

Application Uniformity of a Commercial Center Pivot Variable Rate Irrigation System¹

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Abstract. With the advent of commercial variable rate irrigation (VRI) systems, there is a great interest in using them to improve water use efficiency, implement deficit irrigation strategies in water limited regions and manage water applications for many other important objectives. Multiple catch can trials were performed to determine the application uniformity of a commercial VRI system for a 3-span center pivot. Catch cans were used in radial transects and grid patterns to test the uniformity in multiple zones along the pivot lateral at different watering rates (100%, 80%, 70%, 50%, and 30% of nozzle "ON" time), and in an arc-wise pattern to test the circumferential uniformity and sector-wise resolution of the system. Results showed that the Heerman and Hein coefficient of uniformity (CU_{HH}) and the lower-quarter distribution uniformity (DU_{lq}) were significantly lower when the watering rate was 30%; but there were no significant differences in uniformity for the higher watering levels or among span locations. With respect to circumferential uniformity, the mean CU_{HH} and DU_{lq} values were 88.1% and 0.82; these values were not significantly different from those obtained when catch cans were arranged in a transect pattern. The mean evaporation and drift loss for the transect-type trials was 10.8%.

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Keywords: center pivot system, uniformity of application, variable rate irrigation

INTRODUCTION

Due to increasing competition for quality water and limited water resources, improving irrigation efficiency is a continuing goal for production agriculture. Site-specific or precision irrigation using VRI equipment is one method of improving control of the depth and timing of irrigations. Application uniformity and irrigation control are especially critical for the success of site-specific irrigation.

Commercially available VRI equipment enables a moving sprinkler system to adjust the depth of water applied along the lateral. The commercial VRI software enables a field to be divided into management zones that range in width from 2° to 180° sector angles, while the minimum radial length of a zone is dependent on the number of drop hoses in a sprinkler bank controlled by one valve and the distance between the drops. Sprinkler banks are configurable and controlled by a single solenoid valve that activates hydraulic valves on drops in a bank. Quantifying the uniformity of the depth of water applied within a management zone and determining the resolution of control in an arc-wise

direction is critical for assessing VRI system capabilities and for interpreting experimental results (Stone et al., 2006).

The objectives of this study were to evaluate the application uniformity and practical management zone resolution for a 3-span center pivot irrigation system retrofitted with a commercial variable rate irrigation system.

METHODS AND MATERIALS

Experimental site and existing irrigation system

Experiments took place at the Conservation and Production Research Laboratory, Bushland, Texas (35° 11' N, 102° 06' W, 1170 m above mean sea level) using a three span center pivot system with pivot lateral length of 131-m and drop hoses spaced 1.52-m apart. Catch can trials were performed during the months of April and May 2011 during daylight hours. Meteorological data was collected from a nearby weather station located less than 30 m from the pivot field (Evetts et al., 2011).

Variable Rate Irrigation Equipment

An existing three-span center pivot system with a Pro-panel 2² was retrofitted with a variable rate irrigation (VRI) system that is commercially available from Valmont Industries Inc., Valley, NE. The major VRI components included a programmable logic controller (PLC) that actuates electronic solenoid valves for sprinkler bank control; hydraulic valves plumbed between the pivot lateral and each drop hose (Fig. 1) and arranged in banks, each of which was controlled by a separate electronic solenoid valve; a geographical positioning system (GPS) receiver; and variable rate irrigation prescription firmware and software. Watering application rates were enabled by ON/OFF pulsing of the hydraulic valves; and the sprinkler bank duty-cycle was prescribed through the VRI software. Each of the sprinkler banks was configured to include six drop hoses; and 12 banks were established along the pivot lateral. An electronic solenoid valve controlled each bank and the number of drop hoses within the bank defined the radial dimensions of a management zone.

Flexible drop hoses 19-mm (³/₄") in diameter were made of polyethylene and equipped with a pressure regulator rated at 41.37-kPa (6-psi), and a low drift nozzle system (LDN) with a single concave pad (Senninger, Clermont, FL). Drop hoses were approximately 1.8 m above the ground and spaced 1.5 m apart. Nozzle design flows were between 0.027 and 0.316 L s⁻¹ (0.43 – 5.0 gpm) and the sprinkler operated at an average pressure of 172.4 kPa (25 psi) and the maximum throw diameters ranged from 2.6-m to 4.9-m.

² The mention of trade names of commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture. USDA is an equal opportunity provider and employer.

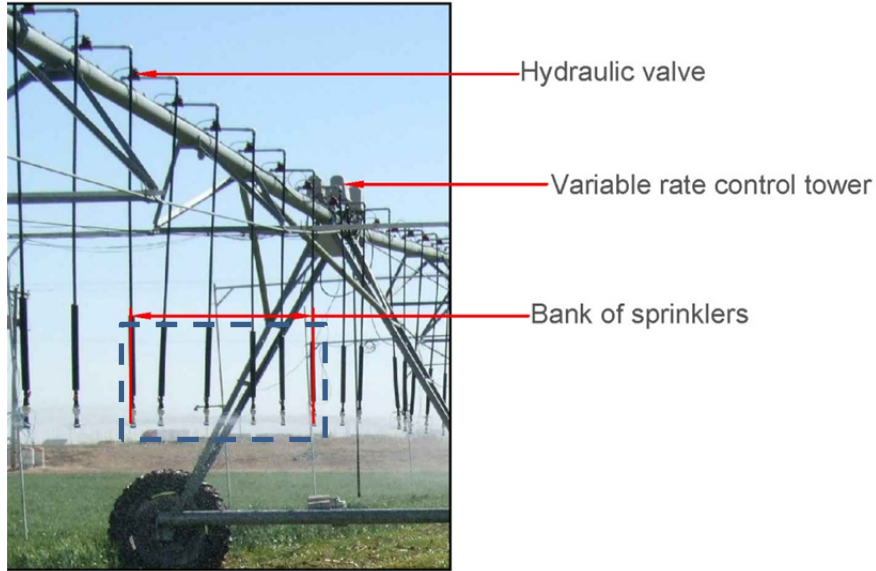


Figure 1. Section of center pivot showing hydraulic valves on each drop hose, variable rate control towers located near the regular tower box, and bank of sprinklers (6 drop hoses) which comprise a zone.

Catch can specifications

Catch cans (15.2 cm ht. × 15.4 cm dia.) were constructed of white rigid polyvinyl chloride (PVC), Schedule-40 (Fig. 2). The top portion of each can was beveled to define the catch area precisely. Can height was chosen to help reduce droplet splashout. The cans were placed over mowed wheat, each on a three-legged wire stand. The top of the stand was approximately 7 cm above the ground and was leveled by adjusting the penetration into the soil. Prior to each trial, dirt and insects were cleaned from the collectors and vegetable oil was sprayed inside the collector to decrease evaporative losses.



Figure 2. Typical positioning of catch can in the pivot field for uniformity testing.

Trials

To evaluate application uniformity of the VRI system, we aligned the catch cans in three patterns: (1) transect; (2) grid; and (3) arc-wise (Fig. 3). The transect- and grid-type patterns were combined during the first five trials. The pivot travel speed was set at 9%

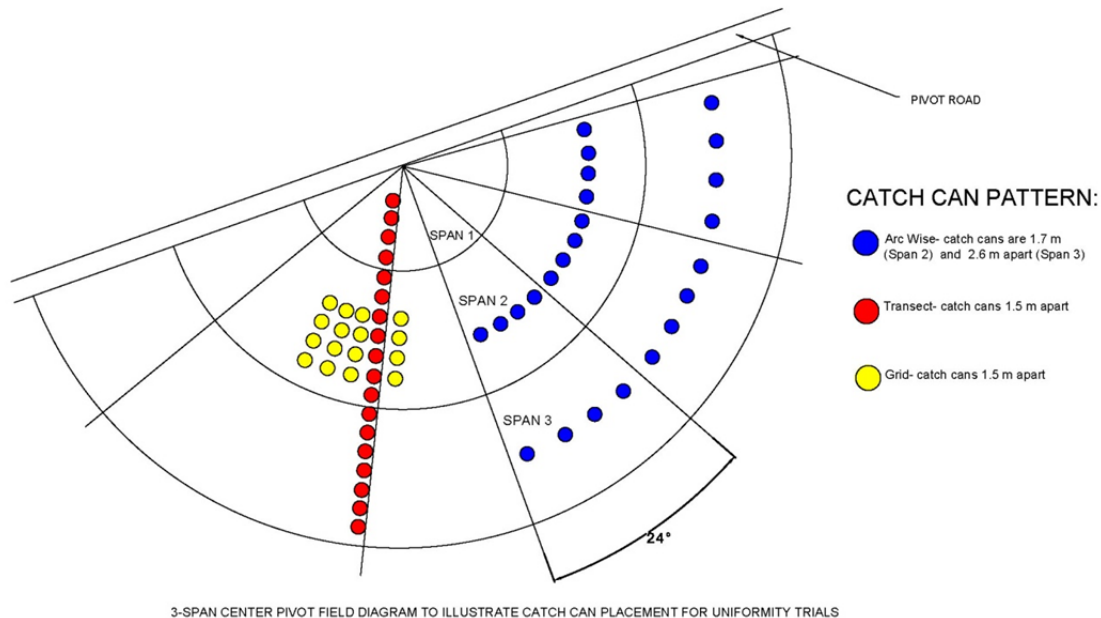


Figure 3. Catch can layout patterns for uniformity testing of variable rate irrigation system over a 3-span center pivot.

for Trials 1-4 and Trials 6-10; and at 4% for Trial 5 (Table 1). Seventy catch cans were placed in a transect the length of the pivot lateral, and an additional 20 were placed to form a 5 x 5 grid within a single zone. During the trials, 12 sprinkler banks were actuated, and every two banks were programmed to deliver water at the same rate; thereby 6 zones were established. The order of the watering rates was randomized along the lateral for Trials 1-5. The minimum collector distance to the pivot point was 21.8-m .

Twelve collectors were placed in each zone for Trials 1-5; a 2 x 14 grid was established in each of the three zones for Trial 6; 10 collectors were placed in each of the 12° sectors for Trial 7; sector length was 13-m. Sixteen collectors were located in each of the 24° sectors for Trials 8-10. Collectors were spaced 1.5-m apart for Trials 1-6; 1.3-m for Trial 7; and 1.7-m in the second span and 2.6-m in the third span for Trials 8-10. The length of the sector between transitions was 26.3-m in span 2 and 99.4-m in span 3. The level of watering rates was chosen to evaluate the pulsing response between rate changes of low-to-medium, low-to-high, and medium-to- high, as well as the converse.

Table 1. Trials, collector patterns, and watering rates per zone for uniformity testing

Trial	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Travel speed
1: Transect/grid	50	30	50	30	80	100 (grid)	9%
2: Transect/grid	30	80	50	100	30	100 (grid)	9%
3: Transect/grid	50	100	80 (grid)	30	50	30	9%
4: Transect/grid	100	30 (grid)	50	80	30	50	9%
5: Transect/grid	100	30 (grid)	50	80	30	50	4%
6: Grid	30	-	50	-	80	-	9%
7: Arc-wise, 12°	-	-	80, 30, 100, 50, 80, 100, 30, 50, 100, 30	-	-	-	9%
8: Arc-wise, 24°	-	30, 70, 100	-	-	70, 100, 30	-	9%
9: Arc-wise, 24°	-	70, 100, 30	-	-	30, 70, 100	-	9%
10: Arc-wise, 24°	-	70, 30, 100	-	-	100, 70, 30	-	9%

Standard methods for center pivot evaluation of application uniformity were followed (S436.1, ASABE *Standards*, 2004). The pivot was started approximately 10° before the approach of the transect line to allow adequate time for the pulsing action of the valves to synchronize. The volume of water collected in each catch can was measured using a funnel and a 1 L capacity graduated cylinder marked every 10-ml. Measurements were made after the pivot moved beyond the target collector(s) and as soon as the spray from the sprinklers was no longer striking the collector.

Calculations

Uniformity of application was evaluated using two approaches. The Heerman and Hein (1968) uniformity coefficient (CU_{HH}) is:

$$CU_{HH} = 100 \left[1 - \frac{\sum_{i=1}^n S_i |V_i - \bar{V}_p|}{\sum_{i=1}^n V_i S_i} \right]$$

where n is the number of collectors, i is the i^{th} collector, V_i is the volume of water collected in the i^{th} collector, S_i is the distance of the i^{th} collector from the pivot point, and \bar{V}_p is the weighted average of the volume of collected water and is calculated as:

$$\bar{V}_p = \frac{\sum_{i=1}^n V_i S_i}{\sum_{i=1}^n S_i}$$

Lower quarter distribution uniformity (DU_{lq}) for each zone was calculated as (Duke and Perry, 2006):

$$DU_{lq} = \frac{\bar{V}_{lq}}{\bar{V}_{tot}}$$

where \bar{V}_{lq} is the average of the lowest one-fourth of the measurements in the zone, \bar{V}_{tot} is the average depth of all applications in the zone. This coefficient represents the spatial uniformity across and within a field (Howell, 2002), and is not a measure of efficiency.

The mean absolute error (MAE) was calculated to compare how close the measured collector volumes were to the expected design volumes:

$$MAE = \frac{1}{n} \sum_{j=1}^n |\hat{P} - O|$$

where \hat{P} is the predicted value and O is the observed value, n is the number of catch cans used in zone j .

Standard error (SE) calculations were used to judge differences in measurements within a management zone:

$$SE = \frac{s}{\sqrt{n}}$$

where s is the sample standard deviation and n is the number of collector measurements within a zone. An analysis of variance (ANOVA) of the coefficients of uniformity was performed using SAS (SAS Institute, Inc., Cary, N.C.).

The calculated evaporation and drift losses were based on the equation (Faci et al., 2001):

$$EDL = \left(\frac{V_c - V_m}{V_c} \right) 100$$

where V_c was the total volume of water discharged (calculated using the speed of the pivot for the particular trial run, $9\% = 0.575 \text{ m min}^{-1}$, and actual nozzle flow rates from previous flow tests); and V_m was the total measured volume of water collected in the catch cans.

RESULTS AND DISCUSSION

During the first six trials, the average air temperature remained relatively cool and the humidity was relatively low. Air temperature did warm up later in May for Trials 7, 9, and 10. The average wind speed was higher than recommended by Standard S436.1 throughout all the trials; however, we did our best to perform the catch can trials on days when the wind was not gusting for the short window of time that was available for the

testing. During several of the trials, 4, 5, 7, and 10, there was a change in wind direction; and wind gusts were particularly high during Trials 5, 8 and 10 (Table 2). High and gusting winds are common at Bushland, Texas.

Table 2. Average meteorological data during the catch can trials and calculated evaporation and drift loss. Losses were not calculated (NC) for the arc-wise runs.

DOY	Trial No. (Time of day performed, CST)	Average RH (%)	Average Wind Speed (m s ⁻¹)	Wind Gusts (m s ⁻¹)	Wind Direction	Average Air Temperature [°C]	EDLs (%)
118 (Apr 28)	1: (930-1130)	35	5.6	6.6	NW	16	8.6
	2: (1330-1500)	17	4.4	4.9	WSW	22	13.7
123 (May 3)	3: (1000-1100)	21	5.7	6.9	NW	15	12.8
	4: (1400-1530)	14	5.5	5.9	N, NW	21	8.9
126 (May 6)	5: (930-1100)	22	9.4	11.9	S,SE, SW	24	9.8
132 (May 12)	6: (1300-1500)	25	4.3	4.9	SE	21	NC
143 (May 23)	7: (830-1840)	15	4.0	6.5	NNE, NW	29	NC
146 (May 26)	8: (830-1500)	31	5.1	10.3	NE,E,S,SE	23	NC
147 (May 27)	9: (830-1500)	19	5.0	7.9	NW,NE	28	NC
152 (June 1)	10: (830-1500)	42	8.2	12.2	S, SE	30	NC

An ANOVA indicated that the CU_{HH} and DU_{Iq} were significantly influenced by watering rate and configuration of the catch cans, but not by span location (Table 3). The grid pattern resulted in significantly higher CU_{HH} and DU_{Iq} values than transect and arc-wise patterns. Zones with a watering rate of 30% had a significantly lower CU_{HH} . Their average CU_{HH} and DU_{Iq} values were 85.1% and 0.80, respectively. The MAE of the collected volumes was positively correlated with watering rate ($F = 11.9$, $\alpha = 0.001$). The SE was inversely correlated ($F = 6.3$, $\alpha = 0.014$) to the distance of the span from the pivot point, i.e. the farther away the bank of collectors from the pivot, the smaller the SE. Although not significantly greater, application uniformity tended to increase from the inner span to the outer span. Overall, the CU_{HH} ranged from a low of 69.6% during Trials 7 and 10 (arc-wise pattern), in zone 2 of span 1 with a watering rate of 30%, to a high of 96.8% during Trial 3 (transect pattern) in zone 3 of span 2 with a watering rate of 80%. For Trials 1-5 and 8-10, the mean absolute application error was 4.4% of the 100% applied amount. Trial 6 results were not included because the 100% watering rate was not utilized, and for Trial 7, the mean absolute application error was 10.9%. The 30% watering rate had the highest mean absolute error (6%) and was typically affected by wind speed and wind direction, especially during Trials 4 and 10.

Analyzing data grouped by transect-type trials indicated that the average CU_{HH} and DU_{Iq} were 87.9% and 0.82, respectively. The application uniformity was greatest in zones 2 and 3 for Trial 3 (Fig. 4a). During this trial, the wind blew out of the Northwest (NW) and the average wind speed was 5.5 ± 0.4 m s⁻¹. In the majority of these five trials, it was typical that the first two collectors within a watering zone had a greater volume (Fig. 4a and 4b) than the mean volume for the zone, if the zone had a lower watering rate and was

distal to the adjacent zone with a higher watering rate. Variations in depth were likely caused by spray overlap and drift from neighboring nozzles. The drift was likely due to variable wind speed, and the change in wind direction. These uniformity values for the transect trials are higher than average values ($CU_{HH} = 81.3\%$ and $DU_{Iq} = 0.70$) reported

Table 3. Test results indicating mean coefficient of uniformity (\overline{CU}_{HH}) and mean distribution uniformity (\overline{DU}_{Iq}) from catch-can trials on 3-span center pivot system for all collectors placed. Letters of the same value in each column indicate no significant difference. The number of samples of each uniformity coefficient is represented by n.

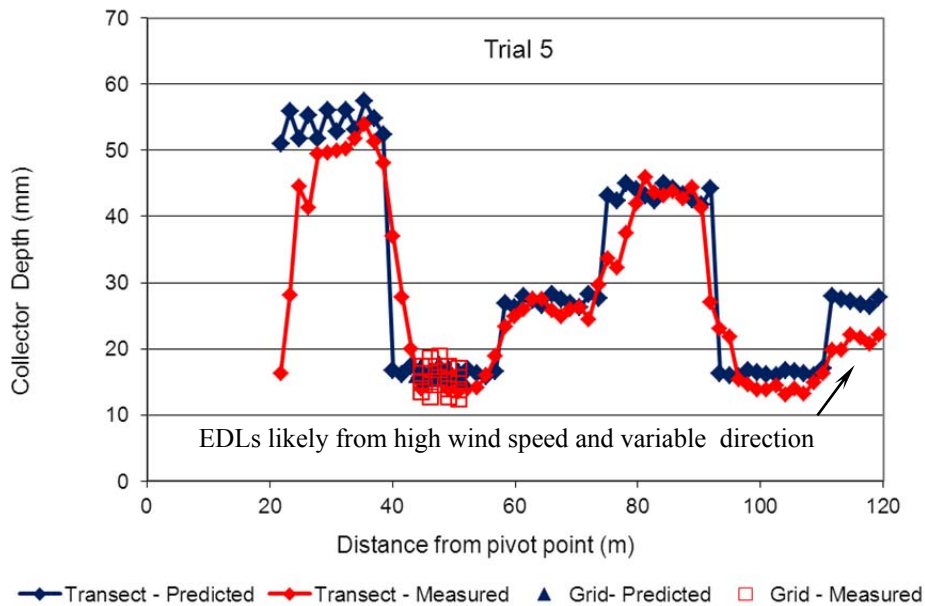
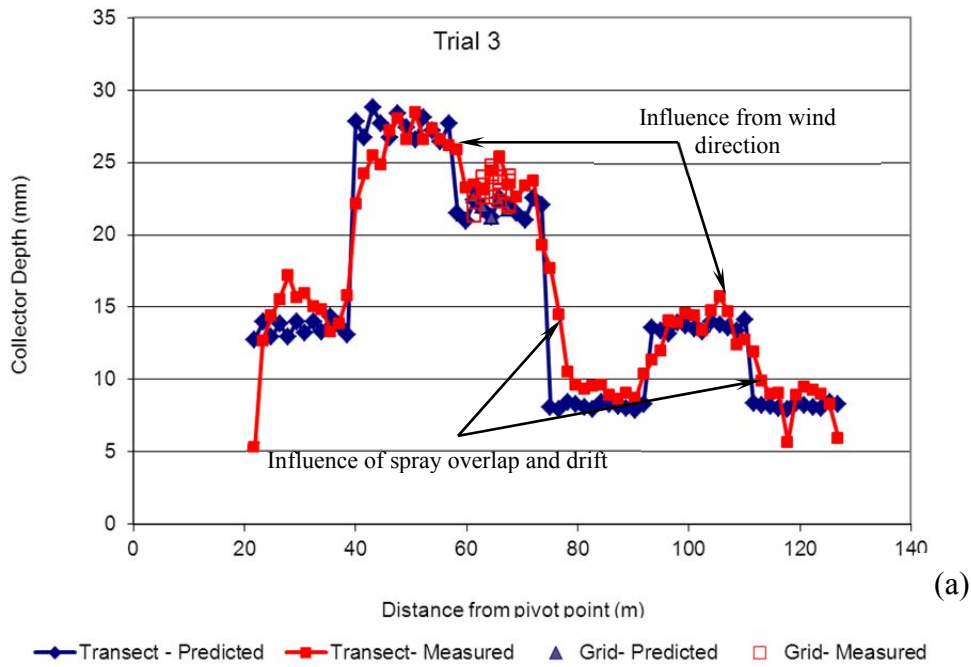
Catch-can Location			
	\overline{CU}_{HH}	\overline{DU}_{Iq}	n
Span 1	86.8a	0.81a	12
Span 2	88.0a	0.83a	32
Span 3	89.8a	0.85a	22
Watering Rates (%)			
30	85.1b	0.81b	22
50	89.3a	0.86a	14
70	91.7a	0.86a	6
80	89.8a	0.85a	9
100	90.1a	0.83a	15
Catch-can Configuration			
Transect	87.9ab	0.82ab	28
Grid	91.1a	0.90a	8
Arc-wise	88.1b	0.82b	30

by Dukes and Perry (2006) for a variable rate center pivot system with LDN nozzles tested in Georgia at a travel speed of 11%, and collectors under spans 3 and 4. Han et al. (2009) reported decreased coefficient of uniformity values for a 25% watering rate for a linear move with a VRI system. The percent EDL for our trials fell within the range (7% – 20%) simulated by Faci et al. (2001) for fixed spray plates at 1-m and 2.5-m; and those measured by Ortiz et al. (2009) for fixed spray plates of 9.2% at a height of 1-m and 13.6% at 2.5-m.

During Trial 5, the average wind speed was 9.4 m s^{-1} with wind gusts up to 11.9 m s^{-1} , and the wind direction was from the S, SW, and SE directions. These influences likely caused the losses in the cans at the end of span 3 (Fig 4b), as the pivot moved against the wind for the majority of the trial.

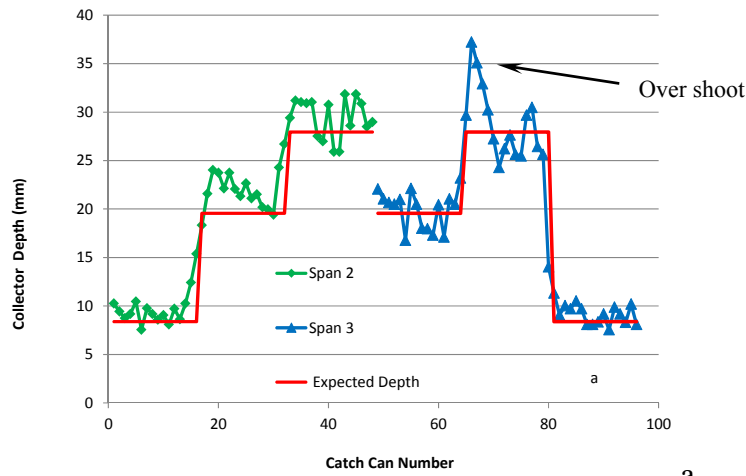
An analysis of the collected depths from the grid-pattern trials indicated that the mean CU_{HH} and DU_{Iq} were 91.1% and 0.90, respectively, neglecting the edges of the zone and the variations near the edges. This level of uniformity is not surprising since the grid patterns were placed within a zone. Neither the span location nor the watering rate significantly influenced the application or distribution uniformity during the trials.

In the case of the arc-wise trials, when the management zones were prescribed as 24° sectors, the average CU_{HH} and DU_{Iq} were 90% and 0.85, respectively; and the minimum

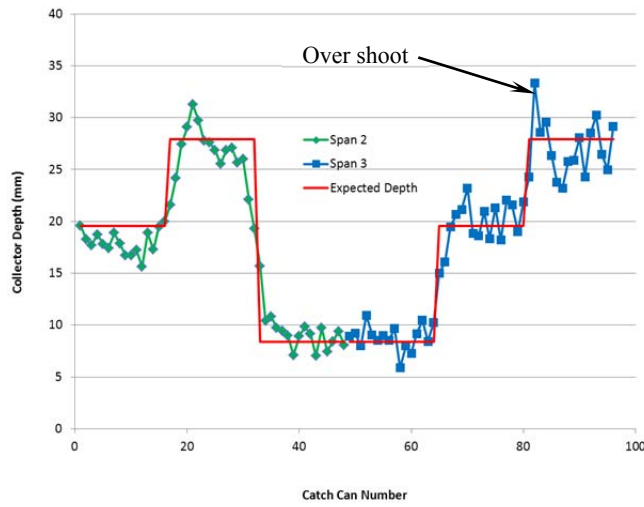


(b)
 Figure 4. Collector depth for transect and grid type configurations for: (a) Trial 3 with a wind direction out of the NW; and (b) for Trial 5 with winds blowing from the SW, S, and SE.

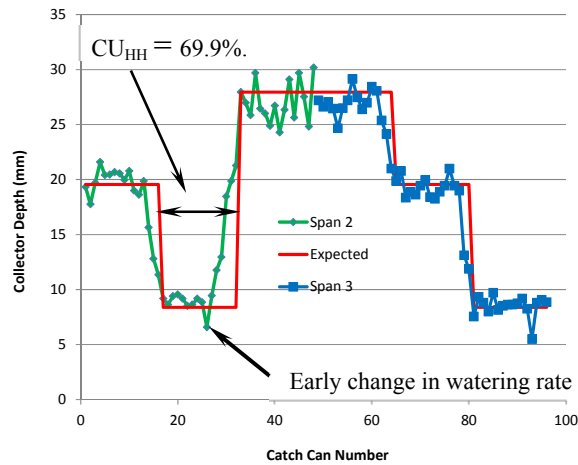
values were 69.6% and 0.71, respectively (Fig. 5). The lowest CU_{HH} occurred during Trial 10 (on DOY 152) from collectors located in zone 3 of span 2, with a watering rate of 30% (Fig. 5c). During this time, the average wind speed was 6.6 m s^{-1} with gusts up to



a



b



c

Figure 5. Catch cans 1-48 were located in the middle of span 2 and 49-96 were located in the middle of span 3. Measured and expected collector depth for Trials (a) 8; (b) 9; and (c) 10 using an arc-wise pattern with watering rates changing between 30%, 70% and 100% after the pivot traversed a 24° sector.

8.7 m s⁻¹, the wind direction was SE to SW while the pivot end-tower was pointed in the SE direction moving SE to SW (Fig. 6). The graphs also show where the collected

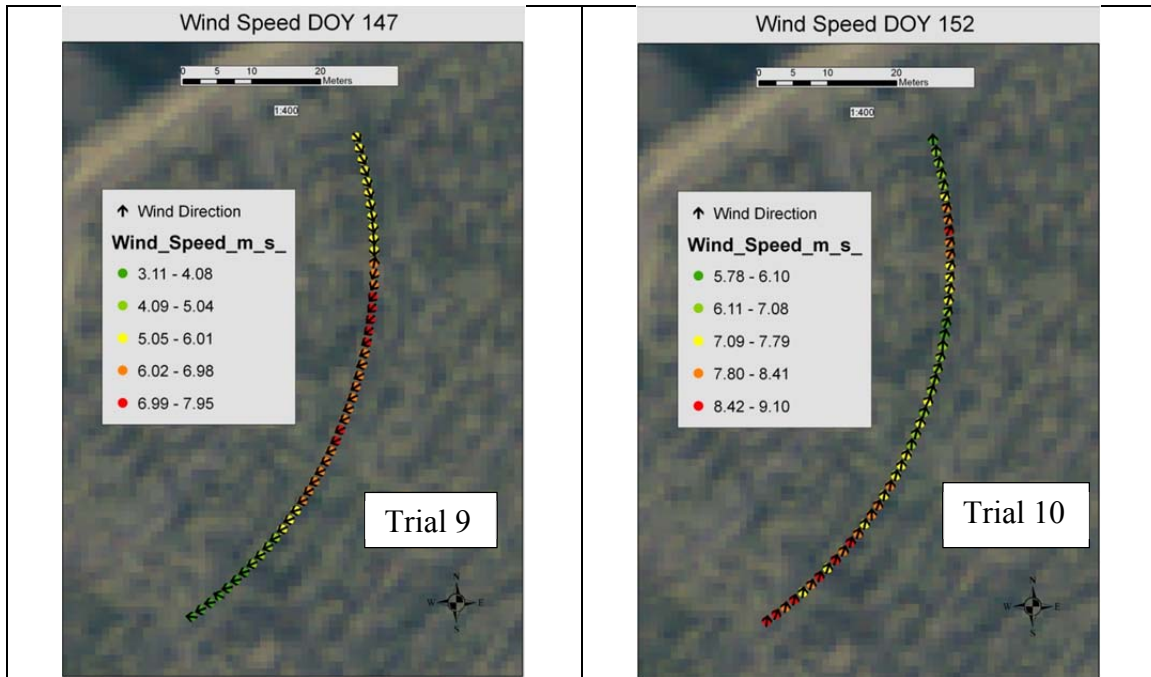


Figure 6. Data showing wind speed and wind direction during: Trial 9 (left) and Trial 10 (right). In both trials, the pivot is moving SE to SW.

volumes over-shot the expected volume when the watering level changed from a lower to a higher rate (Fig. 5a and 5b). This higher than expected values can be a result of the high wind speed and its direction in relation to the movement of the pivot. However, the mean collected depth of the catch cans during the 30% and 70% applications was within 1-2% of the mean collected depth for the 100% watering rate in that same span with the exception of Trial 10, span 2 for a watering rate of 30%.

Trial 7 also had collectors configured in an arc-wise pattern, however, for this trial the management zones were prescribed with sector angles of 12°. During this trial run, the MAE was consistently higher than for previous runs (data not shown). The average CU_{HH} and DU_{lq} were 76% and 0.76; and the average wind speed was 4.0 ± 1.0 m s⁻¹ with a shift in direction from NNE to NNW, and then from W to SW. In comparison to the other arc-wise pattern trials (8-10), the uniformity of application for Trial 7 was much lower. This occurred even though the average wind speed for Trial 7 was also much lower. The low uniformity values were caused by consistent undershoot and overshoot in water delivery rates as the VRI system changed delivery rates while transitioning between the narrower 12° sectors (Fig. 7). Future catch can trials with similar sector angles will be performed to help determine the causes of these results.

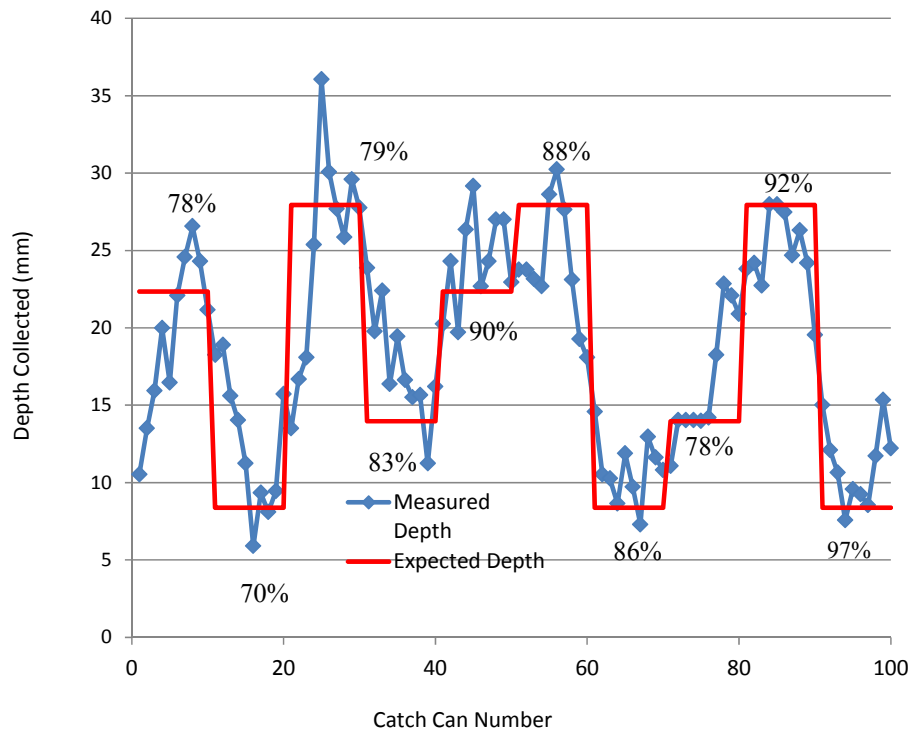


Figure 7. Trial 7 where 100 catch cans were placed in an arc-wise pattern at the same distance from the pivot point in the middle of span 2. The percent coefficient of uniformity is shown for each watering rate.

CONCLUSIONS

Multiple catch can tests were performed to test the application and distribution uniformity of a commercial VRI system along the length of a 3-span lateral and in arc-wise directions in the two outer spans. The CU_{HH} and DU_{lq} were relatively high ($> 87\%$ and 0.82) for an 18-m wide management zone, each comprised of 12 drop hoses, spaced 1.5-m apart in spans 1-3. The uniformity of application was significantly lower when the watering rate was 30%, which may have been caused by high wind speed and changes in wind direction.

The application uniformity measured in an arc-wise direction was also relatively high when the management zones were prescribed with a sector angle width of 24° . Variability in uniformity when the collectors were placed in the 12° sectors may have been affected by wind speed and direction, and a problematic GPS system. The problem has since been corrected and future trial runs will be conducted to test the uniformity of application over smaller sector angles.

The application depth for the different zones compared well to the depth of application that was applied at the 100% watering rate in that same span. The mean application error $< 5\%$ in the management zones for transect trials and arc-wise trials where the

management zone was 24°. Future work is needed to determine the circumferential resolution of the VRI system. Upcoming work will include mechanically addressing the speed of valve closure and catch can tests on a six-span center pivot VRI system.

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