A REFEREED PAPER

EVALUATING VARIABLE RATE GRANULAR FERTILIZER TECHNOLOGIES IN FLORIDA CITRUS

William M. Miller[1], Arnold W. Schumann
and Jodie D. Whitney
University of Florida, IFAS
Citrus Research and Education Center
Agricultural and Biological Engineering Department
700 Experiment Station Road
Lake Alfred, FL 33850

Additional index words. BMPs, nitrogen, control, geographic information system (GIS), global positioning system (GPS)

Abstract. **Granular fertilizer applications through variable-rate technology (VRT) for Florida citrus can be implemented through either real-time sensing, GIS-map based control, or both. Evaluations were undertaken to establish the response of these techniques with two dry fertilizer units with different hydraulic configurations. A test program using ASAE S341.3 has been established for standardized conditions. Additionally, field trials were undertaken to ascertain fertilizer distribution under grove conditions. In these field trials, both spinner disc and pneumatic discharge units were evaluated. Fertilizer distribution under grove conditions yielded distributions quite different from the Gaussian distributions found in open-field standardized tests. Coefficients of variation in tray distribution tests across the fertilizer swath were lower; 41.0% for grove condition versus 93.9% in open field results when comparing the same spreader unit. Grove application rates for three commercial spreaders were determined by under-tree tray collection of fertilizer and varied by 7.7% from the controller set point values. For both units, delay times (on-off) was 30% less than the off-on transition.**

Florida citrus is grown throughout central and south Florida on approximately 304,000 ha (751,000 acres) (CAC, 2003). Currently, best management practices for various growing areas are being implemented to address nitrate levels in groundwater (FDACS-OAWP, 2003). As part of that program, research was undertaken to evaluate the merits of granular fertilizer applications using VRTs (variable-rate technologies). A principal concern for Florida citrus is over-fertilization and the leaching of fertilizer, especially nitrates, into the groundwater. Seasonal timing and fertilizer placement can mitigate some of these problems. As a common practice, citrus trees are not fertilized during the high rainfall summer months. Scholberg et al. (2000) have summarized production considerations to utilize nitrogen (N) more effectively. Further refinement would result from either real-time or site-specific control of the fertilizer application rates. In areas of missing or small trees, no fertilizer or reduced amounts should be discharged, while in other grove areas, the rate may be governed by previous yield production records, tree age, tree health, rootstock selection, soil type, and water table information.

Sogaard and Kierkegaard (1994) evaluated yield reduction resulting from uneven fertilizer distribution in agronomic crops. They concluded that a spatial distribution coefficient of variation less than 20% was necessary to minimize loss of net profit. However, this study was for agronomic crops and not tree crops. Tucker et al. (1995) have produced a nutritional guideline for Florida citrus indicating that N rates greater than 224 kg ha^{-1} $year^{-1}$ (200 lb/acre/year) may not be beneficial in most groves. They also detailed essential minor elements, which included recommended levels of calcium, magnesium, iron, copper, boron, and zinc.

A generalized model to predict fertilizer distribution was developed by Olieslagers et al. (1996) detailing effects of many of the mechanical components of a granular spreader such as discharge orifice, disc angular velocity, and mass flow. Parish (2002) analyzed rate effects and noted distortions at higher levels. Mennel and Reece (1963) concentrated on a study of particle trajectory in granular fertilizer discharge. Other researchers also have developed general performance procedures (Glover and Baird, 1973; Reed and Wacker, 1970).

ASAE Standards EP371.2, Procedure for Calibrating Granular Applicators, and S341.3, Procedure for Measuring Distribution Uniformity, and Calibrating Granular Broadcast Spreaders (ASAE, 2004) specifically address granular fertilizer application calibration and testing. However, these test procedures were developed and structured for steady-state conditions, principally focusing on uniformity. For agricultural VRTs, there has been a realization that dynamic performance must be addressed for liquid (Ayers et al., 1990) and granular applications (Fulton et al., 2001). Performance testing, as related to DGPS (differential global position system) accuracy in agricultural applications, was studied by Stombaugh et al. (2002). However, GPS systems are being deployed to increase the accuracy by 10-fold (Enge, 2004). Chan et al. (1999, 2002) modeled the principal error components for an orchard application but did not pursue field validation. Cugati et al. (2003) evaluated the hydraulic and mechanical sub-components of VRT granular units. Miller et al. (2003) reported on a test track for dynamic performance of granular application.

A project was undertaken to evaluate available equipment and technologies for precise application of granular fertilizer to Florida citrus. Specific objectives of the research detailed herein were to:

1. Develop a test system and protocol for VRT dry fertilizer applications to tree crops, in particular, citrus.
2. Measure distribution patterns and variability found in standardized tests and field trials.

This research was supported by the Florida Agricultural Experiment Station and a Florida Department of Agriculture and Consumer Service Grant No. 6755 and approved for publication as Journal Series No. R-10345. Technical support of Sherrie Buchanon and Gerald Perkins of the Citrus Research and Education Center is gratefully acknowledged. Commercial support and training were provided through Chemical Containers (Kieth Hollingsworth), Newton-Crouch (Steve Smith), Chandler Equipment (Barry Keller), Mid-Tech (Brian Mathis), Tree-See (Charles Roper), and Best Air (Perry Best). Commercial product names are mentioned for the convenience of the reader and do not imply endorsement by University of Florida.

[1]Corresponding author.

3. Identify pertinent variables associated with mechanical performance of current VRT granular fertilizer units.

Materials and Methods

An open area was identified at the University of Florida Citrus Research and Education Center (CREC), Lake Alfred, Fla., to configure a test track with a fertilizer collection grid (Fig. 1). Following the guidelines of ASAE Standard S341.3, collection trays were fabricated from 0.101 cm (0.040 inch, 20 gauge) galvanized sheet metal with overall dimensions of 30.5 × 30.5 × 5.1 cm (12 × 12 × 2 inches) high. A 0.318 cm (0.125 inch) thin pyramid surface rubber mat (Garro Corp, Akron, Ohio) was inserted to cover the bottom of each tray. Dividers were added to make each sub-compartment 10.2 cm × 10.2 cm (4 inches × 4 inches). Slightly larger trays, with one corner cut out, were fabricated to collect discharged material by inverting the collecting trays. Material from individual trays was collected in a small Ziploc™ bag [16.5 × 8.3 cm (6.5 × 3.3 inches); mass = 2.4 g (5.3×10^{-2} lb)] and weighed to 0.1 g accuracy.

Two sections of black ground cover material were placed over the tray collection test area and 2.54 cm (1 inch) fluorescent orange spots were painted on the material to mark placement of the tray collectors. The spacing between the first two North-South rows was 1.2 m (4 ft) to accommodate the tractor and spreader tire spacing and to match with the centerline of the fertilizer spreaders. The remaining portion of the grid was on a 0.9 × 0.9 m (3 × 3 ft) spacing. Each of two grid sections contained 81 collection trays, i.e., a 9 × 9 grid. Offset to the West side of the test area paralleling the tractor-fertilizer spreader drive path, a canvas curtain was erected providing a simulated target to trigger the real-time sensors.

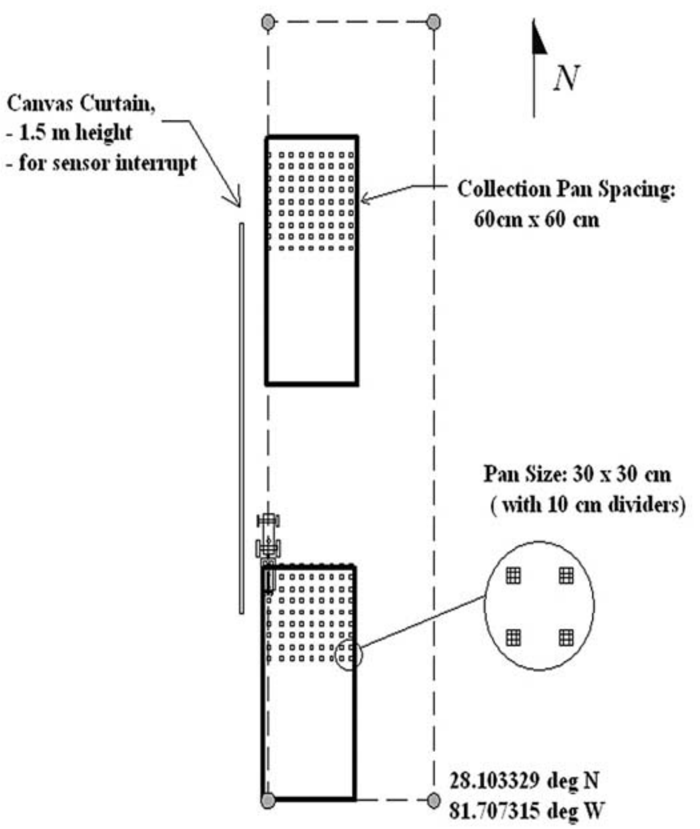

Fig. 1. Test area for dynamic response tests of granular fertilizer applications.

Tests have been conducted on two split-chain spinner type granular fertilizer units. The first spreader (Test Unit #1) was a 2.7-Mg (3-ton) unit (M&D, Arcadia, Fla.) with a Legacy 6000 controller (Midwest Technologies, Springfield, Ill.) and photocell real-time control sensors (Chemical Containers, Lake Wales, Fla.). The second spreader (Newton Crouch, Griffin, Ga.), designated as Test Unit #2, had a 4.6-Mg (5-ton) capacity and was operated under real-time control through two ultrasonic sensors (Tree-See, Roper Growers, Winter Garden, Fla.) on each side of the unit. Actuation of these sensors provided discrete level control through the solenoid dump valves associated with each ultrasonic transducer. Overall flow rate control was set through two MidTech EXRII Modulating valves (Midwest Technology, Springfield, Ill.). In Test Unit #1, all flow control was through the MidTech EXRII servo valves. This included a) overall flow rate based on a set point and b) proportioned output dependent upon photocell actuation. In GIS map-based tests, a Trimble 132 (Trimble, Sunnyvale, Calif.) was utilized at 10 Hz with Coast Guard beacon correction. The key control elements of each system are detailed in Figs. 2 and 3, respectively. Test Unit #1 now has been modified for either solenoid or servo valve flow control.

For Test Unit #1, an encoder wheel with reflective tape was fabricated to measure chain speed on one side. Twenty-four reflective strips, 0.5 cm (0.2 inch) wide, were mounted at 15° increments around the wheel's 63.9 cm (25.1 inches) circumference. An optical tachometer (Ono Sokki model HT-5100, Yokohama, Japan) having an analog output, 1 V = 16.8 Hz (1000 r/min), was used to record the pulse output rate. The tachometer was mounted on a tripod and used to measure chain speed for start-up and shut-off tests. It was necessary for these tests to be conducted under load, accomplished with 454 kg (1000 lb) or more of material in the fertilizer hopper.

Separate tests were conducted to determine the field of view (FOV) of the two most common sensors employed for real-time control. These units were ultrasonic sensors (Tree-See, Roper Groves, Winter Garden, Fla.) and near-infrared 880 nm photocell sensors (Banner QMT 42, Banner Engineering, Minneapolis, Minn.). A nominal 2.5 cm (1 inch) PVC pipe was held vertically and traversed across the front plane of the transducer at a distance of 1.5 m (5 ft). Multiple readings were taken to establish the outer boundaries. The FOV for the ultrasonic units measured experimentally at that distance was determined to be 21.5°. For the photocell sensors, the FOV for that distance was ~1.9°. The photocell's range sensitivity was dependent on the reflective surface. In a controlled lighting

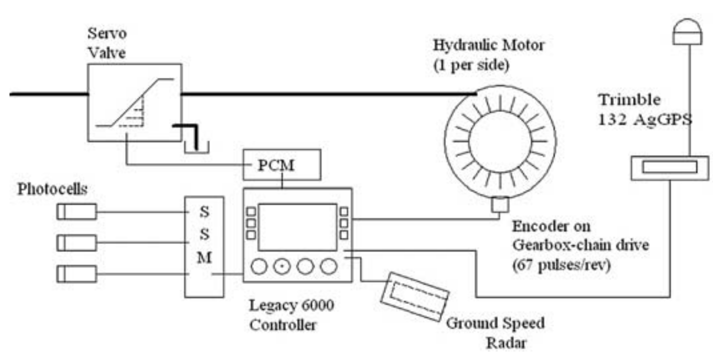

Fig. 2. Principal control elements of test unit #1.

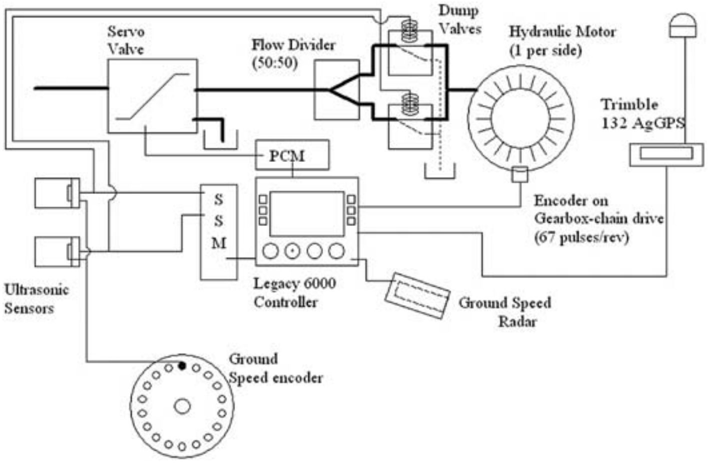

Fig. 3. Principal control elements of test unit #2.

Table 1. Maximum measurable target distance for Banner QMT 42 photocell unit maximum at high and low background light levels.

Target	Background light levels (high/low) (lux)	Max. distance[z] m (ft)
Black felt	388-432	2.3-2.4 (7.4-7.8)
	34	2.1 (6.7)
Green baize	392-449	6.6 (21.7)
	42	6.6 (21.7)
White paper	421-422	7.2 (23.6)
	14	7.2 (23.6)

[z]Cited value from manufacturer: 6 m for white target.

setup, three materials were tested: black felt, green baize, and white paper. These results were summarized in Table 1. Li et al. (2002) previously investigated the ultrasonic sensor response of a prototype system (Durand-Wayland, LaGrange, Ga.) to various surfaces and surface orientations.

For a dynamic test experiment, a fixed rate was established, e.g., 560 kg ha^{-1} (500 lb/acre) at a swath width of 7.6 m (25 ft). With the dual split-chain discharge, spinner speed was adjusted to provide a maximum particulate throw of ~½ total swath width. These projected distances were based on a projectile motion program developed in MathCAD 11 (Mathsoft, Cambridge, Mass.). Initial calibration for the fertilizer discharge rate was performed using collection of ~20 kg (44 lb) of material. Typically, after three calibration tests, the difference between collected material and the controller estimation was <2%. Further calibration tests, if needed, were undertaken until a difference of <2% was achieved. The material used for these tests was a high calcium lime material obtained from a local fertilizer distributor within 4 h of the tests being undertaken. From sieve analyses, average geometric particle size was 1.247 mm (0.049 inch) with a geometric standard deviation of 1.047 mm (.041 inch). Average density was 1181.8 ± 52.8 kg m^{-3} (73.8 ± 3.3 lb/ft^3).

The fertilizer units were pulled with a 48 PTO kW (64 PTO hp) hydrostatic diesel Model 656 tractor (International Harvester, Chicago, Ill.), which also powered the PTO-driven pump of each fertilizer spreader. Typical operating conditions were a ground speed of ~8.0 km h^{-1} (5 mph) and 9 Hz PTO speed. During each test, meteorological conditions, specifically wind speed, temperature and humidity, were logged with a Hobo weather station (Onset, Pocasset, Mass.). A test consisted of one off-on start-up transition and a steady-state operating period followed by an on-off transition. The transition states were controlled by the interrupt of the photocells/ultrasonic transducers by the canvas curtain adjacent to the track. For GPS-based tests, an application map was developed matching the end points of the curtain section. This was accomplished using ArcView 3.2 GIS (ESRI, Redlands, Calif.) and converting to an ARM (application rate management) file for the Legacy 6000. Hence, transitional points were identical within the accuracy limits of the DGPS position, typically 1 m with DGPS Coast Guard beacon correction and transducers' field of view/orientation parameters. Correction for Trimble antenna location with respect to the fertilizer discharge point was made in the Legacy 6000 controller using the *x* left-right offset and *y* distance from antenna to the discharge point.

In a normal trial, two or three tests were completed in one-half day of testing. A coefficient of variation (CV) for the spreader's discharge, perpendicular to the travel path, was tabulated for a steady-state discharge condition. The time delay to achieve steady-state start-up operation was estimated as well as the transitional time in shut-off from steady-state to zero output.

Separate field tests were undertaken with three units: an M&D as described earlier, a pneumatic discharge unit (Best Air Sprayer, Dundee, Fla.) in Immokalee, Fla., and a Chandler unit (Chandler Equipment, Gainesville, Ga.) in Vero Beach, Fla. All units and their configuration are detailed in Table 2. The latter two application tests were conducted in two row bedded groves. For such groves, typical applications are single-sided with the fertilizer units traversing the mounded middles only. Hence, the Legacy 6000 setup for boom widths and resultant discharge rates essentially were doubled.

Results and Discussion

Tests undertaken with Test Unit #1 and Test Unit #2 are reported. Typical data for a transitional off-on state are plotted in Fig. 4. Comparable results with respect to the transition response were obtained for these two systems. Hence, delay times and the coefficients of variation values, established for

Table 2. Granular fertilizer units tested, either at CREC[z] or in-field.

Manufacturer/Model	Control (realtime/GPS)	Hydraulic (valve setup)	Test Site
Best Air/6.5 ton	Ultrasonics (2/side)	Solenoid dump	Field
Chandler/Tandem axle	Photocells (2/side)/GPS	Modulating + Solenoid dump	Field
M & D, Chemical Containers	Photocells (3/side)/GPS	Modulating	CREC/field
Newton Crouch	Ultrasoncis (2/side)	Solenoid dump	CREC

[z]CREC-University of Florida Citrus Research and Education Center, Lake Alfred, FL.

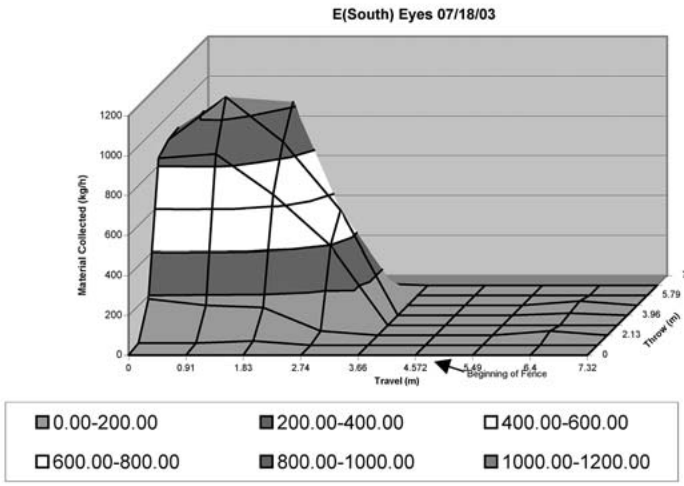

Fig. 4. Typical response start-up pattern and distribution for standardized open-field spreader tests (SI conversions: 1m = 3.28 ft, 1 kg/ha = 0.89 lb/A).

full output, have been combined and compiled in Table 3. Distances and estimated times to reach ½ and full or maximum rate have been tabulated.

One general observation was that the transitional start-up time (off-on) was longer than the shut-off (on-off) time. Delay time to ½ maximum rate was 0.82 s (off-on) compared to 0.58 s (on-off). The controller had two settings, which were adjusted to alter the response. First, the gain could be set between a normalized range of 0.1 to 10 while an initial valve position was adjustable between 5 and 90%. These parameters were set at gain = 5, valve position = 25% for the field grid distribution tests of Table 3. Stationary discharge tests were undertaken to check the effect of gain (Table 4) on the chainbelt response. Overshoot occurred for tests at gain settings of 1, 5, and 10. However, the correction time after overshoot (column 3) was much less for gain settings of 5 and 10. Transitional off-on values ranged from 0.43 s (gain = 5) to 0.87 s (gain = 1). Shut-off times also were higher for the lower gain of 1 and averaged 1.8 s compared to 0.2 s (gain = 5) and 0.7 s (gain = 10).

Response characteristics under GPS map-based control were similar to those found for real-time control. The initiation and shut-off point varied within the expected 1 m accuracy for the DGPS position. From response times and distances of Table 3, it is evident that application control response within a typical ½ tree spacing is achievable. The transition from ½ to full output may not be critical especially under conditions where every row is traversed. When bedded groves are encountered, it would be advisable to run alternate travel patterns between each application. The more precise response to address small trees will be dependent upon exact setting of sensor-controller lead and lag times and a constant travel speed. For very accurate applications, anticipated speed range for proper application is 4.8 to 8 km/h (3 to 5 mph). The general factors for error and offset considerations are presented in Table 5.

Configuration of the Legacy controller was different for Test Unit #2 in that the modulating valves must be set to a hold position. This configuration facilitated resumption of the proper flowrate with the solenoid valve closure. The ultrasonic sensors were switched physically to obtain opposite side control. Certain other features of the test setup with the Legacy controller should be mentioned for Test Unit #1. First, normal product control module assignments were switched, i.e., in that the left side photocells controlled the right side output. Secondly, principal assignment of the output was given to the bottom photocell by assigning it 92% of the swath width, which would correspond to a 92% fertilizer discharge rate. This facilitated testing with only one photocell and matched alignment among the photocells was not critical. Thirdly, the Trimble antenna spatial position assignment was offset 6.1 m (20 ft) back and 3.8 m (12.5 ft) left to assure placement in the prescription map area.

For the tray test conducted at CREC, it was established that the typical distribution from a split-chain banded application was Gaussian. Cross-sectional data, perpendicular to travel path, was best fit to an expanded Gaussian function, $y = a + b{*}\exp[-0.5([x-c]/d)^2]$ with y-material collected, x-swath distance and a-, b-, c-, d-curve fit constants. The average r^2 value was 0.99. Although complex, this equation readily yields a mean peak distance, *c*, which was 3.1 m with a standard deviation of 0.8 m for Test Unit #2 at 280 and 561 kg/ha (250 and 500 lb/acre) application rates. The maximum throw was calculated to be 1 m (offset) + c + 3d or 6.4 m (21.0 ft). This compared favorably with projectile motion estimates developed from a MathCAD 11 program, which indicated 5.9 m (19.4 ft) for horizontal discharge and 8.5 m (27.9 ft) for angular discharge at + 5°.

Field-testing in commercial groves resulted in much different distribution patterns than the open field standardized procedure. In Fig. 5, normalized under-tree variation for 15

Table 3. Delay distances and time delay estimates (Test Units #1 and 2).

		Delay distance, m (ft)		Delay time[z], s		CV[y]
Control action	Sensor control	½Max	Max	½Max	Max	%
Off-on	GIS/GPS	2.2 (7.1)	4.6 (15.0)	0.97	2.05	61.4
Off-on (avg. of 3 tests)	Sensor	1.7 (5.6)	2.7 (9.0)	0.77	1.23	102.9
	Average	1.8 (6.0)	3.2 (10.5)	0.82	1.44	92.5
	St. dev.	0.5 (1.5)	1.2 (3.9)	0.21	0.53	22.8
On-off	GIS/GPS	1.3 (4.2)	2.2 (7.5)	0.57	0.82	95.1
On-off (avg. of 2 tests)	Sensor	1.3 (4.2)	2.2 (7.5)	0.58	1.03	95.4
	Average	1.3 (4.2)	2.1 (7.0)	0.58	0.96	95.3
	St. dev.	0.8 (2.7)	1.7 (4.6)	0.36	0.63	10.9

[z]Assume 8.0 km/h (5 mph) vehicle velocity.
[y]Coefficient of variation found for fertilizer material at maximum discharge level, perpendicular to travel.

Table 4. Transition time for belt-chain speed to obtain various operating conditions (Test Unit #1).

	Operating time parameters (mean/std. deviation), s		
Gain	Response time to operating level	Peak response to operating level	Shut-off
1	0.87/0.27	20.5/3.9	1.8/1.5
5	0.43/0.16	5.4/1.4	0.2/0.1
10	0.72/0.17	1.5/0.1	0.7/0.6

Table 5. General error and lag factors in variable-rate fertilizer application for Florida citrus.

Source	Time, s	Distance lag/error level, m (ft)[z]
A) DGPS-Coast Guard[w]	0.1	1.0 (3.3) (E)[x]
DGPS-WAAS[w]	0.2	2.0 (6.6) (E)
B) Sensor & control	0.1-0.2	0.2-0.4 (0.7-1.4) (L)[x]
C) Hydraulic-mechanical	0.5-1.0	1.1-2.2 (3.7-7.3) (L)
D) Drop time	0.4-0.6	0.9-1.3 (2.9-4.4) (L)
B + C + D	1.0-1.8	2.2-4.1 (7.3-13.2) (L)
B + C + D (experimental)	1.4	3.2 (10.5) (L)
Velocity[y]	0.3	0.8 (2.2) (L)

[z]Based on 8 km/h (5 mph) speed.
[y]10% deviation at 6 m (20 ft) offset.
[x]E-error, L-lag.
[w]Differential correction through U.S. Coast Guard Beacon or wide area augmentation system WAAS.

passes are plotted. All mass values (MV) of collected fertilizer material were normalized based on maximum amount of material collected in each test. Hence, the relationship, MV_i/MV_{max}, was used where MV_i is the material collected for i^{th} position. No obvious peak distribution occurred as the lower tree canopy tended to disperse the material. Hence, the material distributed was quite different from Gaussian pattern observed in open field tests. Further uniformity may have resulted from the dual application as each middle was traversed with the fertilizer unit. The coefficient of variation (CV) across the under-tree swath for fertilizer distribution averaged 41.0%. Data for these plots were obtained for a dual pass application, i.e., the fertilizer applicator traversed each row.

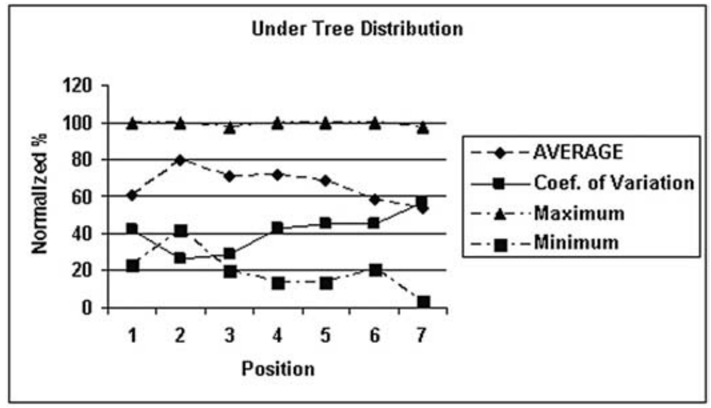

Fig. 5. Under-tree tray collection of dry fertilizer distribution presented as normalized values representing ratio of mass of fertilizer collected at i^{th} position divided by maximum amount of material collected at any position for each test. Trays positioned on 2 ft (51 cm) centers with position 4 at centerline of tree row.

This technique is common practice in interior Florida groves but not employed in bedded grove configurations.

The field tests using three different spreader units were summarized in Table 6. Projected rates were determined based on the actual coverage assuming an under-tree banded application. These rates varied dependent upon tree row spacing and individual versus alternate row travel. For Chandler and BestAir units, groves were bedded and growers were requesting a higher percent distribution on the side of the tree opposite the ditch. Using the in-row tree centerline, a breakdown of percentage of fertilizer collected on near and far side of trees was calculated. The percent of fertilizer deposited on the near side was slightly higher than an anticipated distribution ratio of 60:40. Projected rates were very close to actual rates with the largest difference occurring in two M&D tests where the collected material was 20% greater than the projected amount. Part of the errors can be attributed to calibration errors (product density, ground speed, etc.). Since tray locations were selected in a solid row of trees, the dynamics of the control and mechanical-hydraulic system should have been minimal. As expected, the CV values were higher for the alternate row applications (68.1 to 84.6%).

Table 6. Summary of field tests for rate and distribution.

	Set rate		Projected rate[z]		Actual rate				
Test unit, Trial no.	kg/ha	lb/acre	kg/ha	lb/acre	kg/ha	lb/acre	% Difference[y]	Distribution C.V. %	Near/far ratio (%/%)
Chandler, 1	420	375	484	432.1	479	427.6	-1.0	40.4	71.4/28.6
Chandler, 2	420	375	484	432.1	498	444.9	3.0	55.4	68.1/31.9
BestAir, 1	560	500	1120	1000	1183	1056.3	5.6	97.1	78.3/21.7
BestAir, 2	560	500	1120	1000	1180	1054.1	5.4	130.6	84.6/15.4
M&D/Chem. Containers, 1	772	689	1135	1013	1370	1223	20.7	53.6	39.0/61.0 (2 pass)
M&D/Chem. Containers, 2	672	600	988	882	1187	1060	20.2	32.9	54.7/45.3 (2 pass)
M&D/Chem. Containers, 3	840	750	1234	1102	1407	1256	14.0	17.2	51.4/48.6 (2 pass)
M&D/Chem. Containers, 4	647	578	952	850	949	847	-0.4	24.9	55.0/45.0 (2 pass)
M&D/Chem. Containers, 5	660	589	970	866	965	862	-0.5	70.7	62.5/37.5
M&D/Chem. Containers, 6	1120	1000	1648	1471	1739	1553	5.6	32.7	45.2/54.8
M&D/Chem. Containers, 7	560	500	823	735	918	820	11.6	48.9	50.4/49.6
Average	657	586.9	996	889.4	1080	964.0	7.7	54.9	60.1/39.9

[z]Based on banded application to know between-row spaced trees.
[y]Based on projected rate.

Conclusion

Components of a test system and procedures to evaluate granular fertilizer application under dynamic conditions were developed. A tray grid sampling system was devised to collect discharged fertilizer under controlled transitional states. These transitions were based either on real-time control (photocell or ultrasonic sensor response) or GPS map-based control. Initial tests indicated that transition time to reach steady state ranged from 0.53 to 0.97 s, dependent upon controller configuration. Static and dynamic tests indicated a difference in performance in switch state transitions but comparable performance for real-time and map-based control. Delay time (on-off) was 30% lower than in average off-on transitions. With respect to controller configuration, preliminary results indicated that a setting of gain = 5, initial valve setting = 25%, was superior to much lower or higher gain levels. CV values of fertilizer distribution under steady-state averaged 103.8%.

Fertilizer application under grove conditions yielded distributions quite different from the Gaussian distributions found in open-field standardized tests. Coefficients of variation in tray distribution tests were lower (41.0%) in grove conditions compared to open field trials (93.9%), when comparing the same spreader unit. Actual application rates, determined through under-tree tray material collection, were found to be very consistent with projected controller rates. Differences ranged from <1 to 20.7% and averaged 7.7% in evaluating three different spreader units.

Literature Cited

ASAE Standards, 51st ed. 2004. St. Joseph, Mich., ASAE.

Ayers, P. D., S. M. Rogowski, and B. L. Kimble. 1990. An investigation of factors affecting sprayer control system performance. Appl. Eng. Agr. 6(6):701-708.

CAC. 2003. 2002-2003 season fresh Florida shipments. Citrus Administrative Committee, Lakeland, FL.

Chan, C. W., J. K. Schueller, W. M. Miller, J. D. Whitney, and T. A. Wheaton. 1999. Accuracy in spatially-variable crop production and an illustration in citrus yield mapping, p. 805-813. In: J. V. Stafford (ed.). Precision Agriculture '99. Sheffield Academic Press, Sheffield, UK.

Chan, C. W., J. K. Schueller, W. M. Miller, J. D. Whitney, T. A. Wheaton, and J. A. Cornell. 2002. Error sources on yield-based fertilizer variable rate application maps. Precision Agr. 3:81-94.

Cugati, S., W. M. Miller, and J. K. Schueller. 2003. Automation concepts for the variable rate fertilizer applicator for tree farming. Fourth European Conference on Precision Agriculture. Berlin, Germany.

Enge, P. 2004. Retailing the global positioning system. Scientific American. 290(5):91-97.

FDACS-OAWP. 2003. Florida's Agricultural Water Policy. Florida Dept. of Ag. and Cons. Services—office of Agricultural Water Policy. http://www.floridaagwaterpolicy.com.

Fulton, J. P., S. A. Shearer, G. Chabra, and S. F. Higgins. 2001. Performance assessment and model development of a variable-rate, spinner-disc fertilizer applicator. Trans. ASAE 44:1071-1081.

Glover, J. W. and J. V. Baird. 1973. Performance of spinner type fertilizer spreaders. Trans. ASAE 16:48-51.

Li, B., J. D. Whitney, W. M. Miller, and T. A. Wheaton. 2002. Ultrasonic-based canopy volume measurements of citrus trees. ASAE Paper No. 021053. St. Joseph, MI, ASAE.

Olieslagers, R., H. Ramon, and J. De Baerdemaeker. 1996. Calculation of fertilizer distribution patterns from a spinning disc spreader by means of a simulation model. J. Agr. Eng. Res. 63:137-152.

Mennel, R. M. and A. R. Reece. 1963. The theory of the centrifugal distributor, III. Particle trajectories. J. Agr. Eng. Res. 8(1):78-84.

Miller, W. M., J. D. Whitney, A. Schumann, and S. Buchanon. 2003. A test program to assess VRT granular fertilizer applications for citrus. ASAE Paper No. 031126. St. Joseph, MI, ASAE.

Parish, R. L. 2002. Rate setting effects on fertilizer spreader distribution. Appl. Eng. Agr. 18(3):301-304.

Reed, W. B. and E. Wacker. 1970. Determining distribution pattern of dry-fertilizer applicators. Trans. ASAE 13(1):85-89.

Scholberg, J. M., L. R. Parsons, and T.A. Wheaton. 2000. Some production considerations for more efficient nitrogen use. Citrus Industry 81(2):18-19.

Sogaard, H. T. and P. Kierkegaard. 1994. Yield reduction resulting from uneven fertilizer distribution. Trans. ASAE 39(6):1749-1752.

Stombaugh, T., S. A. Shearer, and J. Fulton. 2002. Elements of a dynamic GPS test standard. ASAE Paper No. 021150. St. Joseph, MI, ASAE.

Tucker, D. P. H., A. K. Alva, L. K. Jackson, and T. A. Wheaton. 1995. Nutrition of Florida citrus trees. University of Fla., Gainesville Publ. SP 169.