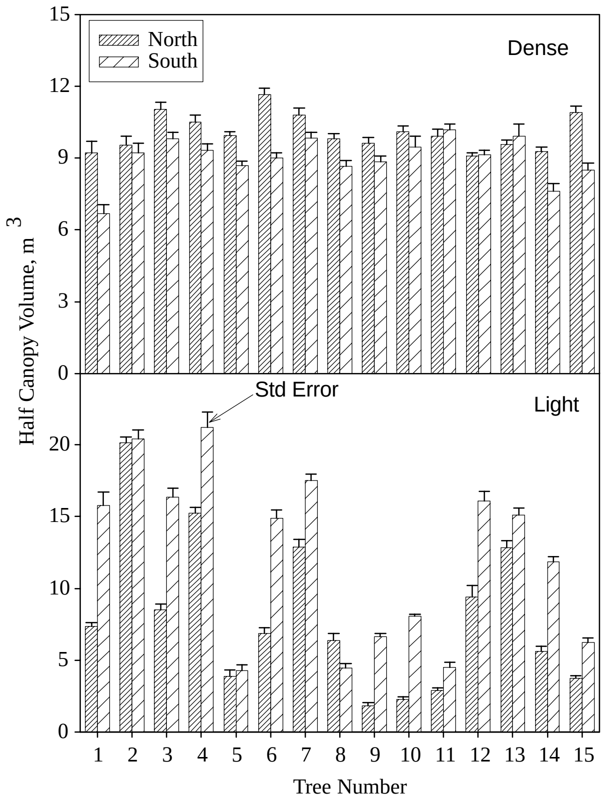

Figure 6. Ultrasonic volumes of the North and South halves of tree canopies.

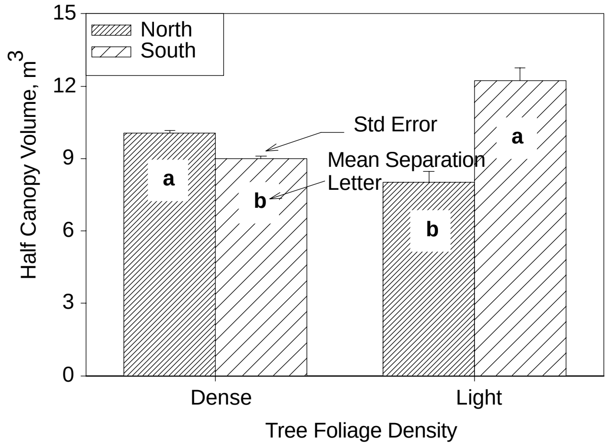

Figure 7. Comparison between ultrasonic volumes of the north and south halves of trees.

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