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RELATING CITRUS CANOPY SIZE AND YIELD TO PRECISION FERTILIZATION

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***Abstract.* Modern granular fertilizer spreaders with variable rate application (VRA) capability can reduce fertilizer requirements and environmental impacts in Florida citrus groves by improving fertilizer application efficiency by up to 40%. A key component to their success is the real-time canopy sensing system which measures the size of the trees before the appropriate dose of fertilizer is dispensed. A strong relationship must also exist between the yield and tree age from which fertilizer recommendations are developed, and the measurable canopy size variables such as height, volume or ground cover that could be used by VRA fertilizer spreaders to calculate fertilizer rates. In this study, the correlations between fruit yield and ground-based ultrasonically measured canopy size, or aerial photograph-based**

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canopy dimensions and the normalized difference vegetation index (NDVI) were compared. The performance of two types of canopy sensors (ultrasonic and photoelectric) were tested using young tree targets of different sizes, representative of a citrus grove. Results showed that canopy height is an acceptable estimate of yield potential from which fertilizer rates can be calculated on-the-go using commercial canopy sensors mounted on a fertilizer spreader. Both photoelectric and ultrasonic sensor systems were capable of fast canopy sensing and 'look-ahead' precompensation that is required for accurate fertilizer dosing and placement. The fertilizer doses applied automatically to a range of young non-bearing reset tree sizes approximated the UF-IFAS-recommended rates. These results demonstrated that a well-tuned fertilizer spreader with high-speed sensors, control electronics and hydraulics can precisely fertilize any tree size from resets to mature hedgerows.

Florida citrus fertilization rates are prescribed according to tree age and yield (FDACS, 2002; Tucker et al., 1995), both of which relate to tree size. Detection of and response to single tree sizes in real time is therefore the basis for most of the variable rate application (VRA) of fertilizer to citrus groves (Schumann et al., 2006a). VRA granular fertilizer spreaders are increasingly important for improving nutrient management efficiency. In Florida citrus production, greater profitability and reduced nitrate contamination of groundwater can both be achieved with VRA spreaders by adjusting fertilizer rates to match tree size, and by not fertilizing dead or missing trees. Zaman et al. (2005) measured a 40% reduction in fertilizer consumption when VRA was used to fertilize 17 ha of variable 'Valencia' orange grove. Zaman et al. (2006a) reported that in the same grove, VRA fertilization significantly ($p < 0.05$) decreased nitrate loading from leachates leaving the root zone

compared to the uniformly fertilized trees. Mean leachate nitrate-N concentrations for all VRA treatments ranged from 1.5 to 4.5 mg/L and were below the maximum contaminant level for groundwater of 10 mg/L, while those under uniformly fertilized small and large trees were 28.5 and 14.0 mg/L, respectively. Leaf nutrient concentrations and fruit yields were not adversely affected during three years of VRA fertilization. Since successful VRA fertilization of variable citrus groves relies on single-tree fertilization, the fertilizer spreader must achieve rapid fertilizer rate changes so that the correct amount of fertilizer is dispensed to the correct tree (Schumann et al., 2006a). Schumann et al. (2006b) optimized a commercial VRA fertilizer spreader to achieve response times for rate changes ranging from 0.31 to 0.46 s. Through the use of 'look-ahead' precompensation in the rate controller, these response times were further improved to a range of 0.19 to 0.30 s, making the VRA spreader suitable for rapid single-tree fertilization, including young 'reset' trees. A key component to the success of rapid VRA fertilization is the real-time canopy sensing system which measures the size of the trees before the appropriate dose of fertilizer is dispensed by the controller. Typical commercial tree sensing systems measure only the heights of mature bearing trees by targeting an array of ultrasonic or infrared transducers to different heights of the canopy (Schumann and Hostler, 2006a). Canopy volumes are usually not measured by those types of sensor systems, although a good relationship between fruit yield and canopy volume was previously established by Zaman et al. (2006b) when using a research-grade ultrasonic system. By continuously measuring the distance between each sensor and the canopy, both tree height and canopy volume can be calculated from a parallel array of sensors (Schumann and Hostler, 2006b). However those ultrasonic systems are not ideal for fertilizer spreaders since they are less rugged and require more skill during their operation. The operation of the rugged commercial height-sensing systems in the

vertical dimension is well described and the resulting fertilizer rates are easily calculated by the VRA controller according to the number of sensors that are activated. However the relationship between fruit yield and canopy height must be confirmed before reliable fertilizer recommendations can be made, based on height alone. There is also a lack of data on canopy sensor and VRA system performance with young trees that have not closed canopy yet and would typically only activate the lowest sensor. A well-tuned canopy sensing and VRA control system should allocate fertilizer to young trees according to their horizontal dimensions, which can be estimated from the time that a lower canopy sensor remains activated at a given ground speed.

The objectives of this study were to (1) validate the recommendation for fertilizing according to tree height by correlating fruit yield with canopy dimensions, including height, sensed either on the ground or by aerial photography in a commercial 'Valencia' grove, and (2) to compare the performance of two commercial tree sensors on a VRA spreader to correctly measure tree size and accurately fertilize young citrus trees.

Materials and Methods

1. Correlation of fruit yield with tree size measurements

A commercial citrus grove near Fort Meade, Polk County, Florida (27.74789° N, 81.69509° W) was selected in 2003 for a long-term experiment testing VRA fertilization according to tree size. The 17.0- ha grove was planted with >40 year-old 'Valencia' sweet orange trees [*Citrus sinensis* (L.) Osb.] on Carrizo citrange (*Poncirus trifoliata* × *C. sinensis*) rootstock. Tree row orientation was N-S with a tree spacing of 10.7 m between rows and 5.3 m within the row (2,980 trees). The tree

canopies were not topped or hedged at the time of measurements. Extreme spatial variability of tree canopy sizes was evident in the grove because of a wide range of tree ages. Many original trees had been replaced due to damage from hurricanes, freezes and disease (Strang, 2004).

The fruit in the grove was harvested manually in 2004 by commercial pickers and placed in tubs that normally have a capacity of ten 40.9-kg Florida field boxes (0.71 m^3) and were designed to contain 0.409 Mg oranges (Whitney et al., 1999). The fruit tubs were emptied into a specialized loading vehicle, equipped with an automatic yield monitoring system, which recorded the position of each full tub (Fig. 1). We used the estimated mass of fruit per tub (0.409 Mg) for subsequent yield mapping purposes. The system comprises a data logger with microcontroller, distance and tilt sensors, cellular phone, RS232 ports, and a DGPS receiver. The complete hardware and software description of the system and procedure to measure and map the fruit yield was reported in Schumann et al. (2004).

Each tree canopy volume and height in the grove was measured during June 2003 (Fig. 2) with a Durand Wayland ultrasonic system (Durand-Wayland, Inc., Lagrange, Ga, USA) and a Trimble AgGPS132 DGPS receiver (Trimble Navigation Limited, Sunnyvale, Calif., USA) using U.S. coast guard beacon correction 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 every 0.6 m on a 6.7 m vertical mast. The mast was mounted on a custom trailer pulled behind a pickup truck. The system was moved at an average ground speed of 1.3 m/s to get adequate vertical and horizontal samples per tree to quantify each tree canopy volume. Technical design of the Durand-Wayland system (hardware and software) and a detailed procedure for the real time measurement and mapping of tree canopy volume in an orchard was reported by Schumann and

Zaman (2005), and recently an improved new ultrasonic instrument design was described by Schumann and Hostler (2006b).

High-resolution color and color-infrared aerial photographs of the citrus grove in 2004 were obtained from the Internet (LABINS, 2004) and processed with an Arcview 3.2 (ESRI, Redlands, Calif.) geographic information system (GIS) software package. A normalized difference vegetation index (NDVI) was calculated from the infrared and red bands of the color-infrared image in order to enhance the vegetation pixels and reduce the tree shadows. The NDVI values were scaled to a percentage where 100% was the maximum NDVI value calculated in the grove. A binary image was then created by thresholding the NDVI image so that only the tree canopy pixels were selected and percentage ground area covered by canopy could be calculated from the two areas of the image (Fig. 3).

Using the GIS, 40 equal-sized rectangular 'plots' were superimposed onto the fruit yield, tree size, and aerial photography data (Figs. 3-4). For each plot, tree canopy volume per hectare, average tree height, average NDVI, percentage canopy cover, and total fruit yield per hectare were calculated. The correlation of each variable with fruit yield was assessed by fitting least squares regression models and by comparing the resulting coefficients of determination (R^2).

2. Comparison of two canopy sensor systems on young trees

A 2.7-Mg capacity split-chain, spinner-disk VRA fertilizer spreader (M&D, Arcadia, Fla.) and its powering John Deere 5525 tractor (John Deere, Moline, Ill) were instrumented to gather spreader performance data from two canopy sensor systems. The spreader was configured for independent delivery of granular fertilizer to two rows of trees (left and right sides), using a dual-channel

DICKEY-John Land Manager II VRA controller (DICKEY-John, Auburn, Ill.) described by Schumann et al., 2006b. A commercial ultrasonic tree canopy sensor system (TreeSee[®], Roper Growers Cooperative, Winter Garden, FL) with six transducers (3 per side), a control box and a wheel rotation encoder for measuring ground speed, was installed on the fertilizer spreader (Fig. 5). A second tree canopy sensor system was installed on the spreader using eight commercial photoelectric sensors (QMT-42, Banner Engineering Corp., Minneapolis, MN), connected to an experimental control box. A differentially corrected global positioning system (DGPS) receiver (iSPEED[®], DICKEY-John, Auburn, Ill.) was used for measuring ground speed (Fig. 5). The construction and configuration of the photoelectric sensor system were described by Schumann and Hostler (2006a). The outputs from both canopy sensor systems were connected to the boom section switch inputs of the Land Manager II VRA controller.

For this experiment, young trees in a citrus grove were simulated with flat rectangular plastic sheet targets of variable widths (0.91, 1.82, 2.74, 3.65 m) and fixed height (2.0 m) placed on open level ground. Targets were small enough to be detected only by the lowest sensor in the left-hand sensor array, which was aimed at a tree canopy height of about 1.0 m. Data were collected separately for each target size, using three targets replicated three times. The targets were spaced 4.56 m apart to represent a typical 7.6 x 4.56-m tree spacing in an orange grove. An annual fertilizer nitrogen (N) rate of 202 kg/ha/y, applied as four equal N splits of 50.5 kg/ha was assumed for this study. Each split N application therefore equated to 336 kg/ha of fertilizer material, assuming a 15% N concentration. The VRA controller was calibrated with granulated clay used as fertilizer filler material and then programmed to assign 50% of the full fertilizer rate (168 kg/ha) to the lowest sensor. Tests were conducted at two ground speeds (1.34 m/s and 1.92 m/s), driving past the targets

at a distance of 3.8 m (half a row spacing). The granular clay dispensed from the conveyor chain during each test run was collected into a stainless steel calibration container and weighed on a digital scale. Weights of granular clay were averaged to represent the amount of fertilizer dispensed to one tree.

Results and Discussion

1. *Correlation of fruit yield with tree size measurements*

Average fruit yield mapped in the 'Valencia' grove in 2004 was 33.6 Mg/ha, with a minimum of 18.1 Mg/ha and a maximum of 54.3 Mg/ha (Fig. 6). Since citrus fertilizer recommendations are based partially on fruit yield (Tucker et al., 1995), the 3x range in fruit yield obtained from different parts of the grove would justify a range of variable fertilizer rates of at least 2x (50% to 100%, as achieved by the array of 3 to 4 canopy sensors). Tree canopy volumes measured ultrasonically in 2003 showed a maximum tree-to-tree spatial variability of about 100x (Fig. 7). Tree size variability was much higher than yield variability because the yield map zones represent the average yield collected from many different sizes of trees in each zone. The method of yield mapping currently implemented for manually harvested fruit does not allow single tree yield estimation. There were three distinct main populations of trees in the grove, discernible by the bell-shaped curves in the histogram of tree canopy volumes (Fig. 7). The age of this grove and the combination of many different tree ages contributed to the enormous size ranges observed. Consequently, the range of fertilizer adjustment needed for variable rate application should be more than 2x when based on individual tree size, and no fertilizer should be applied to gaps where trees are missing.

Fruit yield was significantly correlated to both canopy volume ($R^2=0.64$) and height ($R^2=0.55$) measured with ground-based ultrasonic equipment in the grove (Figs. 8a-b). Extrapolation of these

nonlinear regressions to zero yield (equivalent to young, non-bearing trees) produced a realistic canopy volume of 16 m³/tree and a canopy height of 2.1 m. Although the correlation of yield with canopy volume was best, the correlation with canopy height was considered adequate for fertilizer rate calculation and could be achieved with the existing commercial ultrasonic or photoelectric canopy height sensing systems. Using aerial photographs of the grove to calculate canopy dimensions, the correlations of yield with both NDVI ($R^2=0.56$) and ground area covered by canopy ($R^2=0.70$) were also significant (Figs. 8c-d). NDVI from high resolution aerial photographs was less correlated to yield than canopy volume and about the same as height measured with ground-based equipment. However, the percentage ground covered by canopy can be readily calculated from aerial photographs and achieved the best correlation with yield, slightly better than the ground-based canopy volumes. Some disadvantages of aerial photograph-based canopy size estimates are high cost, infrequent measurement scheduling and the need for GIS processing. Ground-based canopy measurement systems mounted on fertilizer spreaders are always up-to-date, and don't need GIS processing, prescription maps or a DGPS receiver since canopy measurement and fertilizer rate calculations are made "on-the-fly".

2. Comparison of two canopy sensor systems on young trees

The full rate of fertilizer that would be dispensed by the spreader to the largest mature tree in this hypothetical grove would be 1.17 kg/tree (336 kg/ha / 286.5 trees/ha), four times a year. Converted to an annual amount, each fully mature tree would receive N at 0.704 kg/tree/y. Young trees with less than 2.74 m canopy width would typically have a height similar to their width, and would therefore be detected only by the lowest sensor. The VRA controller was configured to

allocate 50% of the full fertilizer rate to the lowest sensor, which for a continuous canopy over an entire tree space, would equate to a N dose of 0.352 kg/tree/y. Smaller tree canopies not occupying the entire tree space would therefore receive proportionately less than the 50% rate.

The fertilizer output of the spreader increased linearly with increasing tree target sizes detected with both sensor types, but was consistently higher than the amount of fertilizer calculated from the proportion of a linear tree space in the row (4.56 m) occupied by a tree target (Figs. 9a-b). The systematic nature of the error suggests that it was caused by the different sensor beam widths of the photoelectric or ultrasonic systems. A finite beam width would cause the sensing system to detect the target outline's leading edge too early and the trailing edge too late, thus calculating a wider target width. The electrostatic ultrasonic transducers used in this study have a beam pattern with about a 15° divergence angle, so that the field of view at 3.8 m distance from the target is about 1.0 m (SensComp Inc., 2003). The photoelectric sensors have a much narrower beam pattern of about 1° divergence angle, with a field of view at 3.8 m from the target of about 0.06 m (Banner Engineering, 1998). The observed relative difference in intercept between the curves for the two sensor types compared to the 'ideal' calculated curve (Figs. 9a-b) confirms this hypothesis. The slightly lower refresh frequency (7.85 Hz) of the ultrasonic system compared to the photoelectric system (10 Hz) was not likely to have influenced these results noticeably.

Both sensor systems performed equally well at the two ground speeds tested, since they both incorporate 'look-ahead' precompensation, and the VRA controller automatically compensates for ground speed when adjusting fertilizer rates (Figs. 9a-b). Average fertilizer amounts dispensed for the three smallest tree targets (0.91, 1.82, 2.74 m) were calculated from the regression equations for each sensor type and ground speed, and converted to the equivalent amount of N per tree per year,

assuming 4 split applications and a 15% N content (Table 1). The amount of fertilizer that should be dispensed per tree was calculated from the amount of fertilizer allocated per linear tree space in the row and the proportion of the total tree space (4.56 m) occupied by a tree target width (Table 1). To assess the validity of these results, they were compared with the University of Florida's Institute of Food and Agricultural Sciences (UF-IFAS) citrus nutrition recommendations for young trees published by Tucker et al. (1995) and adopted by the Florida Ridge Citrus N-BMP (FDACS, 2002). Their recommendations are based on tree age (years in the grove), which we approximately related to our size-based results as year 1 = 0.91 m, year 2 = 1.82 m, year 3 = 2.74 m (Table 1). The calculated N amounts agreed well with the ranges of N recommended by Tucker et al. (1995) for different young tree sizes / ages (Table 1). Using the photoelectric sensor, the amounts of fertilizer dispensed per tree were also in good agreement with the range prescribed by Tucker et al. (1995), regardless of ground speed (Table 1). Similar good results were obtained with the ultrasonic sensor, with the exception of the smallest tree target (0.91 m), which received an annual N dose that was slightly higher than the recommended range (Table 1). Since the fertilizer amounts recommended for young citrus trees cover a wide range for each size / age class, the slightly higher amount dispensed by the ultrasonic system should not be a problem. Due to the systematic nature of the upward bias in fertilizer rates as a result of the ultrasonic beam width, the error could easily be removed by calibration.

Conclusions

The large spatial variability in citrus fruit yield and canopy size measured in a typical mature 'Valencia' grove strongly justified the use of variable rate fertilization of >2x range. The best ground-based estimator of fruit yield was the canopy volume, and the best aerial photograph-based estimator was percentage ground covered by canopy. Canopy height measured with ground-based ultrasonic equipment was slightly less correlated with yield but is an acceptable compromise because it is simpler to measure than canopy volume and more up-to-date and convenient than aerial photography. Commercial canopy sensors installed on fertilizer spreaders measure canopy height only.

The two different canopy sensing systems (photoelectric and ultrasonic) mounted on a VRA spreader and tested on a range of young tree targets showed very good agreement with the existing recommended fertilizer rates for young trees. The maximum range of N rates (excluding zero) achieved with the VRA spreader in this configuration was 0.11 to 0.70 kg/tree/y (photoelectric sensor) and 0.20 to 0.70 kg/tree/y (ultrasonic sensor). This 3.5 to 6.4x range of N rates should be sufficient to address the large spatial variability in fruit yield and tree sizes that exist in the grove. Both the photoelectric and ultrasonic sensor systems compared in this study incorporated automatic 'look-ahead' precompensation, which ensured that the correct amount of fertilizer was dispensed to the correct tree and that the placement of fertilizer to the base of the canopy was spatially accurate. Some commercially available canopy sensing systems do not use 'look ahead' features or they are not automatic. In those cases, growers may achieve unsatisfactory results with VRA fertilization because large trees tend to be under-fertilized, small trees are over-fertilized, and fertilizer is wasted on bare ground when 'look-ahead' is not properly implemented.

Results from this study demonstrated that a well-tuned fertilizer spreader with high-speed sensors, control electronics and hydraulics can precisely fertilize any tree sizes from resets to mature hedgerows with realistic fertilizer rates recommended by UF-IFAS research.

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Table 1. Fertilizer N rates dispensed by the VRA spreader for different tree target sizes, and compared with UF-IFAS recommendations

Target tree width (m)	Approximate spherical canopy volume (m ³)	Year in grove	UF-IFAS fertilizer N recommendation ^z (kg/tree/y)	N rate calculated from target width (kg/tree/y)	Ground speed (m/s)	N rate dispensed using photoelectric sensor (kg/tree/y)	N rate dispensed using ultrasonic sensor (kg/tree/y)
0.912	0.397	1	0.07-0.14 (6) ^y	0.07	1.34	0.11	0.20
					1.92	0.13	0.20
1.82	3.16	2	0.14-0.27 (5)	0.14	1.34	0.18	0.27
					1.92	0.19	0.26
2.74	10.8	3	0.20-0.41 (4)	0.21	1.34	0.24	0.34
					1.92	0.20	0.33

^z adapted from table 6.1.1, Tucker et al., 1995

^y recommended number of applications per year

Figure captions

Figure 1. Automatic fruit tub mapping during harvesting of the 'Valencia' grove. Small (red) dots on the aerial image between tree rows are the locations of full tubs.

Figure 2. Tree canopy size mapping of the 'Valencia' grove. Large (green) dots on the tree rows are proportional in size to the canopy volume of each tree. The equipment shown is the new ultrasonic system developed by Schumann and Hostler (2006b).

Figure 3. Tree canopy cover calculated by binary thresholding of an enhanced NDVI image of the 'Valencia' grove.

Figure 4. Partial view of the 40 rectangular plots superimposed on the 'Valencia' image to combine and relate the different canopy size measurements with yield.

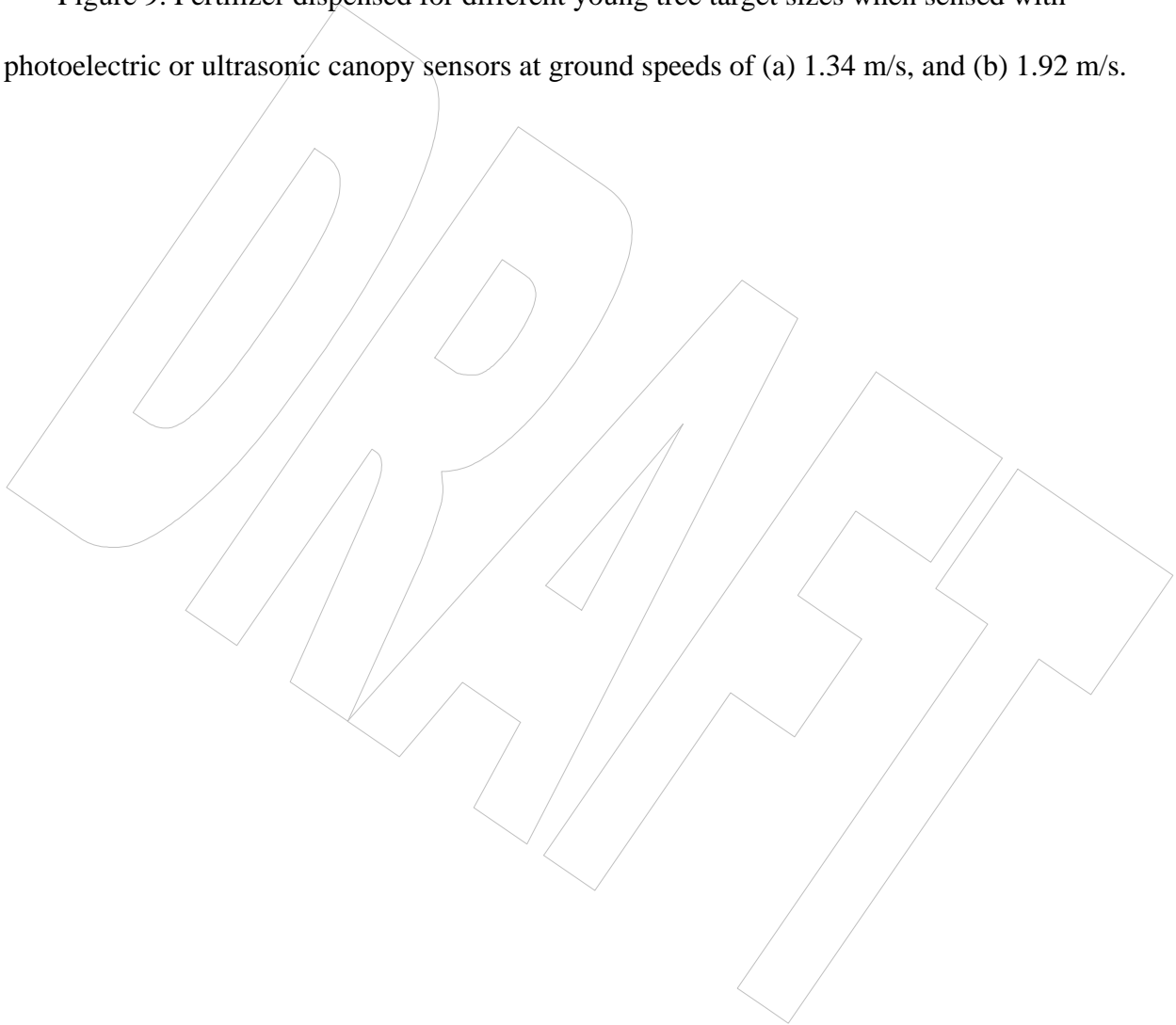
Figure 5. Ultrasonic and photoelectric canopy sensors mounted to the front of a variable rate fertilizer spreader for the experiments.

Figure 6. Fruit yield map of the 'Valencia' grove in 2004.

Figure 7. Frequency distribution of canopy volume for 2,980 'Valencia' trees in the grove during 2003.

Figure 8. Correlation between fruit yield and (a) canopy volume, (b) canopy height, (c) NDVI, and (d) canopy ground cover of the 'Valencia' grove.

Figure 9. Fertilizer dispensed for different young tree target sizes when sensed with photoelectric or ultrasonic canopy sensors at ground speeds of (a) 1.34 m/s, and (b) 1.92 m/s.



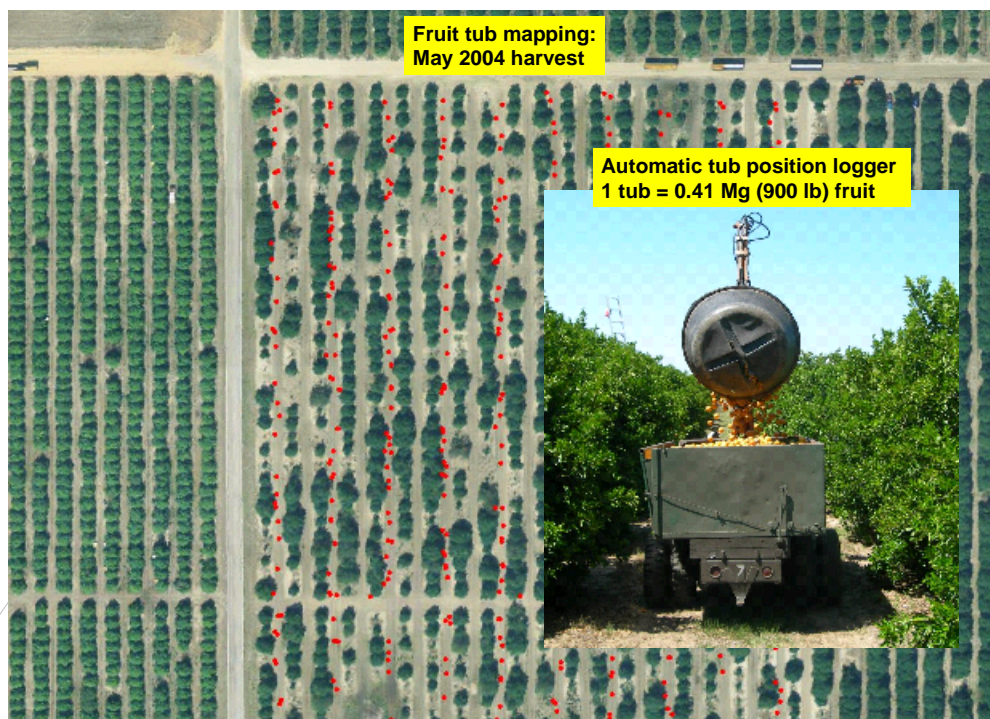


Figure 1

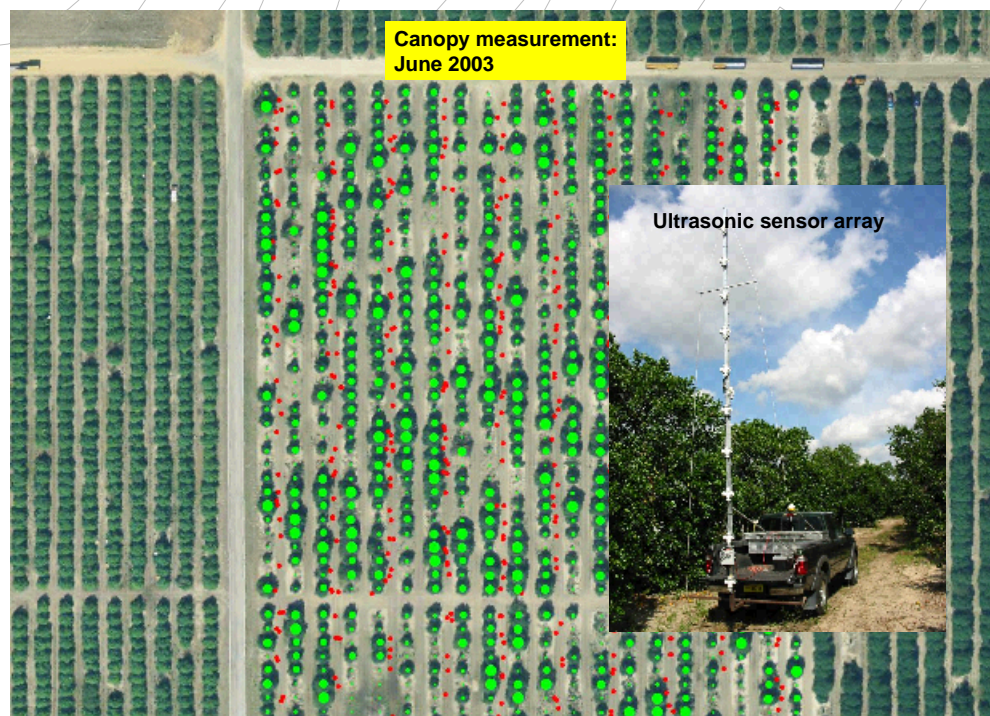


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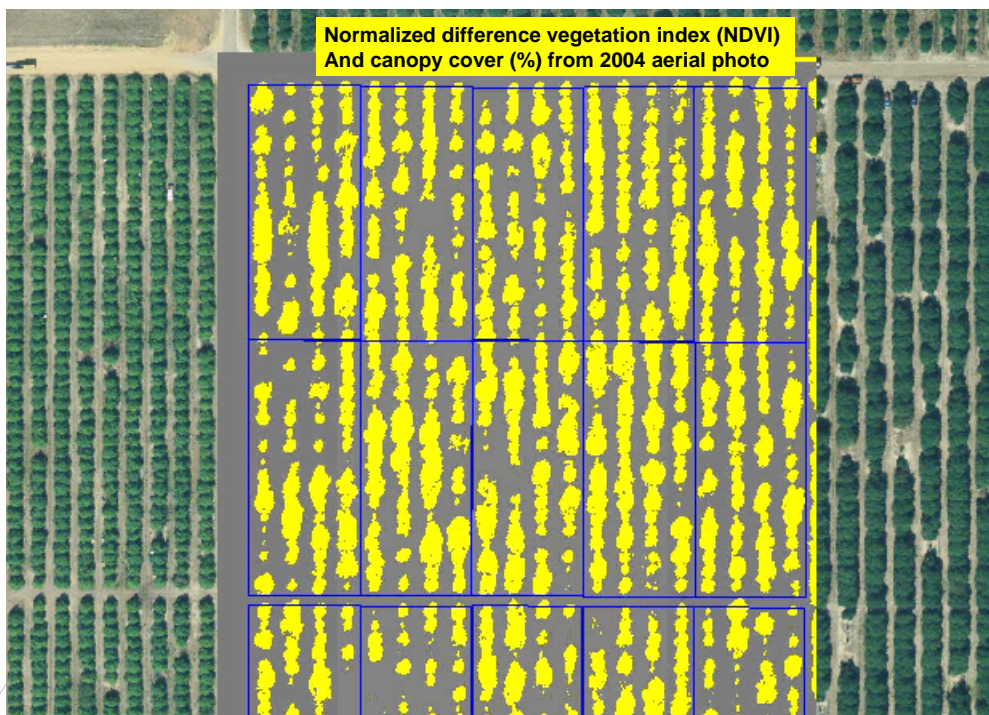


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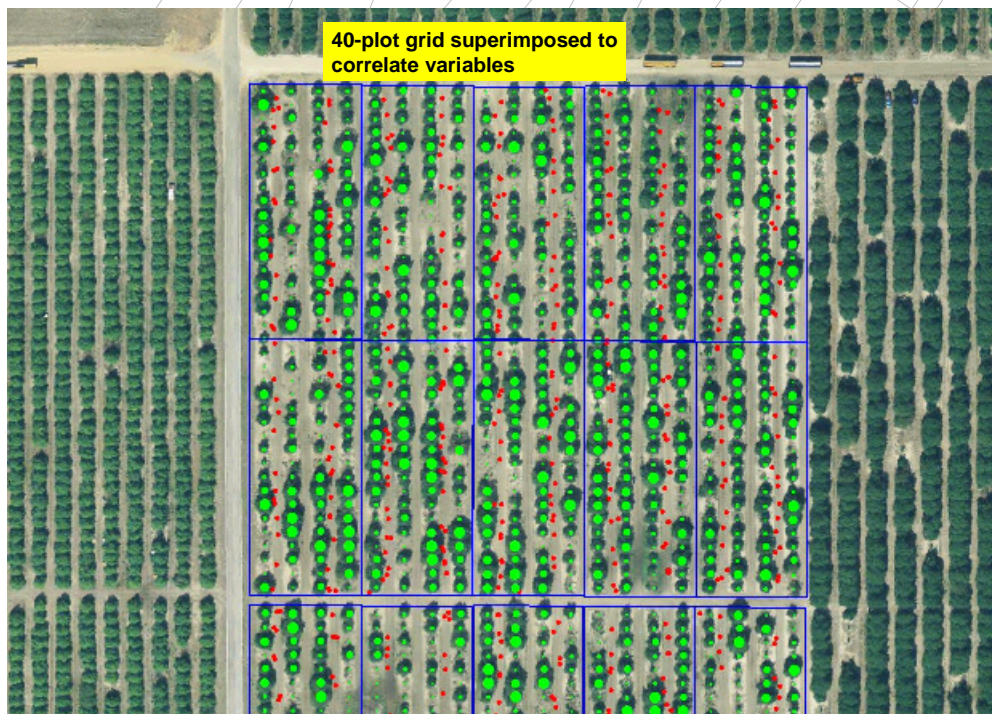


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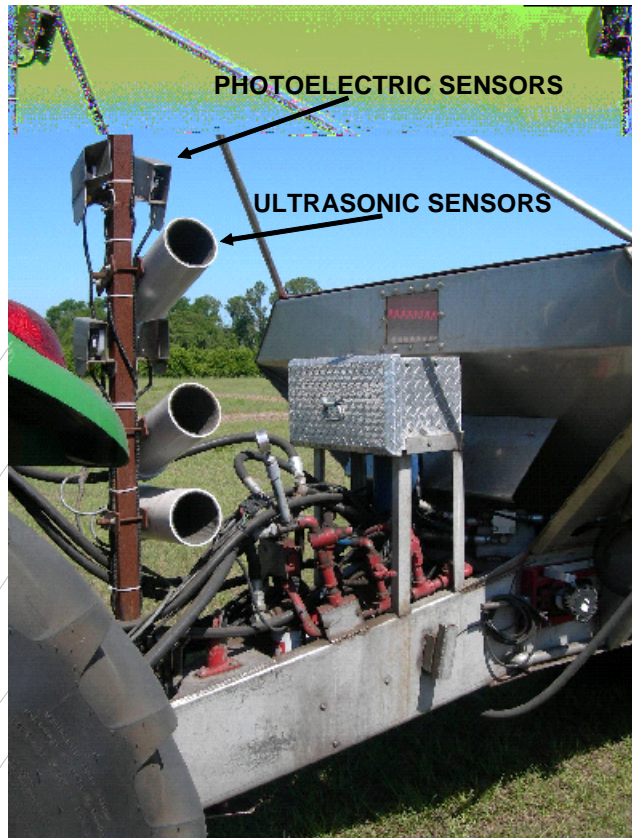


Figure 5

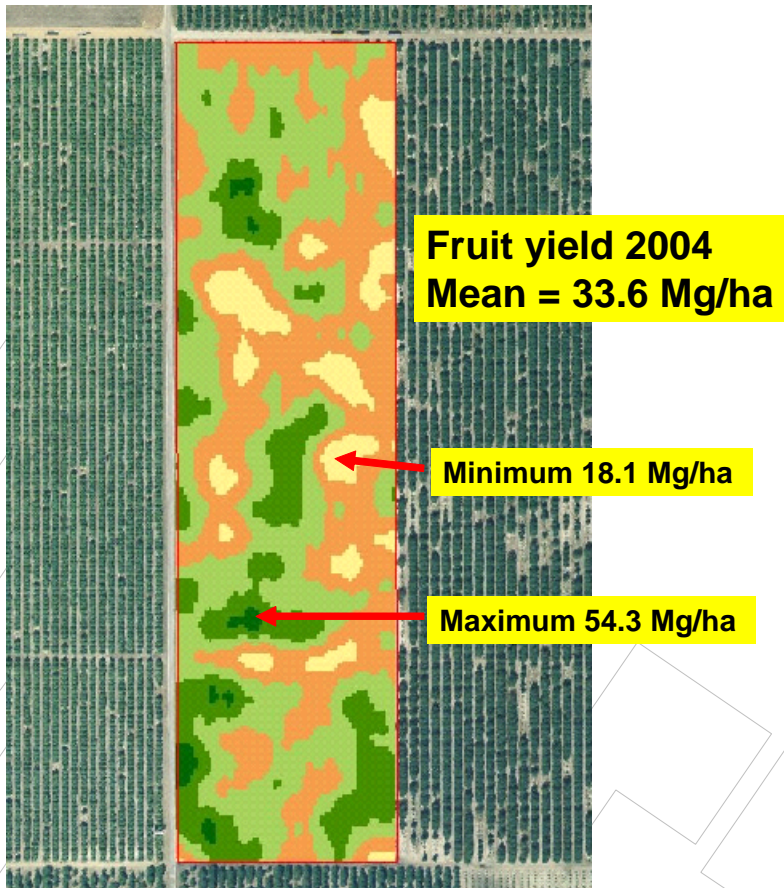


Figure 6

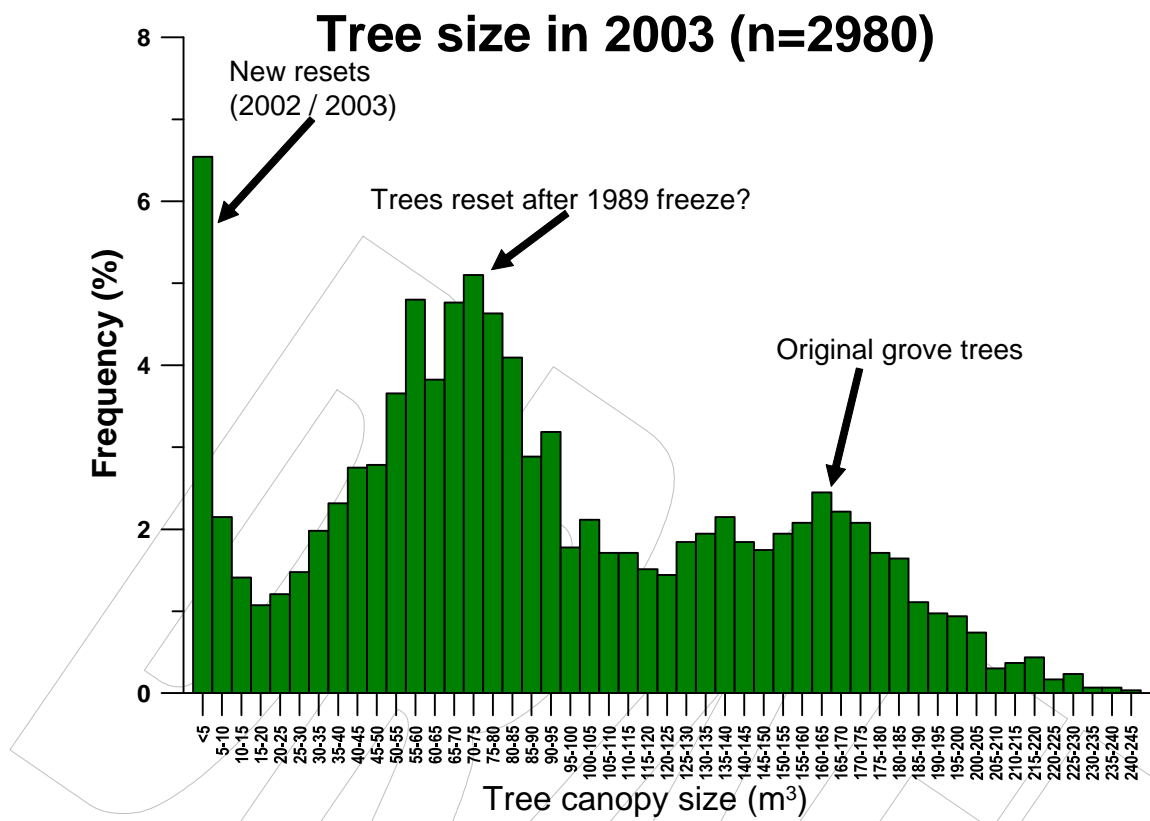


Figure 7

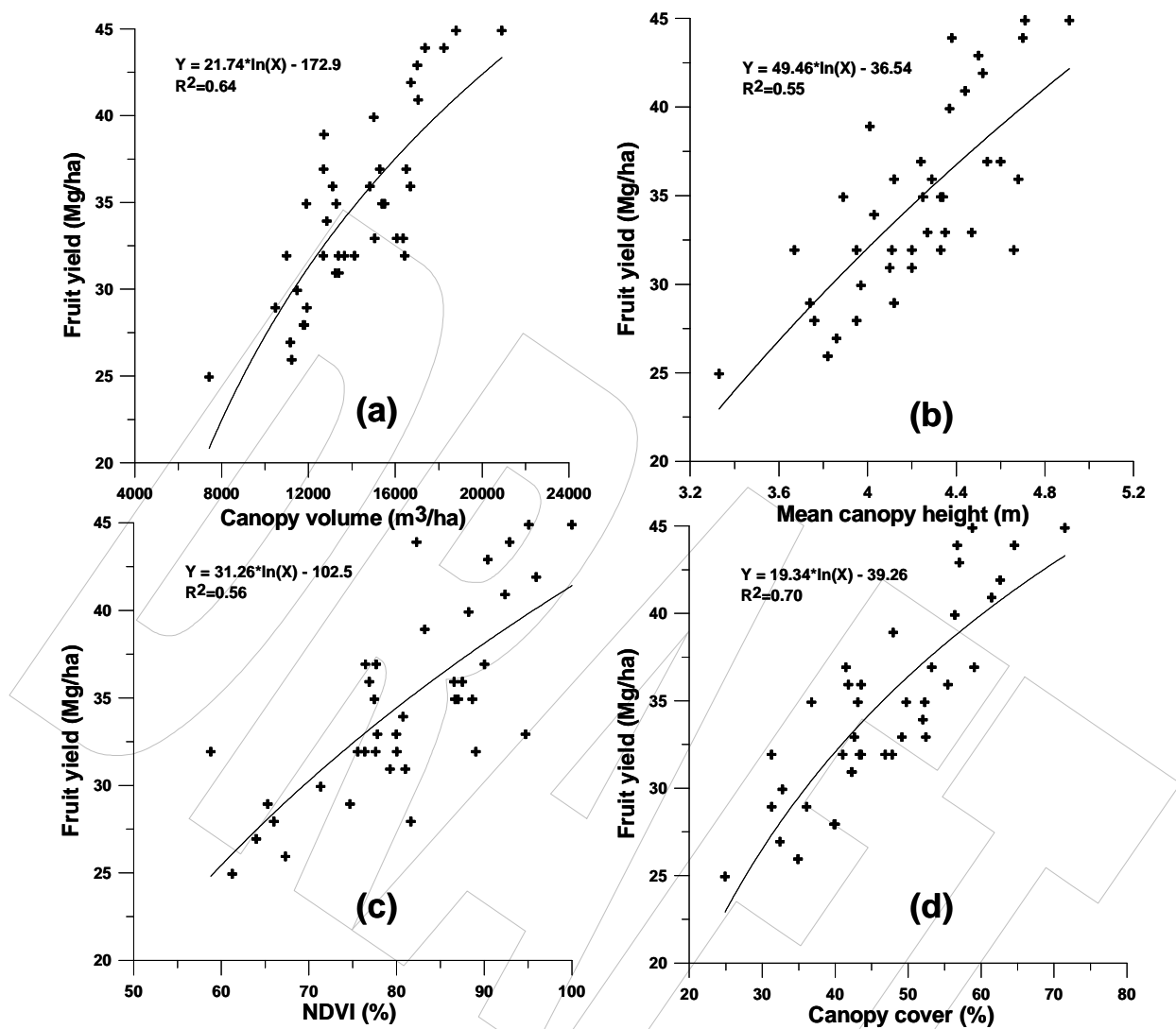


Figure 8

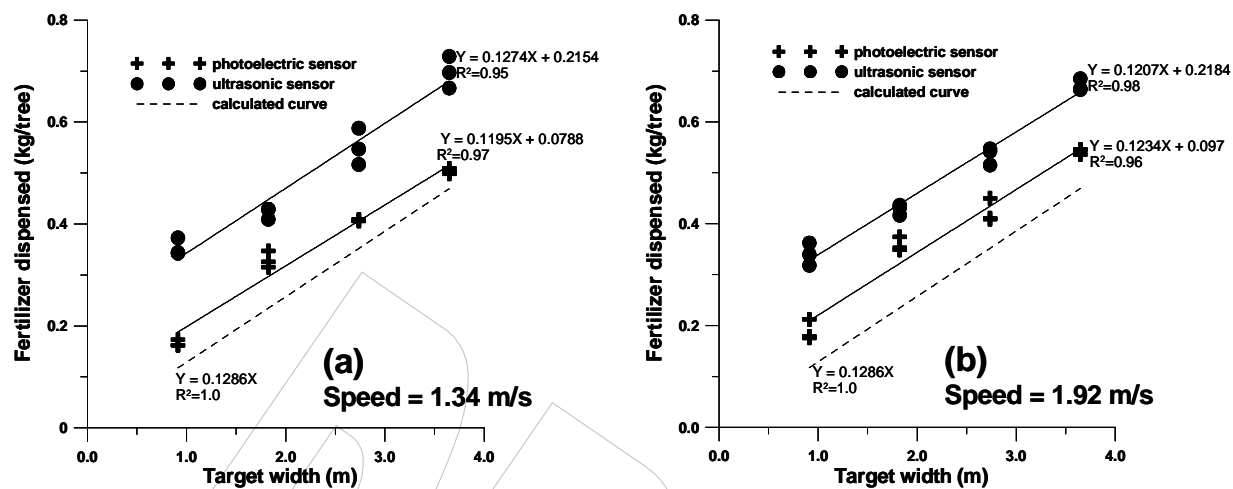


Figure 9