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Performance of an Ultrasonic Tree Volume Measurement System in Commercial Citrus Groves

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Abstract. Florida growers have planted citrus groves at varying spacings to improve resource efficiency and to optimize fruit production for maximum economic return. Four commercial groves with different row spacings and tree ages were scanned with a Durand-Wayland ultrasonic system to measure and map tree volumes and to examine the effect of row spacings and tree ages on ultrasonic measurements. The ultrasonically measured volumes (UVs) were compared with manually measured tree volumes (MVs) of 30 trees in each grove to examine the performance of the ultrasonic system.

The ultrasonic system measured tree volumes reliably in different groves with an average prediction accuracy (APA) $>90\%$, and correlation with manual measurement of $R^2 = 0.95$–0.99. Standard error of prediction and root mean square errors were relatively higher in widely spaced old groves than closely spaced young groves. The ultrasonically sensed tree volume map showed substantial variation in canopy volumes (0–240 m^3 $tree^{-1}$) within the grove. Therefore, the use of ultrasonic systems is a better option to quantify and map each tree volume rapidly (real-time) for planning site-specific management practices accurately in commercial groves and for estimating fruit yield.

Keywords: citrus, DGPS, GIS, row spacings, ultrasonic sensors

Introduction

Florida citrus growers have planted trees at increasingly closer spacings (higher tree densities) since 1960 (Commercial Citrus Inventory, 2002). Factors motivating increased planting density include increased land values and taxes, a decreasing availability of desirable citrus land, improved management techniques with greater resource efficiency in higher density plantings and the need for earlier fruit production resulting in earlier economic return (Reitz, 1978). Closely spaced trees have higher fruit production and net returns than widely spaced groves at an early stage (Koo and Muraro, 1982). However, early yield advantages tend to diminish as the trees increase in size and competition for space, light, water and nutrients becomes more intensified in closely spaced groves (Savage, 1965; Carry, 1977; Tucker *et al.*, 1991). The results of numerous studies indicated that, when practised in moderation, higher planting densities (closer spacing) and techniques to control tree size can be of considerable benefit, not only in ensuring high yields during early life of trees but also in increasing the efficiency of harvesting and spraying operations (Childers, 1978; Wheaton *et al.*, 1995). Therefore, proper control of tree size is essential to the success of closely spaced groves (Tucker and Philip, 1967).

Whitney *et al.* (1994) reported that fruit production, soluble solids and net returns were associated with tree canopy volume for moderately vigorous rootstock with 6.0×2.5 m spacings and 5.5 m height. Schumann *et al.* (2003) also found that yield increases as tree canopy volume (ultrasonically sensed) increases. Whitney *et al.* (1999) described yield maps showing spatially variable yield correlated to tree canopy size determined from aerial photography. Most Florida citrus groves are still managed as large contiguous uniform blocks, despite significant internal variation, mainly in tree canopy size. The spatial variation of tree size may decrease resource use efficiency (Schumann *et al.*, 2003). Therefore, it is important to measure and map tree sizes for site-specific application of the grove production and protection inputs in order to increase net economic returns.

Manual measurement of tree volume using many tree dimensions (Albrigo *et al.*, 1975; Wheaton *et al.*, 1995) is laborious and time consuming. One possible reliable and rapid method is ultrasonic-based tree size measurement (Giles *et al.*, 1988; Tumbo *et al.*, 2002; Zaman and Salyani, 2004). Ultrasonic sensors have been used for the control of agrochemical application rates in sprayers and fertilizer spreaders for tree crops for two decades.

Advances in DGPS technology and the rapid evolution of portable laptop computing power have offered new opportunities for enhanced processing and mapping of ultrasonically sensed orchard/grove data. Schumann and Zaman (2005) developed and evaluated a Windows-based software application for a 10-sensor Durand-Wayland ultrasonic tree size measurement system (Durand-Wayland, Inc., Lagrange, Ga, USA) and Trimble (Trimble Navigation Limited, Sunnyvale, CA, USA) AgGPS132 DGPS that could allow real-time sensing, monitoring, calculation, storage and mapping of citrus tree canopy volume and height rapidly and reliably. Data and maps generated by such a sensor system could be used for site-specific management practices within a grove.

Ultrasonic sensors measure horizontal distances from a given sensor to the nearest foliage by way of an ultrasonic wave sent to a target (foliage), which would reflect the wave back to the sensor. Canopy volume was calculated based on distance measurements of several vertically mounted sensors (Tumbo *et al.*, 2002; Schumann and Zaman, 2005). Ultrasonic sensing is affected by several factors including the target surface, size, angle and the distance from the sensor. The returning echo will be stronger if distance is shorter from the sensor to the foliage. A strong echo, which is the result of a shorter distance, will increase the accuracy of ultrasonic distance measurements (Shirley, 1989). Therefore, as the distance increases from sensor to foliage in widely spaced citrus tree rows, the returning echo will be weaker, possibly leading to greater errors in ultrasonically measured tree volumes.

Because of the lack of information about the appropriate row spacings for optimal management practices to improve fruit production, Florida growers have continued to plant citrus groves at various row spacings. The impact of differing grove architectures on tree size sensing systems is unknown. Therefore, the objective of this study was to determine the performance of an ultrasonic system in four commercial citrus groves with different row spacings and different tree ages for real-time tree volume measurement and mapping.

Methods and materials

Grove history

Four citrus groves with different row spacings and tree ages [N-40 (G-1), Southern farms (G-2), Revell (G-3) and Gapway (G-4)] were selected in Florida State to measure and map tree volumes in June 2003 (Table 1). The tree canopies were not topped or hedged at the time of measurement with the exception of some parts of the Revell grove.

Thirty trees were selected randomly in each grove for manual tree volume (MV) measurements to compare with ultrasonically measured tree volumes (UVs) to cover the different sizes of trees within the groves (Figure 1). Trees were positioned from a digital aerial photograph (LABINS, 1999) of the groves using a Garmin XL12 Global Positioning System (GPS; Garmin International Inc., Olathe, Ks, USA.) and Fugawi moving map software (Northport Systems Inc., Toronto, Canada) on a laptop computer. The canopies of selected trees were not touching each other. The locations of selected trees were mapped on the grove aerial photographs with the G-4 map presented as an example (Figure 1).

Manual tree volume computation

A digital pole (Senshin Industry Co., Ltd. Japan) and measuring tape were used to measure the height and diameters of selected trees to compute the MV. The formula used for MV was based on one-half of an ellipsoid considering canopy diameters parallel and perpendicular to the row (near ground level) and maximum canopy height (Wheaton *et al.*, 1995; Tumbo *et al.*, 2002; Schumann and Zaman, 2005).

Ultrasonic tree volume measurements

The volume of each tree was measured real-time in all groves using the ultrasonic system (Durand-Wayland, Inc., Lagrange, Ga, USA) equipped with a Trimble AgGPS132 DGPS (Trimble Navigation Limited, Sunnyvale, CA, USA) using coast guard beacon correction in June 2003 and customized software developed at the University of Florida (Schumann and Zaman, 2005). The system consisted of a microprocessor controlling 10 ultrasonic sensors that were mounted at 0.6 m increments (D_S) on a vertical PVC mast (Figure 2). Sensor 1 was nominally 0.6 m above ground level and sensor 10 was 6.0 m high. The mast was mounted on a custom trailer that was pulled by a pickup truck (Figure 3). The system was moved at an average ground speed of 1.3 m s^{-1} (S_i) to get adequate vertical and horizontal

Table 1. Brief description of groves

Grove	City/County	Location	Row-orientation	Variety	Rootstock	Row-spacings (m)	Grove age (years)	Area (ha)
(G-1)	Lake Alfred/Polk	28.12996° N, 81.71818° W	N-S	"*Hamlin*"	*Swingle*	7.6×4.6	11	1.74
(G-2)	Venus/Highlands	27.05206° N, 81.53771° W	N-S	"*Valencia*"	*F80–3*	7.6×3.8	12	34.41
(G-3)	Bowling Green/Hardee	27.63089° N, 81.82467° W	E-W	"*Hamlin*"/"*Valencia*"	*Sour orange*	9.1×4.6	> 40	45.00
(G-4)	Ft-Meade/Polk	27.74789° N, 81.69509° W	N-S	"*Valencia*"	*Carizzo*	10.7×5.3	> 40	16.19

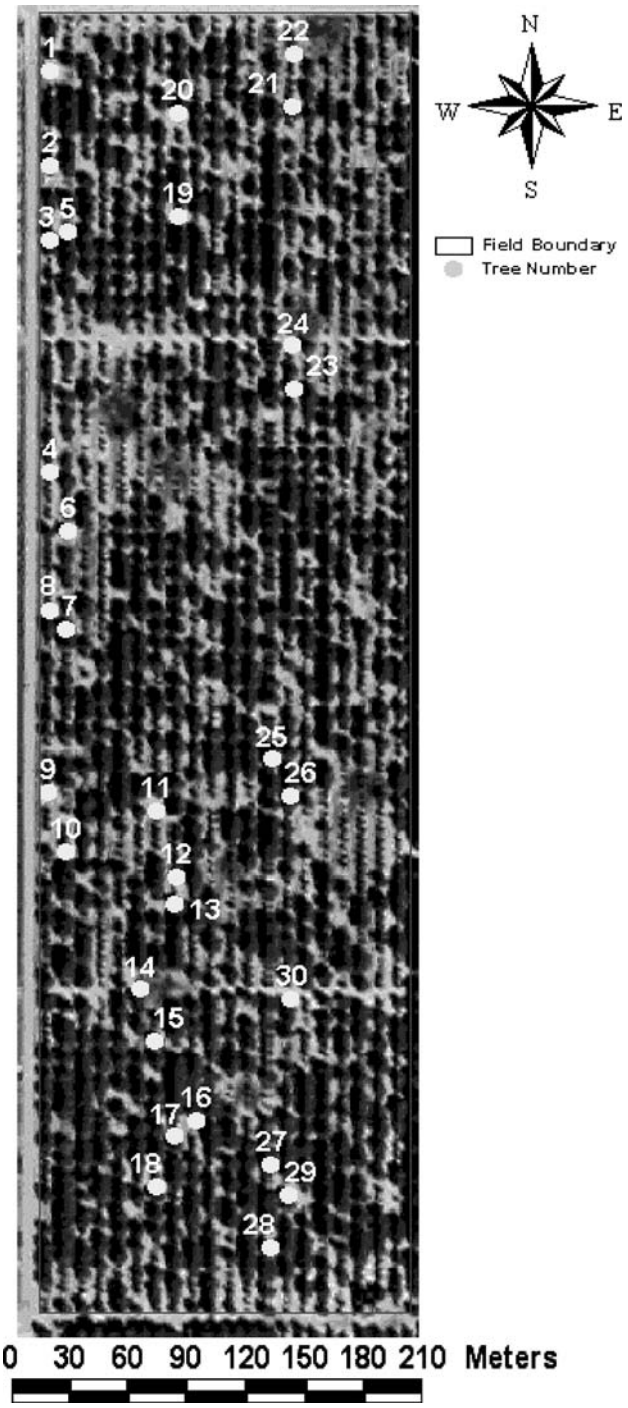

Figure 1. Aerial photograph of the G-4 grove, showing tree number and locations (30 selected trees) and survey boundary.

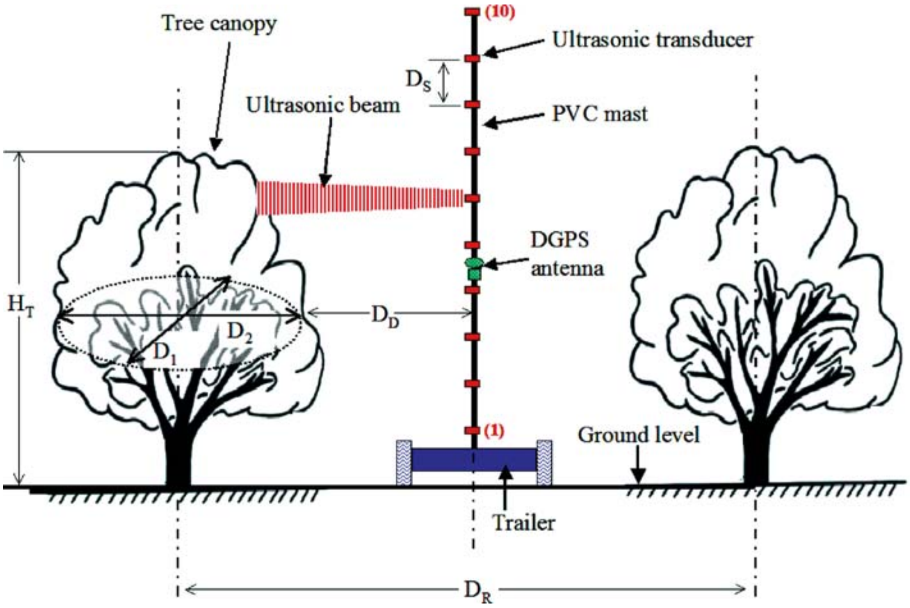

Figure 2. Schematic layout of the ultrasonic transducer system and manually measured tree dimensions used for calculation of tree canopy volumes in a citrus grove.

samples per tree after each second (1 Hz). In this configuration, each transducer would measure the horizontal distance (D_D) between the mast and the nearest peripheral foliage of the tree canopy (Figure 1). System design and other limitations such as the speed of sound (346 m s^{-1} in air at 25°C) resulted in a complete 10-sensor scan rate of 5.1 Hz. The following equations were used to calculate ultrasonic tree canopy volume.

$$A_C = 2\sum_{i=1}^{i=10} (0.5D_R - \overline{D}_{Di})D_S \tag{1}$$

Where:

A_C = cross-sectional canopy area (m^2)
D_R = tree row spacing (m)
$\overline{D}_{Di}$ = *i*th mean distance (averaged for 1 s) measured from the *i*th ultrasonic transducer to the tree canopy foliage (m)
D_S = distance between ultrasonic transducers (m)

$$V_{TC} = \sum_{i=1}^{i=n} tS_i A_{Ci} \tag{2}$$

V_{TC} = canopy volume for a single tree (m^3 $tree^{-1}$)
n = number of complete averaged scans per tree ($tree^{-1}$)
t = time interval for one complete averaged scan (s)
S_i = ground speed at the *i*th averaged scan (m s^{-1})
A_{Ci} = *i*th cross-sectional tree canopy area (m^2)

Figure 3. Vehicle and trailer with vertical array of 10 ultrasonic transducers and DGPS used to measure tree volumes.

The technical design of the system (hardware and software) and detailed procedures for the measurement and mapping of tree volume real-time in a grove were reported earlier in Schumann and Zaman (2005).

Some groves are developed into hedgerows where individual tree volume quantification is difficult. A semi-automated method using the Arcview extension "Orchard" (Lincoln Ventures Ltd, Hamilton, NZ) is applicable for grove canopies with strongly developed overlapping between trees (hedgerows). This Arcview extension could be used to generate regular grid of tree spaces for every tree in the grove and the sum of products of cross-sectional canopy areas and corresponding ground speeds for each tree space could be readily computed with the "summarize zones" function in Arcview. The resulting sum represented canopy volume in cubic meters per tree space. The detailed procedure was described in Schumann and Zaman (2005).

Data analysis

The datasets (MVs and UVs of selected trees) of all groves were analyzed using classical statistical techniques with SAS software (SAS Institute, Cary, NC, USA) to obtain minimum, maximum and mean values. The MVs and UVs of selected trees in each grove were compared by the *t*-test at a 5% level of significance. Six trees; two trees (# 1 and 14) from G-3 and four trees (# 2, 6, 15 and 25) from G-4, were removed from the datasets because they were taller than the height of the ultrasonic sensor boom i.e. 6 m.

The linear regression method was used to test the relationship between MVs and UVs of selected trees. Calibration equations/models, coefficients of determination (R^2), average prediction accuracy (APA), standard error of prediction (SEP) and root mean square error (RMSE) were calculated to examine the performance of the system based on the following equations (Kramer, 1998; Borhan *et al.*, 2004) using SAS and Excel (Microsoft Office 2000) spreadsheets. The performance of a model was based on high APA (%) and R^2 and lower SEP (m^3) and RMSE (m^3).

The calibration model of each grove was cross-validated using datasets of the other three groves in an Excel spreadsheet. A combined model was developed using the datasets from all four groves and validated with the same dataset. Then the combined dataset was divided into two datasets randomly to develop and validate the model (50% data for calibration and 50% for validation model). The R^2, APA, SEP and RMSE were calculated for calibration and validation models to examine the performance of the ultrasonic system. The survey data files of DGPS, MVs and UVs were imported into ArcView GIS software for mapping.

Results and discussion

The UVs were not significantly different from MVs in each grove (Table 2). Overall mean UVs were consistently higher (~5%) than MVs in all groves. The ultrasonic sensors would detect and measure distances to some extended individual branches on the sides and at the top of the tree canopy because of a wide divergence angle, resulting in over-predicting canopy volumes compared to those calculated from manual measurements. The manual measurements were made to calculate canopy volume considering the outer peripheries of canopy and ignoring individual extended branches. These results are in agreement with the findings of Li *et al.* (2002).

The linear regressions between UVs and MVs were highly significant (R^2 varied from 0.95 to 0.99) and the APA was >92% in all groves (Table 3). The results indicated that the ultrasonic system performed better, with lower SEP and RMSE, in young groves (G-1 and G-2) with closer row spacings, where the trees were relatively more dense, healthy and uniform than the old groves (G-3 and G-4) having resets and partially defoliated trees (Table 3). The smooth and uniform targets of young trees provided relatively better reflectance surfaces to produce stronger returning echoes than rough, irregular targets (Shirley, 1989). The calculated SEP and RMSE values were relatively higher for the G-3 model than other grove models (Table 3), possibly due to the greater tree size range in G-3. Partial defoliation of old and diseased trees might also be the cause of more errors in ultrasonic measurements in G-3. Excessive soil copper (originating from fungicidal sprays in G-3 over many years) probably induced iron deficiency in citrus trees resulting in disorders of the foliage, stunting and thinning of tree canopies in the grove. The openings in the

Table 2. Summary statistics for manual and ultrasonic tree volumes in different groves

Grove (*n*)	Method	Minimum (m^3)	Maximum (m^3)	Mean (m^3)	*t*(D.F.) *F*-prob
G-1 (30)	*M*	4.00	26.28	13.84	0.87(58)
	U	4.80	27.90	15.13	0.39
G-2 (30)	*M*	6.28	38.50	19.61	0.73(58)
	U	7.00	40.10	21.43	0.47
G-3 (28)	*M*	6.06	195.75	81.30	0.31(54)
	U	6.37	208.00	84.95	0.76
G-4 (20)	*M*	26.88	178.19	72.32	0.20(38)
	U	28.20	187.60	75.25	0.84

n = number of trees.

M = Manually measured volume.

U = Ultrasonically measured volume.

canopy foliage could weaken the ultrasonic echo and adversely affect the ultrasonic distance measurements. In previous studies, the difference between MVs and UVs was significantly higher for partially defoliated trees than dense trees (Zaman and Salyani, 2004). The results of this study suggested that the frequency of scans per tree should be increased in groves containing partially defoliated trees.

The cross-validation results of calibration models using different grove datasets indicated highly significant correlation between MVs and UVs in all groves (R^2 ranged from 0.95 to 0.99). However, results of the G-1 and G-2 validation model revealed that the calculated SEP and RMSE were relatively higher and accuracy was relatively less using the G-4 dataset (Table 4). When the very young trees (resets) were removed from the G-4 data set, the accuracy of G-1 and G-2 validation models increased by ~15% and RMSE and SEP were also decreased (Table 4). The very small size trees in some parts of the G-4 were from resetting after tree loss from freezes and disease (John Strang, personal communication). The ultrasonic system either under-predicted the volume for resets or completely ignored the resets, (where UV = 0 or nearly 0 m^3, while MV = varied from 1.0 to 2.0 m^3 per tree). The reason for the missing UV or measurement of partial UV of resets might be that the sensors could not detect the presence of a replant from large distances (10.67 m spacing between rows in G-4). The second reason might be attributed to a lower number (2 or 3) of active transducers and also a reduction in number of scans per tree for resets at an average ground speed of 1.3 m s^{-1}. Whitney *et al.* (2002) found that the

Table 3. Development of calibration equations/models using the ultrasonic volume (UV) and manual volume (MV) for different groves

Grove	Equation	*n*	R^2	APA (%)	SEP (m^3)	RMSE (m^3)
G-1	MV = 0.925(UV)–0.152	30	0.95***	92.31	1.29	1.27
G-2	MV = 0.932(UV)–0.367	30	0.97***	92.94	1.65	1.63
G-3	MV = 0.939(UV) + 1.481	28	0.99***	96.59	2.66	2.61
G-4	MV = 0.951(UV) + 0.852	26	0.99***	94.51	2.02	1.98

*** very highly significant ($p < 0.001$).

Table 4. Cross-validation of calibrations equations/models using different grove datasets

	Grove (*n*)	R^2	APA (%)	SEP (m^3)	RMSE (m^3)
Model (G-1) ($n = 30$)	G-2 (30)	0.97***	93.01	1.65	1.62
	G-3 (28)	0.99***	96.23	2.74	3.93
	G-4 (26)	0.99***	81.94	2.44	3.44
	G-4 (20)†	0.99***	95.86	2.32	3.38
Model (G-2) ($n = 30$)	G-1 (30)	0.95***	92.52	1.29	1.27
	G-3 (28)	0.99***	97.11	2.66	3.23
	G-4 (26)	0.99***	80.15	2.11	2.80
	G-4 (20)†	0.99***	96.72	2.09	2.71
Model (G-3) ($n = 28$)	G-1 (30)	0.95***	81.86	1.29	2.25
	G-2 (30)	0.97***	84.10	1.65	2.58
	G-4 (26)	0.99***	92.39	2.10	2.06
	G-4 (20)†	0.99***	96.57	2.08	2.04
Model (G-4) ($n = 26$)	G-1 (26)	0.95***	85.25	1.30	1.89
	G-2 (26)	0.97***	86.35	1.65	2.29
	G-3 (26)	0.98***	96.83	2.71	2.68
Model (G-4) ($n = 20$)†	G-1 (30)	0.94***	86.56	1.30	1.72
	G-2 (30)	0.97***	87.40	1.66	2.16
	G-3 (28)	0.99***	97.03	2.73	2.69

† Six resets were removed from the data set of G-4.

*** very highly significant ($p < 0.001$).

correlation between MV and UV volume was adversely affected by reducing the number of transducers. In widely spaced groves, containing resets, it might be prudent to increase sampling frequency (both reduce ground speed and spacing between sensors) to obtain more precise measurements.

The RMSE and SEP values for G-1 and G-2 validation models using the G-3 dataset were also relatively high and APA was low (Table 4). The reason might be the partial defoliation of trees in G-3 as described above.

Results in Table 5 indicate highly significant correlation ($R^2 = 0.99$) between MVs and UVs for calibration and validation models using the datasets of all four groves. The average predicted accuracy (91%), SEP and RMSE values (1.13 and 1.13 m^3, respectively) of the combined model using all grove datasets suggest that the existing ultrasonic system could be used for real-time measurement and map the tree volume

Table 5. Development and validation of a calibration model using all four groves data sets

Model (*n*)	Method	Min–Max (m^3)	Mean (m^3)	*t*(D.F.) *F*-prob.	R^2	APA (%)	SEP (m^3)	RMSE (m^3)
Calibration (57)	*M*	1.46–195.75	43.91	0.24 (112)	0.99***	90.04	1.58	1.63
	U	0.00–208.00	46.31	0.80				
Validation (57)	*M*	1.05–169.68	39.26	0.30 (112)	0.99***	90.76	1.30	1.29
	U	0.19–175.20	41.38	0.76				
Combined (114)	*M*	1.05–195.75	41.58	0.38 (226)	0.99***	91.20	1.13	1.13
	U	0.00–208.00	43.75	0.76				

*** very highly significant ($p < 0.001$).

reliably and rapidly in large commercial groves with different row spacings and tree ages.

It should be noted that the errors in ultrasonically measured distances in field conditions could, in part, be due to some deviation from the intended driving path (change in distance between the sensors and the tree row line), the mast vibration as well as roll and yaw of the sensors (due to rough terrain) during travel. However, the mast was tied up with supporting ropes in four sides to minimize the sensor vibration and the error in ultrasonic distance measurements. The ground speed was monitored and measured with a Trimble AgGPS132 to compute the tree volume. Schumann and Zaman (2005) reported that DGPS could be used in grove conditions with the ultrasonic system to locate tree position for GIS mapping purposes within 1.37 m, 95% of the time. The errors in ultrasonic measurements calculated also included the errors in tree canopy volumes calculated based on manual measurements.

Tree size mapping

The four groves were surveyed to obtain the canopy volume of each tree in June 2003 using the Durand-Wayland ultrasonic system. Due to space constraints, only the survey of G-4 is discussed here.

Canopy volumes of 2980 trees were measured and georeferenced real-time, at a mean speed of 1.3 m s^{-1}, taking 4 h to complete the survey of 17.0 ha (4.25 ha h^{-1}). The UV of each tree in the grove was mapped and the locations and MVs of selected trees were overlaid on the UV map. However, four trees in G-4 (taller than 6 m) were not included in the statistical analysis as mentioned in materials and methods section. The relationships between MVs and UVs (Tables 3 and 4) support the relations identified from the map (Figure 4). The UVs in the grove ranged from 0 (missing) to 240 m^3, due to the age of the grove (>40 years), and the practice of continuous replanting (resetting) of dead, damaged or diseased trees (Strang, 2004). The substantial variation in tree volumes within the grove emphasizes the need for real-time volume measurement of each tree and mapping using an automated ultrasonic system.

Accurate, repeatable measurement and mapping of tree canopy size with an automated ultrasonic system is useful to produce nutrient prescription maps for site-specific fertilizer application on a per tree UV basis. The practical implication of uniformly fertilizing such a grove is to over-fertilize small trees or under-fertilize large trees (Schumann *et al.*, 2003). Zaman *et al.* (2005) saved 40% fertilizer with site-specific fertilization as compared to the grower's uniform rate of 270 kg N ha^{-1} y^{-1} in the same grove (G-4). Prescription map for VRT fertilization was generated on the basis of each tree UV. The application of fertilizer through VRT shows the potential to match the 32–43% rate reductions that were needed in previous Nitrogen Best Management Practices (N-BMP) studies to lower groundwater nitrate concentration to acceptable levels (Lamb *et al.*, 1999). Therefore, site-specific application of nutrients on an individual tree volume basis would improve horticultural profitability and eliminate prolonged nitrate excesses in the root zone which can potentially leach to ground water.

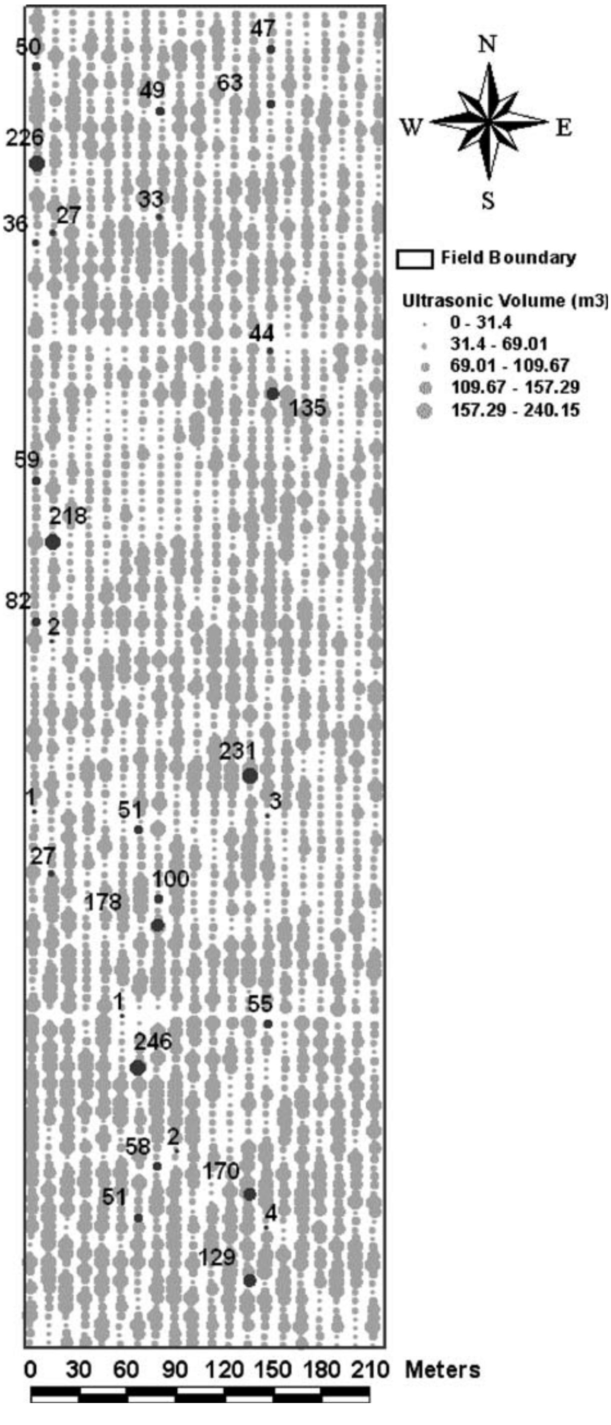

Figure 4. Ultrasonically sensed canopy volume (m^3) of each tree and the manual tree volume (m^3) of 30 selected trees (above tree locations) in G-4.

Conclusions

The results of this study indicated that an automated ultrasonic system can measure and map tree volumes in real-time rapidly and reliably in citrus groves with different row spacings and ages. The ultrasonic system performed better in young groves with closer spacings (lower SEP and RMSE) than in widely spaced old groves. These results suggest that in groves with wide row spacings and different tree ages (having substantial tree size variability), sampling frequency should be increased to obtain more precise ultrasonic measurements.

Based upon the results, it is suggested that each tree should be routinely scanned for the real-time measurement and mapping of canopy volume using the ultrasonic system. This information could be used to generate prescription maps for precise variable application of agrochemicals in the groves on a single tree basis to improve horticultural profitability and environmental protection.

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