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ZONE EDGE EFFECTS WITH VARIABLE RATE IRRIGATION

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ABSTRACT

Variable rate irrigation (VRI) systems may offer solutions to enhance water use efficiency by addressing variability within a field. However, the design of VRI systems should be considered to maximize application uniformity within sprinkler zones, while minimizing edge effects between such zones along the lateral pipeline and in the direction of sprinkler movement. A number of factors influence edge effects, including equipment design, sprinkler-wetting pattern, wind speed and direction, and differences in watering application rates between adjacent sprinkler zones. This paper reviews the performance of a commercial three-span VRI center pivot system designed with drops spaced 5 feet apart, equipped with fixed spray plates and low drift nozzles at an elevation of 5 feet above the ground. Multiple catch can tests were conducted in a windy location to assess the application uniformity of the VRI system within sprinkler zones along the pivot lateral and in the direction of pivot movement, and to quantify edge effects within these zones. Watering application rates were varied at levels of 100%, 80%, 70%, 50% and 30% of 1.0 or 2.0 inches. The overall mean coefficient of uniformity and distribution lower quarter values within the sprinkler zones were 89.9% and 84.5%, respectively. The width of edge effects at the borders of the sprinkler zones varied between 5 and 20 ft., while the mean length of the edge effect in the direction of pivot travel was 30 ft. Edge effects were mainly imposed by the operation of the VRI system, but wind speed and direction intensified the edge effects.

INTRODUCTION

Variable rate irrigation systems may offer solutions to enhance water use efficiency by mitigating variability within a field. However, it is important to first characterize water application of VRI systems, i.e. the accuracy and uniformity of application within each sprinkler management zone and the edges of the zones along the sprinkler lateral and in the direction of sprinkler movement. This allows evaluation of the system's potential for distributing water efficiently as the system moves across a field. High water use efficiencies are achieved when water applied is made available at the root zone of the crop rather than evaporated due to wind drift, or applied at a rate that exceeds soil infiltration resulting in run-off or deep percolation. Good fertilization management is partially dependent on good irrigation management since deep percolation can push fertilizers beyond crop root uptake zones, reducing yields. In the case of a shallow water table, deep percolation can leach nitrates into groundwater causing degradation. When managing VRI systems, it is reasonable to assess factors that impact WUE at the management zone scale.

Sprinkler system designs that affect application patterns include variations in travel speed at the towers, end gun operation, sprinkler spacing, nozzle elevation, operating pressure, sprinkler package type (e.g. rotating versus fixed spray), and sprinkler and nozzle combinations (Scherer et al., 2009). Often the combination of these factors affects application uniformity. For example, the coefficient of uniformity (CU) decreased as the ratio of sprinkler spacing to wetted diameter increased (Clark et al., 2003). Inadequacies, such as poorly controlled system pressure, variable performance in pressure regulators, and plugged or worn nozzles and spray plates can also influence spray application patterns (Burt et al., 1997) and therefore sprinkler performance.

Wind speed and direction can also influence sprinkler application uniformity, sometimes improving CU and at other times decreasing it. The degree to which wind affects application uniformity of a sprinkler may depend on the design of the sprinkler system. Vories and von Bernuth (1986) determined that sprinkler systems operating at lower pressures were generally less affected by wind speed. Dukes (2006) reported that under high wind speed (10 to 15 mph), CU was improved for sprinklers with low drift nozzle (LDN) packages operating at low pressures (15 - 20 psi). For Tarjuelo et al. (1999), the major variability in uniformity caused by high wind speeds occurred at the outer end of the pivot lateral where flow is greatest. Evaporation and drift losses were shown to increase exponentially as a function of wind speed and vapor pressure deficit (Yazar, 1984; Playan et al., 2005). Edling (1985) showed that small droplets were significantly affected by greater wind speeds and nozzle elevations. In addition to speed, wind direction can also affect CU by distorting the base-shape pattern of droplet distribution. Han et al. (1994) developed models from catch can measurements under windy conditions that demonstrate the droplet distribution pattern generally takes on an elliptical footprint when wind direction is aligned with the major axis of the ellipse, however, wind has also shown to shrink the base-shape.

With zone controlled-VRI systems, application uniformity is influenced by all of the aforementioned variables. Unique to VRI systems, however, uniformity is also naturally affected at the borders of sprinkler zones, especially between adjacent zones along the pivot lateral. This is due mainly to sprinkler spray overlap, which is a function of sprinkler spacing and the wetted radius of sprinklers near the border of adjacent zones. These edge effects on borders between zones were recognized by others when performing research studies (McCann et al., 1997) or assessing application uniformity (Ortiz et al., 2010) of sprinkler systems, but the studies did not involve VRI sprinkler systems. Dukes and Perry (2006) evaluated both a VRI center pivot and a VRI linear move sprinkler system. They reported overall means for the coefficient of uniformity (CU) and distribution lower quarter (DU_{lq}) at varying water rates, but provided no details concerning edge effects between sprinkler zones. It is important to assess edge effects induced by the operation of a VRI system to determine if the total system design is appropriate for VRI management. This paper reviews the uniformity of application performance of a recent study involving a three-span VRI center pivot system conducted in a windy location (O'Shaughnessy et al., 2013) and compares the results with other published studies involving VRI systems.

MATERIALS AND METHODS

Equipment

The three-span VRI center pivot sprinkler system was located at the Conservation and Production Research Laboratory in Bushland, Texas. The three-span center pivot (Valley, model 8000 series) was installed in 2006 and retrofitted with a commercial VRI package in the fall of 2010. The VRI center pivot was configured with 12 sprinkler banks; each bank was 30 ft. wide and comprised of 6 drop hoses (spaced 5 ft. apart). Trials were run with two sets of sprinkler zones programmed to water at the same application rate (making each sprinkler management zone 12 drops wide). Zones within all three spans were evaluated. Drops located in Zone 2 of the three span system were split between the first tower with six drops located on either side of the tower. Nozzles were at a height that is typically used for mid-elevation spray application, with spray plates approximately 5 ft. above the ground. Fixed spray plates, pressure regulators rated at 6 psi and a low drift nozzle assembly (Senninger Irrigation Inc., Clermont, Fla.) were outfitted onto each drop. The sprinkler system was operated at an average pressure of 25 psi measured at the pivot point. The nozzle diameters on the three span center pivot ranged from 6/64 in. to 16 /64 in. with radii of throw ranging from 10 to 15 ft. The application depth delivered by each drop hose was regulated by a solenoid valve in a nearby VRI tower, which controlled the “on/off” pulsing of a hydraulic valve plumbed at the goose neck.

Ten catch can trials were performed in 2011 from April 28 through June 1. Catch cans were approximately 6 inches in height and diameter, and made from white, rigid polyvinyl chloride (PVC) pipe, beveled at the top end to define the receiving area. Each can was placed on a leveled wire stand positioned 3 in. above ground, and a small amount of vegetable oil was placed in the cans to reduce evaporative losses. The collected water was measured using graduated cylinders as soon as the spray from the sprinklers was no longer striking the cans. Cans were arranged in transect, arcwise and grid patterns (Fig. 1). When cans were arranged in the grid pattern they were located in the center of the sprinkler zone and buffered from spray overlap of sprinklers in adjacent zones of different watering application rates. Zone edge effects in the direction of pivot travel were evaluated using cans arranged in an arc-wise pattern. Watering rates were applied at 100%, 80%, 70%, 50%, and 30% of full application depth [using a depth of 1.0 inches (Trials 1-4, 6-10) or 2.0 inches (Trial 5)] over all patterns. A weather station was located within 30 feet of the pivot point and one-minute averages of air temperature, relative humidity, solar radiation, wind speed, and wind direction were recorded during each trial. Peak “instantaneous” wind speed measured during each evaluation was reported as wind gust (Table 1).

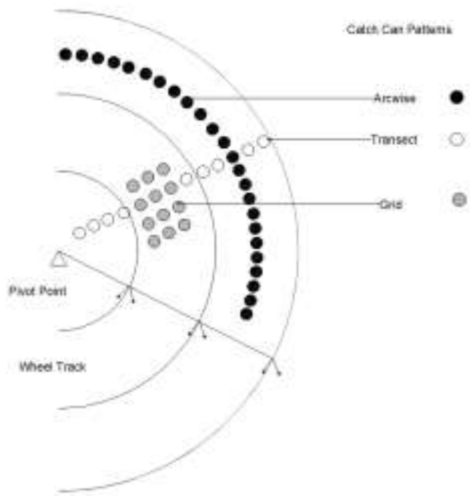


Figure 1. Transect, grid, and arcwise patterns used for application uniformity testing of a three-span variable rate irrigation (VRI) system at Bushland, Texas in 2011. (Not to scale)

Calculations

The lower quarter-depth distribution of uniformity (DUlq) is the ratio of the average lower one-fourth depth to the average depth of water. The value was calculated for each sprinkler management zone as in Eq. 1 (ASCE, 1978):

$$DU_{lq} = 100\left(\frac{\sum_{i=1}^{j} S_i V_i \Big/ \sum_{i=1}^{j} S_i}{\overline{V_p}} \right) \quad [1]$$

where the numerator is the mean application volume of the lowest one-quarter of catch-cans (*j*) in the management zone, S_i is the distance of the i^{th} can from the pivot point, V_i is the volume of water collected in the i^{th} can, and $\overline{V_p}$ is the weighted average of the volume of collected water in the management zone as represented in Eq. 2.

$$\overline{V}_p = \frac{\sum_{i=1}^{n} V_i S_i}{\sum_{i=1}^{n} S_i} \quad [2]$$

where n is the number of catch cans, *i* is the i^{th} can, V_i is the volume of water collected in the i^{th} can, S_i is the distance of the i^{th} can from the pivot point, and $\overline{V_p}$ is the weighted average of the volume of collected water in the management zone.

The coefficient of uniformity was determined separately for each management zone using the Heermann and Hein (1968) uniformity coefficient (CU):

$$CU = 100\left[1 - \frac{\sum_{i=1}^{n} S_i \left|V_i - \overline{V_p}\right|}{\sum_{i=1}^{n} V_i S_i}\right] \quad [3]$$

When catch cans were arranged in an arc-wise pattern to test accuracy and uniformity of application in the direction of pivot travel, Equation [3] was reduced to the Christiansen Coefficient (Christiansen, 1942) since all values of S_i were identical.

The coefficient of variation (CV), the ratio of the standard deviation of collected volumes to the mean value, was calculated for catch cans located within a sprinkler zone or areas near borders of sprinkler zones to help quantify edge effects.

RESULTS AND DISCUSSION

Of the 10 catch can trials conducted, seven were performed under high wind speeds (mean wind speed > 11 mph) (Table 1). The DU_{lq} and CU were analyzed using mixed models (Proc Mixed, SAS, Ver. 9.3, Carey, NC) for all trials with sprinkler zone, pivot span, watering rate and catch can pattern as main effects, and wind speed as a covariate. Significantly lower values of CU and DU_{lq} occurred at the 30% water application rate and for catch cans arranged in an arcwise pattern. However, uniformity of application was not significantly different among sprinkler zones (Table 2).

Table 1. Catch can trials performed on the three-span variable rate irrigation (VRI) center pivot located at Bushland, Texas during 2011.

Day	Time of Day	Avg Wind Speed (mph)	Wind Gust (mph)	Wind Direction (Origin)
Apr 28	9:30 – 11:30	12.5	14.8	W,WNW
Apr 28	13:30 – 15:00	9.9	10.7	W,NW,WS,W
May 3	10:00 – 11:00	12.8	15.4	N,NW
May 3	14:00 – 15:30	12.3	13.2	N,NW
May 6	9:30 – 11:30	21.2	26.6	SSW, S, SSE
May 12	13:00 – 15:00	9.2	11.0	S
May 23	8:30 – 18:45	9.6	14.5	WNW,N,ENE
May 26	8:30 – 15:00	11.1	23.0	SW, SSW
May 27	8:30 – 15:00	11.1	17.7	NNW, N , ENE
June 1	8:30 – 15:00	18.3	27.3	S, SE

Application uniformities were greatest when the cans were arranged in a grid pattern. Cans arranged in a grid pattern were located in the middle of a sprinkler zone and represented conditions under which zone effects were nearly zero.

Table 2. Analysis of main effects on coefficient of uniformity (CU) and distribution lower quarter (DU_{lq}) for the three-span variable rate irrigation center pivot system evaluated at Bushland, Texas in 2011. Mean values followed by the same letter in each column grouped by category are not significantly different.

	CU	DU_{lq}
Watering Rate		
100	91.2a	85.7a
80	90.9a	85.3ab
70	92.0a	84.9ab
50	89.7a	86.7a
30	85.4b	80.0b
Span		
1	83.9a	79.0a
2	88.3a	81.8a
3	97.3a	92.8a
Catch Can Pattern		
Grid	94.1a	92.4a
Transect	89.4a	82.1b
Arcwise	86.1b	79.2b
Zone		
1	94.6a	82.0a
2	94.5a	93.3a
3	91.5a	87.9a
4	90.5a	87.5a
5	86.3a	81.6a
6	81.8a	74.9a

Differences in within-zone application uniformity were compared between adjacent zones along the pivot lateral. This analysis confirmed the existence of a significant positive linear relationship between differences in CU and differences in the watering application rate. The coefficient of determination was greater when the transition was from a greater to a lower application rate in the direction of flow through the lateral pipeline (Fig. 2a). There was also a positive linear relationship between differences in DU_{lq} values and differences in watering application rates between adjacent sprinkler zones. The DU_{lq} values increased within zones of greater application rates distal to zones of lower application rates (Fig. 2b). The width of the edge effect between sprinkler zones varied from 5 to 20 ft.

Influences on application uniformity within sprinkler zones caused by differing application rates were also reported by Gossel et al. (2013) for a three-span VRI center pivot system using rotating sprinklers (Nelson, S3000) spaced 8 ft. apart and elevated 8 ft. above ground. Their evaluations were conducted under conditions of low wind speed (< 11 mph), using watering rates that were 100%, 60%, and 40% of 0.6 inches.

Wind speed affected within-zone application uniformity, and created variability of CU and DU_{lq} values at the edges of adjacent zones when watering application rates differed between adjacent zones (O'Shaughnessy et al., 2013). The width of a zone edge effect between sprinkler zones along the pivot lateral was determined by recalculating CU and DU_{lq} values after removing the collected catch from one can at each border within a specified zone. This was repeated until CU and DU_{lq} values became significantly different from the previous value (O'Shaughnessy et al., 2013).

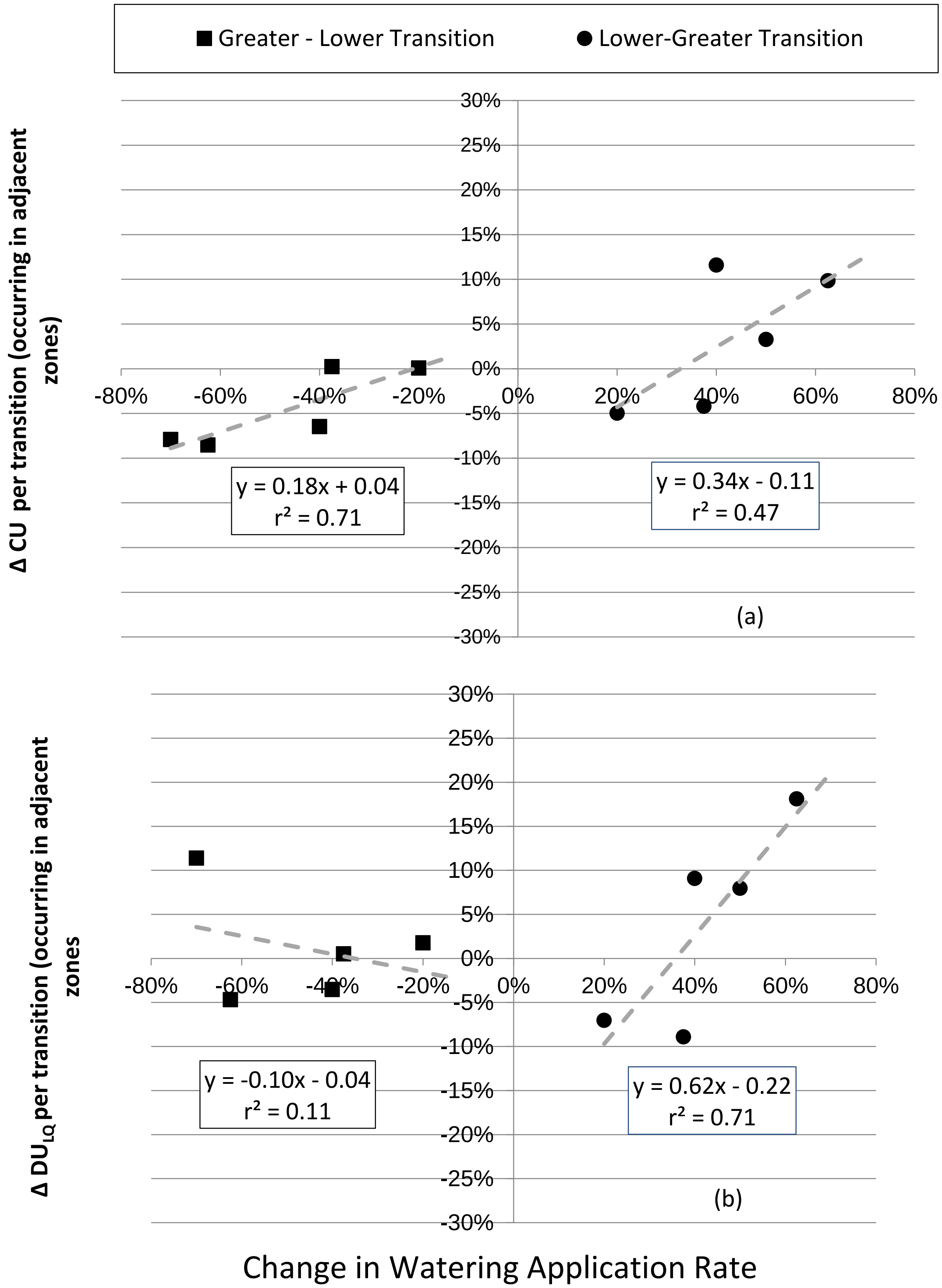
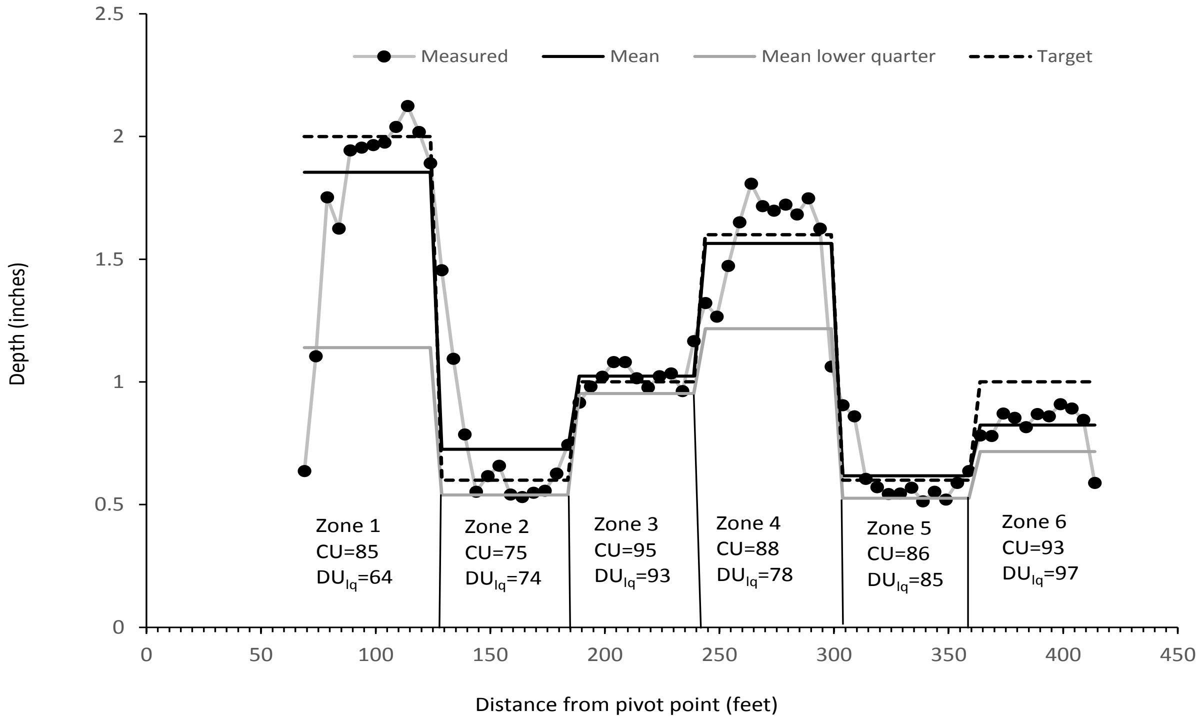


Figure 2. Relationship between changes in applied watering rates between adjacent sprinkler zones along the pivot laterals and changes in: (a) coefficient of uniformity (CU); and (b) distribution lower quarter (DU_{lq}) (lower graph). The relationships are shown both for transitions from greater application rates to smaller application rates and vice versa. Data was ascertained from catch cans aligned in a transect pattern.

Zone edge effects can also be described in terms of variability in application depth using the coefficient of variation. As an example, the CV for the water collected by the first five cans in Zone 2 (at the border of Zone 1) was 49%, as compared with a CV of 25% for measurements from all cans in Zone 1, and a CV of 38% for measurements from all cans in Zone 2 (Fig. 3). For this trial, the calculated mean CV for depths at the edges of the zones was 24%, while the mean CV within all sprinkler zones was 19%. The effects of wind speed (mean value = 21 mph) and recorded wind gusts up to 27 mph during this trial likely intensified the variation in catch at the edges of the zones (Zones 1 and 2, Zones 3 and 4).

The performance of this system compares well to that of the linear move system discussed by Dukes (2006). Although a conventional system, the linear move was operated at 15 psi using LDN sprinklers under wind conditions up to 15 mph. The mean values of CU (89.8%) and DU_{lq} (84.5%) for all zones tested in this study using catch cans in a transect pattern were better than reported by Dukes (2006) where the mean CU was 83%, and DU_{lq} was 71% for two trials under windy conditions. Mean CV for this study (19%) was similar to that in Dukes (2006), where the mean CV for catch collected in each zone for the two trials was 18%. However, uniformity of application for this study was less than that reported by Chávez et al. (2010) where the mean CU was 92% for two trials using a VRI linear move system and watering rates that differed between 20% and 100% of 0.80 inches. For the Chávez system, the drops were spaced 10 ft. apart and equipped with rotating nozzles. The nozzles were elevated 3 ft. above the ground. Han et al. (2009) reported CU of 94.0%, 94.8%, 91.7%, and 79.5% for watering application rates of 100%, 75%, 50%, and 25% of 1.0 inches using a VRI linear move system. The system was outfitted with drop hoses spaced 10 ft. apart with rotating sprinklers, and nozzles elevated to a height of 7.5 ft. There was no discussion of edge effects.

It is difficult to mitigate edge effects between sprinkler zones along a lateral pipeline, since these effects are mainly a function of the sprinkler package and system design. Omary et al. (1997) suggested use of half-circle spray heads to mitigate edge effects between borders, but Gossel et al. (2013) noted that the 180° spray heads caused spikes in applied depths that at times were twice as much as the target depth. An alternative would be to change the application system from a mid elevation spray set-up to an in-canopy method, i.e. either a low elevation spray application (LESA) or low energy precision application (LEPA) method. These methods could reduce the wetted radius of the sprinklers and therefore the width of the edge effects, but result in greater instantaneous application rates that may cause runoff.



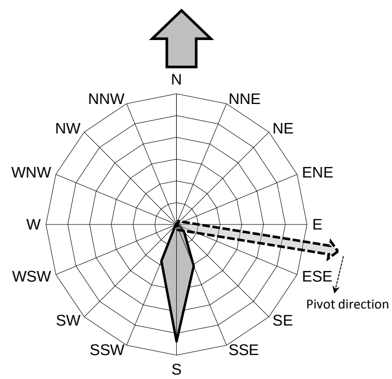


Figure 3. Plot of collected catch for cans arranged in transect and grid patterns (not shown) along the length of a variable rate irrigation (VRI) pivot lateral. The trial was conducted on May 6, 2011 from 9:30 to 11:00 am, prevailing winds were from the SSW, S, SSE directions, and the mean wind speed was 21 mph.

Zone edge effects also occur in the direction of pivot lateral travel when the watering rate changes as the pivot crosses from one zone into another. Using cans arranged in an arcwise pattern, the effects on uniformity of 10 transitions were evaluated where the VRI system changed the application depth from a lesser to a greater amount. The results generally demonstrated an improvement in CU and DU_{lq} by approximately 10% and 9%, respectively, regardless of wind speed. In the case of a change in application depth from a greater to a lesser amount, CU and DU_{lq} commonly decreased by approximately 6% and 8%, respectively. During the "arcwise" catch can trials (the last four in Table 1), the direction of the prevailing wind relative to the direction of pivot movement appeared to affect the width of the zone edge effects. As an example, in the case where the prevailing wind direction was mostly perpendicular to the direction of pivot travel and opposite to the direction of flow through the pivot lateral, spray was displaced rearwards of the target collectors, and the width of the edge effect was 40 ft (Fig. 4a). When the prevailing winds originated from the NNW, N and ENE directions and were mostly in the same direction as pivot travel and perpendicular to flow through the pivot lateral, spray was displaced forward of the expected target collectors (Fig. 4b). However, in this case the change in application depth between zones was less gradual making the edge effect narrower than in the previous example. The mean length of edge effects in the direction of pivot travel was 30 ft., which was within the range of values (15 to 30 ft.) reported by Gossel et al. (2013).

Chávez et al. (2010) also reported an edge effect of 16 ft. in the direction of sprinkler movement when the system changed from a uniform irrigation of 70% to a variable rate irrigation pattern. Again, minimizing edge effects in the direction of sprinkler movement can be accomplished by changing the application method to either LESA or LEPA. It should be noted that Lindsay Corporation offers a VRI system, GROWSMART that allows individual sprinkler control. The higher resolution of control may help minimize edge effects (Lindsay, 2015).

CONCLUSIONS

Several catch can tests were performed on a three-span VRI center pivot system to evaluate the application uniformity of the system within the sprinkler management zones and in the direction of travel and to assess edge effects between sprinkler zones along the pivot lateral and between zones as the application depth was changed in the direction of pivot movement. Seventy percent of the trials were performed under windy conditions (wind speed was > 11 mph). The mean uniformity of application within sprinkler zones operating under varying watering rates was high with an overall mean CU = 88%. The lower value of DU_{lq} = 75.5% was similar to that reported for a conventional linear move system with a similar sprinkler package. Edge effects at the borders of the sprinkler zones were mainly due to the operation of adjacent zones at differing application depths. Edge effects in the direction of pivot travel occur gradually as the watering application rate changed from one zone to another. The mean length of variation in application depth was determined to be 30 ft. However, wind speed and wind direction also influenced edge effects, by either increasing or decreasing the zone of variation. We note that while these results characterize the performance of a VRI system in terms of application uniformity and control of application depth, they do not take into consideration the long term effect of repeated operation of a VRI system on plant available water or plant growth and yield. In our trials, there has been visual evidence of more distinct plant growth differences between irrigation zones than would be suggested by these performance results.

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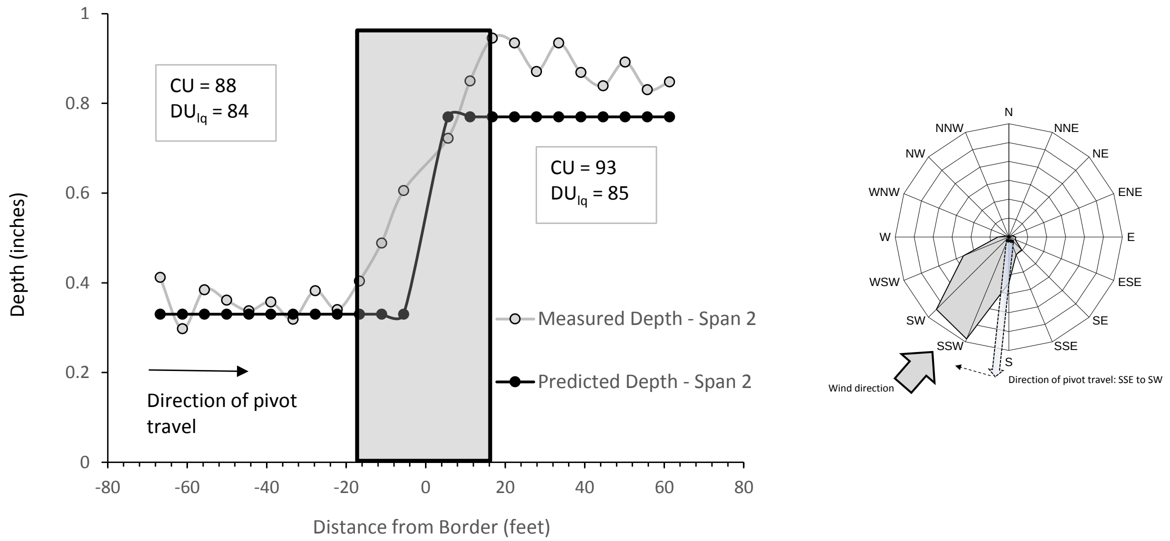
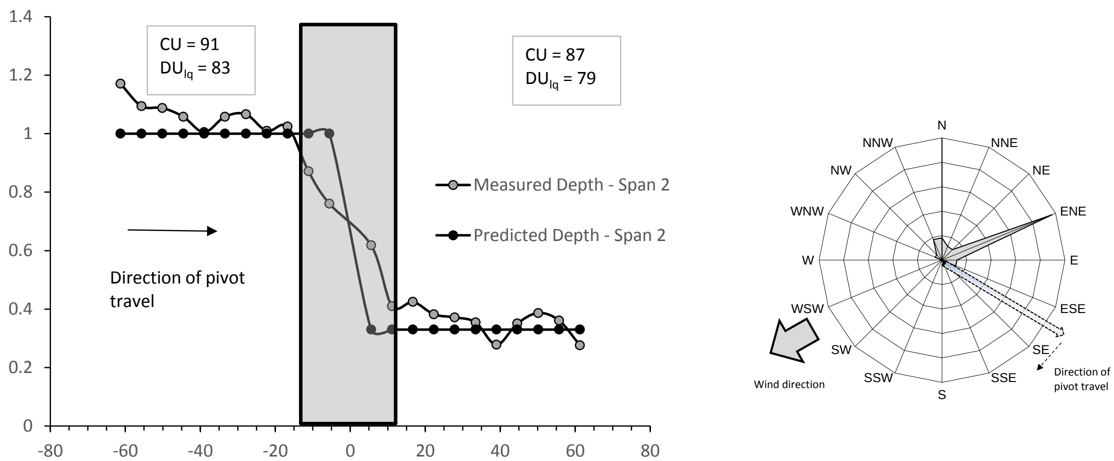


(a)



(b)

Figure 4. Plots of depth collected from cans arranged in an arcwise pattern within Span 2 during the trial conducted on: (a) May 26, 2011, prevailing wind originated mainly from the SW and SSW directions and was mostly perpendicular to the direction of pivot travel and opposite to the direction of flow through the pivot lateral; and (b) May 27, 2011, prevailing winds originated mainly from the ENE direction, and were mostly in the same direction as pivot travel.

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