VARIABLE RATE GRANULAR FERTILIZATION OF CITRUS GROVES: SPREADER PERFORMANCE WITH SINGLE-TREE PRESCRIPTION ZONES

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ABSTRACT. *Commercial variable rate technology (VRT) fertilizer spreaders for citrus are currently being implemented in Florida groves to improve profitability and reduce nitrate contamination of groundwater. Although VRT spreaders incorporate proven embedded controllers and tree sensors which permit changing fertilizer rates according to tree size, there is currently limited information on their performance characteristics in spatially variable groves. This study investigated the performance characteristics of a split-chain, spinner-type VRT spreader during fertilization of a commercial citrus grove. Six nitrogen rates (0, 134, 168, 202, 236, and 270 kg* ha^{-1} y^{-1}*) were varied according to a prescription map developed from ultrasonically measured tree size information. Missing trees and one-year-old reset trees were not fertilized with the spreader. Target fertilizer rates for 1490 trees in an 8.1-ha experimental area were compared with actual fertilizer rates calculated from geartooth speed sensors monitoring the conveyor chain speed. Through classification and regression analysis, spreader performance and response times during transitions from zero or low fertilizer rates to high rates and vice versa were compared. In this grove, 73.1% of the fertilizer rate changes were required between a single-tree space of 5.3-m linear row distance, taking about 4 s to drive at 1.34 m* s^{-1}*. The spreader had an average on-off response time of* ≤ 3 *s, and an average rate changing response time of 2 to 5 s. Based on these data, the spreader design is not suitable for rapid fertilizer rate changes between single tree spaces, but could be greatly improved by substituting its hydraulic servo control valves with faster devices.*

Keywords. *Variable rates, Fertilization, Citrus, Tree size, Response times.*

Florida is the world's leading producer of grapefruit and second only to Brazil in orange production. Currently, best management practices (BMPs) for various growing areas are being implemented to address nitrate levels in groundwater (FDACS-OAWP, 2003). A principal concern for Florida citrus is over-fertilization and the leaching of nitrogen (N) fertilizer, especially nitrates, into the groundwater (Jones et al., 1990; Alva et al., 1998; Lamb et al., 1999). In general, loss of N only occurs when mineral N (NH_4 and NO_3) are present in excess of plant needs (Johnson and Raun, 1995). Florida citrus fertilization rates are prescribed according to tree age and yield (Tucker et al., 1995), both of which relate to tree size. Due to the high variability of tree sizes in typical central Florida citrus groves, a research program was undertaken to evaluate the merits of granular fertilizer applications using variable-rate technologies (VRTs). By matching N rate to tree size and not fertilizing small resets, VRT fertilization can save fertilizer costs, reduce N leaching, and potentially increase yields per hectare (Zaman et al., 2005). Industry reports on VRT fertilization for citrus quote up to 30% reduction in fertilizer consumption, and a new study by the authors achieved a 38% reduction in fertilizer use for the first year in a variable Valencia grove (Zaman et al., 2005). Despite limited supporting research data, commercial variable-rate granular fertilizer spreaders for citrus are currently being implemented in Florida, and the interest is growing as support for the BMPs increases.

Currently, VRT spreaders are often hybrids of variable rate technology borrowed from crop and vegetable production and existing conventional dry fertilizer spreaders used elsewhere for decades. The performance of these spreaders in tree crop applications has not been validated. The first goal of our research program was to measure the dynamic performance of several VRT fertilizer spreaders in order to measure accuracy of various systems and compare their control performance. A test procedure using ASAE S341.3 (*ASAE Standards*, 2004) and a field-testing facility were developed to generate two-dimensional dynamic performance information (Miller et al., 2003). Results indicated that spreader rate transition time to change and reach steady state ranged from 0.53 to 0.97 s, dependent upon controller configuration. A difference in performance between increasing (off-on) or decreasing (on-off) rate transitions was noted, but comparable performance was achieved for real-time (sensor) and map-based control. Times required for on-off transitions were 30% lower (faster) than those for average off-on transitions. Miller et al. (2003) concluded that further tuning of the spreader's controller should be investigated to obtain optimal performance. The implementation of variable

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granular fertilizer rates in typical older Florida citrus groves is particularly challenging because in excess of 70% of the rate changes required can occur within the distance of a single tree space (3 to 6 m). The second goal, discussed in this article, was to implement the VRT spreader in such a commercial citrus grove with variable tree sizes to test its performance under field conditions. The specific objective was to test the capability of the VRT controller and hydraulic drive system to change fertilizer rates rapidly over short distances required for single tree prescription zones.

MATERIALS AND METHODS

The experiment was conducted during 2004 in a commercial 'Valencia' orange (*Citrus sinensis* [L.] Osb.) grove of central Florida's ridge region near Fort Meade, in Polk County (27° 44' N, 81° 42' W). The canopy volumes of trees in this grove ranged from 0 (missing) to 240 m^3, due to the age of the grove (>40 years), and the practice of continuously replanting (resetting) of dead, damaged, or diseased trees. Tree canopy volumes were measured in 2003 with an automated ultrasonic ranging system described by Schumann and Zaman (2005). We selected the 8.1-ha western half of the grove (1490 trees) for testing variable fertilizer rates, while the eastern half was treated uniformly as before for control purposes. The previous fertilizer N rate used uniformly across the grove by the grower was 270 kg ha^{-1} y^{-1}, split equally into four applications for February, April, May, and October. For the VRT experiment, we established six different fertilizer rates (0, 134, 168, 202, 236, 270 kg N ha^{-1} y^{-1}), which were directly related to tree canopy volumes (Zaman et al., 2005). Missing trees and one-year-old reset trees were not fertilized with the spreader. A prescription map with 1490 single tree spaces as prescription zones (fig. 1) was constructed from ground-truthed grove dimensions using a Trimble AgGPS132 DGPS (Trimble Navigation Ltd., Sunnyvale, Calif.), Arcview 3.2 GIS (ESRI, Redlands, Calif.) and the "Orchard" extension (Lincoln Ventures Ltd., Hamilton, NZ). Trees were spaced at 10.6 × 5.3 m in the grove. The same prescription map was used for VRT fertilizer application in February, April, and May. Commercial granular fertilizer material containing 10% N, 0% P, 10% K was used in February, and during April and May this was changed to 15% N, 0% P, 14% K. Due to substantial tree damage from hurricanes in August and September, the same prescription map could not be used in October, so that application date was omitted from this analysis.

The configuration of the tractor-drawn, 2.7-Mg capacity, split-chain, spinner-type VRT spreader (M&D, Arcadia, Fla.) and Legacy 6000 controller (Midwest Technologies, Springfield, Ill.) was fully described by Miller et al. (2003) as "Test Unit #1." The spreader used a radar sensor for speed measurement, and the Trimble AgGPS132 DGPS, running at 5-Hz output and U.S. Coast Guard beacon correction was used for positioning. Fertilizer was applied to both sides of the trees by driving each row middle at an average spreader speed of 1.34 m s^{-1}. Target and actual fertilizer rates for data points within the 1490 tree spaces were calculated from the prescription map, and geartooth speed sensors monitoring the chain speed at a frequency of 1 Hz, respectively. These data were combined with timestamps and DGPS coordinates and continuously stored in the controller's memory during operation. After each fertilizer application, the data sequence for each side of the spreader was processed with a custom computer program written in Pascal to identify the direction of rate change (increasing or decreasing) and the duration of a given rate setting in seconds. The data were then filtered and classified to obtain average target and actual fertilizer rates for all combinations of rate duration and direction changes using Genstat 6.0 (VSN International Ltd, Oxford, U.K.). Average data were plotted as time series for each fertilizer rate to determine the average spreader response times. Linear regression and Student's two-sided t-test procedures (Genstat 6.0) were used to test the goodness of fit and bias of the actual and target fertilizer rates at increasing time periods after rate changes.

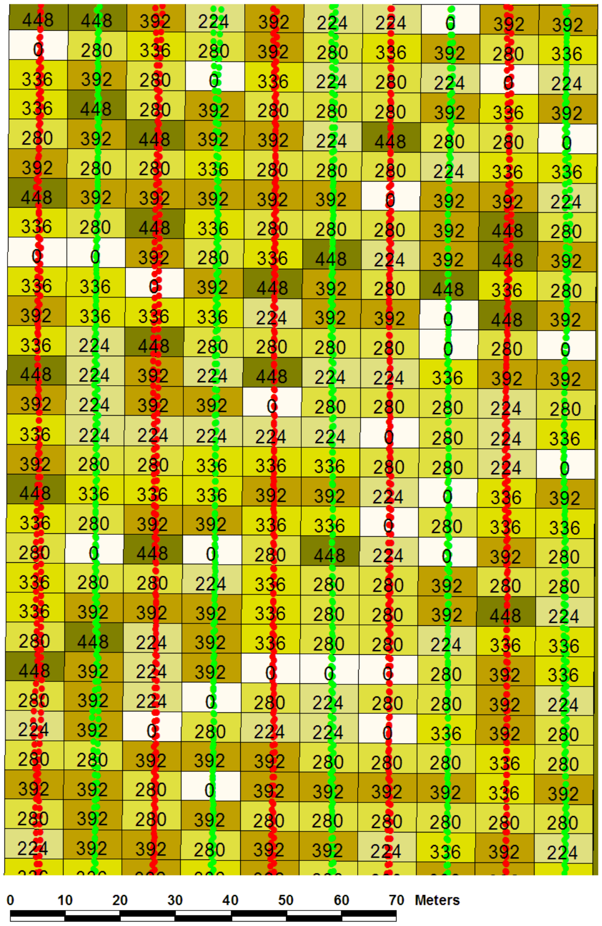

Figure 1. Representative portion of the prescription map in April 2004. Tree rows and directions of travel are N-S, S-N. Numbers represent fertilizer rates in kg ha^{-1}. Colored points (red, green, or dark, light) represent left and right sides of the spreader's data log, respectively.

RESULTS AND DISCUSSION

In this grove, 73.1%, 17.2%, 6.01%, and 1.98% of the rate zones extended over 1, 2, 3, and 4 contiguous tree spaces, respectively. The remaining larger zones were negligible (0.871% of the grove). At the 1.34-m s^{-1} driving speed, approximately 4 s was required to pass one tree space. In February, the rates were 50% higher than in April and May due to the different analysis (15% vs. 10% N) of fertilizer used. The left and right chains of the spreader behaved nearly

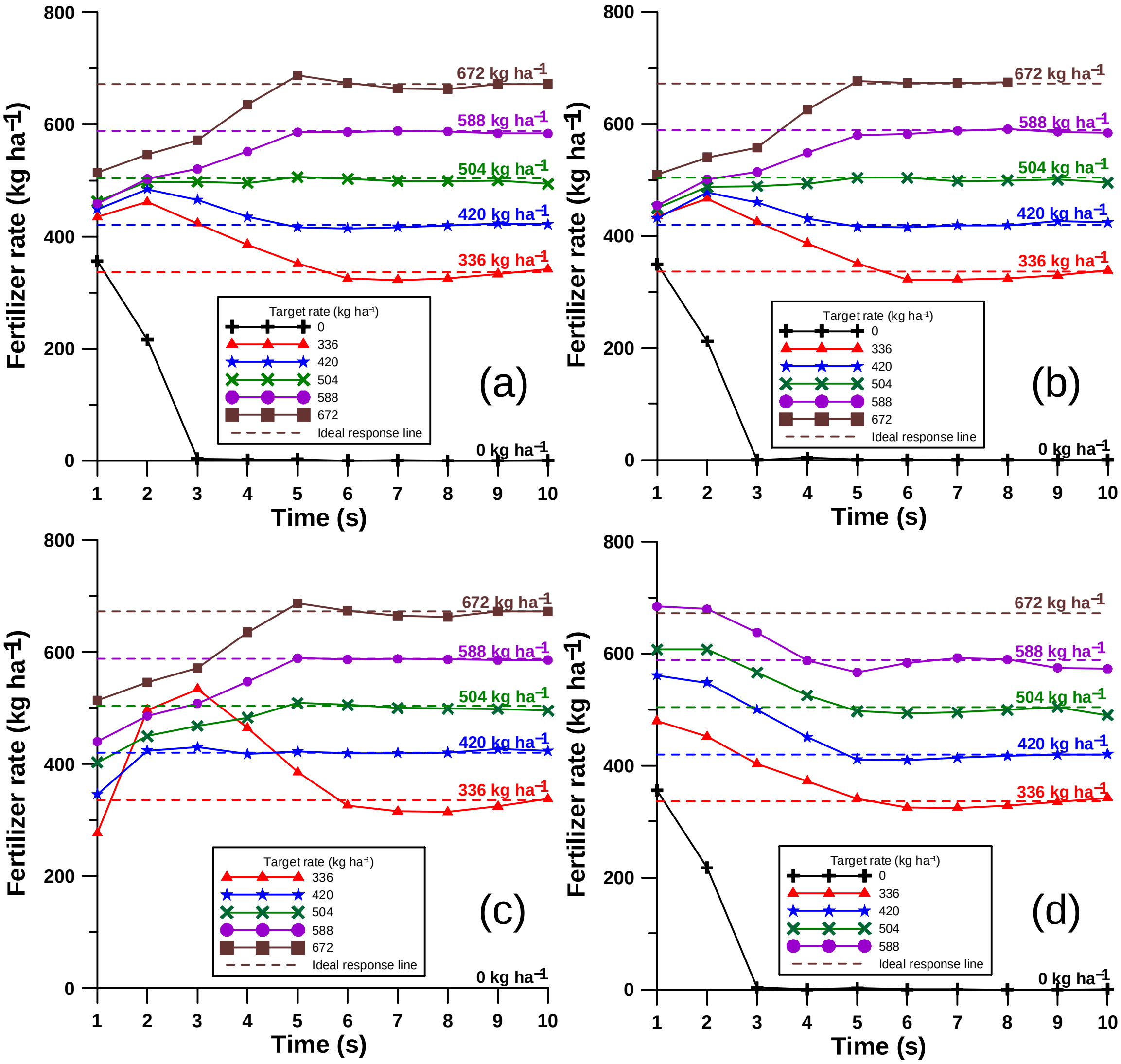

Figure 2. February time series of average actual fertilizer rates for (a) left, (b) right sides (chains) of the spreader, and (c) increasing, (d) decreasing rate changes.

identically, with an average on-off response time of ≤ 3 s, and an average rate changing response time of 2 to 5 s (fig. 2a, b). The middle rate achieved the best response time while the low rate showed signs of overshooting. This behavior was probably caused by the controller's gain and initial valve position settings, which were intended for the middle rate.

During rate transitions from low to high, there was considerable initial overshooting of the lowest rate during the first 4 s (fig. 2c). This was probably due to the initial valve position and gain settings used in the controller when starting from zero, both of which were optimized for medium rates. Insufficient feedback frequencies from the 67-pulses-per-revolution geartooth encoder at the slowest chain speed may also explain the overshooting of low rates by the controller. Overshooting of rates was less evident during high to low transitions (fig. 2d). In April and May, ≤ 3-s response times were measured again for the on-off transition (figs. 3 and 4). Other rate changes were generally attained in 2 to 5 s, except for the right side high rate in April (fig. 3b) and May (fig. 4b). In both cases, it appeared that the high rate was not properly attained on average. This situation might arise when the hydraulic motor driving the chain on the right side of the spreader was unable to reach the higher rotation speeds required. In April, there was also more overshooting during low rate changes, especially on the right side (fig. 3b, c) than in February or May.

Linear correlation between actual and target fertilizer rates increased rapidly during the 1 s ($R^2 < 0.06$) to 6 s ($R^2 > 0.95$) after a rate change (tables 1-3). On average it took at least 3 to 4 s for a rate to stabilize sufficiently so that the actual and target rates were not significantly different by the t-test (tables 1-3). It took at least 6 s for the root mean square error (RMSE) of the fertilizer rates to reach reasonably low levels (RMSE < 24 kg ha^{-1}). Miller et al. (2003) reported reduced response times of 0.53 to 0.97 s for the same spreader. However their calculations included a distance offset from the DGPS antenna to the spinner discharge point. Their data were therefore collected and reported on an absolute position and not a time basis. Thus with an antenna to discharge offset of 4.9 m and a vehicle speed of 1.34 m s^{-1}, their reported values should be increased by ~3.8 s for direct comparison with these results. Fulton et al. (2001) reported transition distances of about 22.5 m for VRT fertilizer rate changes of 56 to 168 kg ha^{-1}, traveling at a speed of 20.4 km h^{-1}. These

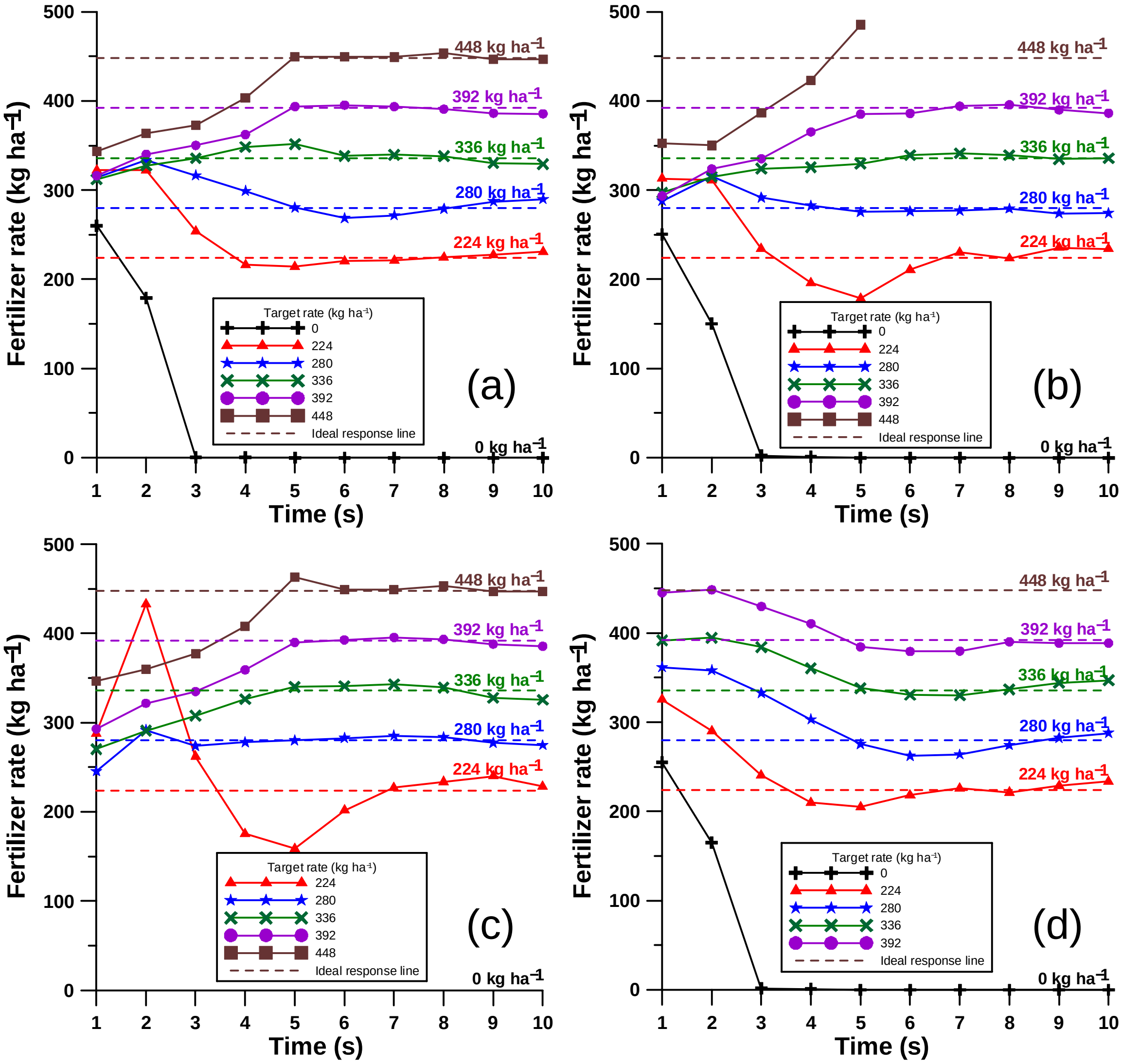

Figure 3. April time series of average actual fertilizer rates for (a) left, (b) right sides (chains) of the spreader, and (c) increasing, (d) decreasing rate changes.

results translate to a time lag of about 3.9 s for the completion of the rate change.

Based on these experiments, it appears that this fertilizer spreader does not have the performance characteristics required for single-tree VRT fertilization. At the tree spacing and driving speed used in this study, the first tree in a zone could already be passed by the time (up to 4 to 5 s, or 5 to 7 m down the row) the control system achieves a sufficiently accurate rate.

At faster driving speeds, which are common for commercial operators, the 4-s latency in the system would be even more inappropriate for single-tree VRT fertilization. Since 73.1% of the contiguous prescription zones in this grove were one tree space in size, the response times of this spreader would be inadequate in most of the grove area. The measured time delays in this analysis do not include latency derived from the DGPS or from the Legacy controller reading the appropriate rate from the prescription map. Additional mechanical latency in the spreader system, including the time lag for fertilizer particles to fall to the ground, are also not included in these analyses. Although these additional delays could further deteriorate system response, some of the constant time lags (such as fertilizer drop time) can be factored out by the ‘look ahead’ feature of the Legacy controller. However if a system delay is not constant or repeatable, such as the time period required to change rates, then a look-ahead feature will not be useful. By example, looking ahead for small single-tree management zones would imply changing the rate ahead of arrival at the desired zone. Doing this would require changing the rate while the spreader is still in the previous tree zone, with obvious detrimental effects to that tree’s application rate. The only solution to this lag error is faster rate change response times, which is why the portions of the system tested in these experiments, i.e. the hydraulic drive and conveyor chain control system, were considered the most critical components affecting performance of the spreader with single tree prescription zones.

According to Miller et al. (2003), the controller has two settings, which can be adjusted to alter the spreader’s response. First, the gain can be set between a normalized operating range of 0.1 to 10 while the initial valve position can be set between 5% and 90%. These normally were set at gain = 5%, valve position = 25% for these experiments, based

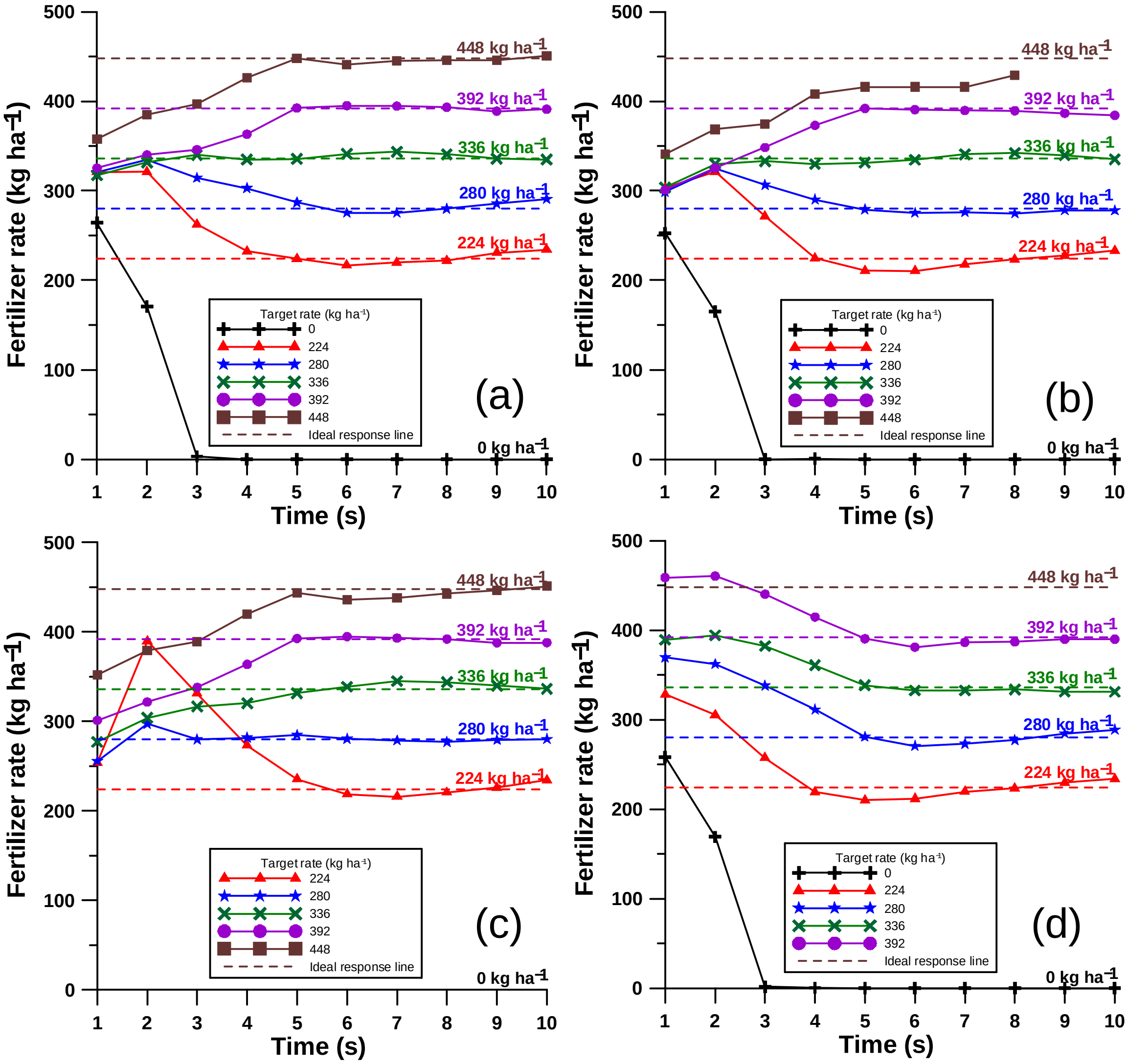

Figure 4. May time series of average actual fertilizer rates for (a) left, (b) right sides (chains) of the spreader, and (c) increasing, (d) decreasing rate changes.

Table 1. Comparison of mean target and actual fertilizer rates recorded in February during the 6 s after a rate change.

Time (s)	Fertilizer Application	Data Points (n)	Mean Rate (kg ha^{-1})	R^2	RMSE (kg ha^{-1})	t (D.F.)[a] F-Probability
1	Target	2080	353.9	0.055	161.0	-8.17 (4008)
	Actual	2080	392.3			$<0.001^{***}$
2	Target	1968	349.4	0.311	139.6	-9.76 (3879)
	Actual	1968	398.9			$<0.001^{***}$
3	Target	1796	348.1	0.726	88.6	-2.21 (3590)
	Actual	1796	360.8			0.027^{*}
4	Target	1444	335.0	0.878	61.6	-0.79 (2886)
	Actual	1444	340.2			0.427 NS
5	Target	848	305.1	0.956	38.9	-0.27 (1694)
	Actual	848	307.5			0.789 NS
6	Target	658	323.4	0.982	23.3	0.4 (1314)
	Actual	658	319.5			0.692 NS

[a] t (D.F.) Student's 2-sided t-test at specified degrees of freedom.
*, **, *** significant differences ($P < 0.05$, $P < 0.01$, $P < 0.001$, respectively).
NS non-significant.

Table 2. Comparison of mean target and actual fertilizer rates recorded in April during the 6 s after a rate change.

Time (s)	Fertilizer Application	Data Points (n)	Mean Rate (kg ha^{-1})	R^2	RMSE (kg ha^{-1})	t (D.F.)[a] F-Probability
1	Target	2128	235.2	0.018	108.5	-10.0 (4254)
	Actual	2128	268.5			$<0.001^{***}$
2	Target	2029	233.8	0.154	102.3	-9.7 (4026)
	Actual	2029	269.1			$<0.001^{***}$
3	Target	1832	231.6	0.616	70.8	0.26 (3602)
	Actual	1832	230.6			0.792 NS
4	Target	1427	223.8	0.754	59.4	1.20 (2826)
	Actual	1427	218.1			0.230 NS
5	Target	834	205.8	0.906	38.8	0.77 (1666)
	Actual	834	200.8			0.438 NS
6	Target	580	221.2	0.954	24.2	0.50 (1158)
	Actual	580	217.9			0.620 NS

[a] t (D.F.) Student's 2-sided t-test at specified degrees of freedom.
*, **, *** significant differences ($P < 0.05$, $P < 0.01$, $P < 0.001$, respectively).
NS non-significant.

Table 3. Comparison of mean target and actual fertilizer rates recorded in May during the 6 s after a rate change.

Time (s)	Fertilizer Application	Data Points (n)	Mean Rate (kg ha^{-1})	R^2	RMSE (kg ha^{-1})	t (D.F.)[a] F-Probability
1	Target	2077	234.7	0.029	109.0	-11.6 (4106)
	Actual	2077	272.5			<0.001***
2	Target	1940	232.8	0.193	101.2	-11.2 (3878)
	Actual	1940	273.4			<0.001***
3	Target	1727	231.0	0.677	65.3	-1.56 (3422)
	Actual	1727	237.4			0.119 NS
4	Target	1279	219.9	0.836	49.4	0.04 (2556)
	Actual	1279	219.7			0.969 NS
5	Target	799	203.3	0.953	27.3	0.15 (1596)
	Actual	799	202.3			0.883 NS
6	Target	563	222.8	0.978	16.7	0.45 (1124)
	Actual	563	222.8			0.650 NS

[a] t (D.F.) Student's 2-sided t-test at specified degrees of freedom.
*, **, *** significant differences ($P < 0.05$, $P < 0.01$, $P < 0.001$, respectively).
NS non-significant.

on the previous research, where a gain or valve setting which was too high tended to cause excessive over-shooting during rate changes.

CONCLUSIONS

In order for VRT fertilizer spreaders to have reasonable accuracy for tree-to-tree rate changes, they need to have response times for rate changes in the order of <1 s. The slow response times of >4 s measured in this study would be acceptable only for applications requiring larger prescription zones or less abrupt rate boundaries, such as in soil management zones. Although these experiments were conducted with prescription maps for repeated use, similar response rates are expected for real-time sensor-driven rate changes, described in previous studies. The maximum on-off rate response time of 3 s measured in this study agrees well with the 3-s response time for fully open to fully closed in the hydraulic servo valve's specifications, but the overall response times were much longer than those previously recorded by Miller et al. (2003) in a test track. Our ongoing and future research will be testing and modeling how every component in the VRT spreader system can affect system performance in the field and what steps can be taken to reduce response times.

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