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VARIABLE-RATE IRRIGATION USING LOW ENERGY PRECISION APPLICATION (LEPA)

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Abstract

Cotton production might benefit from planned, non-uniform distribution of irrigation as a function of soil water holding capacity (SWHC) and topography leading to better utilization of both rainfall and irrigation in water short regions of the Texas High Plains. The four most outer spans of an 8-tower center pivot system were modified to deliver variable-rate (VR) irrigation within cells no larger than 0.1 acre. LEPA applicators were modified to provide relative flow rates of 2x, 3x, and 4x allowing stepwise increases in irrigation discharge of 20% of a base irrigation quantity. A control system was installed to actuate solenoid valves relative to field location, thereby controlling irrigation quantities at specific sites.

Field experiments were conducted in 2001 and 2002 to evaluate equipment and to document potential advantages of VR irrigation of cotton over standard practices. Alternating strips of cotton, 20 to 22 rows wide, were irrigated by either variable-rate (VR) or uniform-rate (UR) irrigation. In 2001, the VR irrigation strategy attempted to level lint yields by reducing irrigation in areas of high SWHC and adding water to areas of low SWHC. Management zones were based on soil texture and slope in a 12-acre area. In 2002, irrigation quantities were increased above the base rates in areas thought to be "more productive". Soil electrical conductivity (EC) was used to determine the management zones on a 15.4-acre test area for site-specific irrigation.

Final hydraulic evaluations of the VR irrigation system following construction in 2001 and modification in 2002 resulted in actual applicator flow rates within 5% of achievable flow rates. Errors in initial pivot positioning were documented. Based on the preliminary comparisons and the criteria used to designate management zones, VR irrigation of cotton produced no significant increase in total lint yield or total irrigation water use efficiency (WUE) over uniform LEPA application in 2001 or increases in WUE in 2002. Using soil EC as the criterion to establish management zones for VR irrigation resulted in lint yield increases of 2 to 4 % over uniform irrigation, but at the cost of additional water inputs.

Introduction

More than 20,000 center pivot systems are used to irrigate 3 million acres of cropland in the Texas High Plains. However, available irrigation capacity is typically less that the evapotranspiration (ET) demand of crops grown in this region. Furthermore, irrigated soils are seldom uniform due to differences in texture and depth, and seasonal water availability within a field can differ due to topography and its effect on rain runoff. Crop production could benefit from the planned, non-uniform distribution of irrigation water based on SWHC and topography, leading to better utilization of both rain and irrigation water in this semi-arid environment.

The "multiple manifold" method of dispersing variable quantities of water with irrigation systems has been used at the Texas Agricultural Experiment Station (TAES) at Halfway for small plot research for many years (Bordovsky, et al., 1992). This method uses manifolds with different sized nozzles in combinations to create a stepwise range of rates. The USDA/ARS in South Carolina also uses this method (Omary, et al., 1997). Other VR irrigation systems use pulsing applicators for time proportional volume control and altering the aperture of nozzles with a pin to achieve multiple flow rates (Sadler, et al., 2001).

This paper addresses the construction and initial evaluation of a site-specific LEPA irrigation system and initial criteria evaluation for variable-rate irrigation of cotton in the Texas High Plains.

Materials and Methods

Spans 6, 7, and 8 of an 8-tower Zimmatic™ center pivot irrigation system were modified to provide VR irrigation coverage during the summer of 2001. The pivot was located at the Helms Research Farm, 2 miles south of the TAES Research and Extension Center at Halfway, TX. The hydraulic and control components of the VR system were evaluated as cotton was irrigated in July and August of that year. Field evaluations comparing VR to uniform (UR) water application on cotton were conducted with water treatments beginning in August 2001. Management zones in 2001 were based on soil texture and slope down the furrow. An additional VR section (span 5) was installed in 2002. Irrigation management zones were delineated based on soil electrical conductivity (EC) measured by the Veris 3100 system (Veris Technologies, Salina KS).

Variable-Rate Irrigation Equipment Construction and Evaluation

The VR system routes water from the pivot lateral through pressure regulators and solenoid valves to each of three manifolds comprising the manifold unit. There are three manifold units per 160-ft pivot span. Hoses are used to direct water from the manifolds to specially designed LEPA irrigation applicators. In 2001, nozzle sizes for each applicator provide relative flow rates of 1x, 2x, and 3x, which, when actuated in various combinations, provide six discrete irrigation amounts ranging from 25 to 150% of a base irrigation (BI) rate. LEPA applicators were modified in 2002 to provide relative flow rates of 2x, 3x, and 4x allowing stepwise increases in flow of 20% of BI. With additional water sources in 2002, the base flow rate for the 133-acre pivot was increased to 600 gpm with equivalent flow rates in the modified spans ranging from the low of 240 to a high of 840 gpm.

The VR equipment evaluation began in July 2001. Original LEPA application devices were extensively modified to accommodate high water volumes without causing runoff. The final LEPA applicator consisted of a group of four nozzles, three of which were individually connected to one of the three manifolds of a VR manifold unit, and the fourth connected to the pivot mainline and sized at the BI flow rate. The entire nozzle assembly was inserted into a custom made "sock" with the lower portion of the open-ended sock dragging the ground and dispensing water between pairs of crop rows. All irrigated crops were planted in circular rows. The fourth nozzle was valved so that its flow would be off when the VR system was in use.

Applicator flow rates were determined by volumetric catchments from individual LEPA applicators of each of the manifold units during irrigation events from July through August in 2001 and in June and July in 2002. Water pressure taps were positioned at strategic locations throughout the manifold units to determine pressure losses and help diagnose causes of poor water distribution. Water wells supplying the VR pivot were equipped with Cycle Stop® (Cycle Stop Valves, Lubbock, TX) pressure regulating valves to compensate for changes in pivot flow rates.

An electronic control system was installed to actuate solenoid valves at each manifold unit relative to field location, thereby controlling irrigation quantities at specific sites. A SNAP-LCSX-PLUS industrial controller (Opto 22, Temecula, CA), two remote terminal units (SNAP-B3000), software, and related accessories were installed for this purpose. The control system was programmed to provide four control signals to each manifold unit (3 signals for 3 water manifold solenoids and an additional signal for a future chemigation actuator). Programming further allowed changes in solenoid status every 3^0 around the 360^0 perimeter of the pivot. Therefore, the largest control area under this VR pivot was < 0.1 acre (53' manifold unit length x 71' in a three degree arc) resulting in more than 2000 potential water/chemical control cells under this 133-acre pivot. A standard incremental encoder (Dynapar™ Series E15) was used to provide input signals to the controller to determine pivot location.

Crop Response to VR Irrigation

Field experiments were conducted to explore potential advantages of VR irrigation compared to standard LEPA irrigation of cotton on the High Plains. The 2001 experiment was conducted in a 12.2-acre area irrigated by the VR system. This portion of the field contained the greatest elevation changes and the most notable differences in surface soil texture. The 60^0 arc was divided into 9 strips with each strip either 20 or 22 rows wide and falling beneath one of the 9 VR manifold units. Alternating strips were irrigated by either VR or UR irrigation. Comparisons of crop responses from these areas were used to evaluate VR irrigation. Figure 1 shows the position of the 12.2-area relative to the Helms pivot and the locations of the nine VR and UR treatment strips in the 2001 experiment.

Past research at Halfway had shown variability in cotton lint yield most strongly correlated with factors associated with crop water use such as slope, elevation, soil texture, and seasonal irrigation (Bordovsky and Keeling, 2000). Profile elevations and soil texture at 64 sites within the area were used to determine different irrigation zones in the VR strips. Elevation and row direction were used to determine the "slope down the furrow" at each of 64 referenced sites (Figure 2). Soil texture below 16 inches had not been determined prior to initial VR irrigation on 2 August, therefore, the only textural data used in the initial decision on water placement in VR strips was clay content in the top 16-inches (Figure 3). The general VR irrigation strategy was to level lint yields by reducing irrigation in areas of high SWHC and adding water to areas of low SWHC. A decision was made to divide the field into three zones. The low-rate zone was irrigated at a rate equal to 75% of the UR in the area where "slope down the furrow" was 0% and clay content in the top 16 inches was > 40%. This area contained soils with high SWHC and limited risk of rain runoff. The medium-rate zone was irrigated at 100% of UR and included the area of "slope" from 0.0 to 0.5% and clay content of < 40%. The high-rate zone was irrigated at 125% of the UR in the area where slope down the furrow was > 0.5%. The high-rate zone had the highest risk of rain losses. Previously defined sampling sites also affected decisions on irrigation boundary positions since yield analysis required representative numbers of sites per zone.

A Microsoft Excel™ program was written to create coded map files from the desired irrigation application map. The application sequence was then loaded into the VR controller with a laptop computer. Boundaries between zones of different irrigation levels are shown in Figures 1, 2, and 3.

2001 Growing Season. Cotton (Paymaster 2326RR) was planted in the 12-acre test area on 24 May 2001 and the crop maintained using normal cultural practices. Nutrients were applied based on aggregate soil sampling and pests were treated at recommended thresholds. Irrigation was initiated on 26 May and continued through 30 August. Due to the dry growing season and limited pumping capacity, irrigations in UR treatments were less than the planned 80% of estimated ET. Irrigation amounts of 5.6 inches were uniformly applied across the entire 12.2-acre field from 26 May to 27 July. From 2 through 30 August, irrigations totaled 3.9, 5.2, and 6.4 inches in the VR strips of the low-, medium-, and high-irrigated zones, respectively. Therefore, the difference in total irrigation quantity between the low and high irrigation zones within the VR treatments was 2.5 inches.

2002 Growing Season. Soil EC was used as the criterion to determine the general productivity of a 15.4-acre area for site-specific irrigation of cotton in 2002. Soil EC measurements of the top 1-m of the soil profile were recorded using the Veris system in 2001 (Figure 4). The VR irrigation strategy followed the general hypothesis that, when resources are limited, the highest overall production results from applying those resources to the more productive areas of the field (Lascano, 2002). The 2002 research area had been planted to corn in 2001 and, in 2002, was divided into strips irrigated by individual manifold units with alternating strips managed as either VR or UR (Figure 5). Areas with 1-m soil EC measurements > 35 dS/m were assumed "more productive" and received 120% of the base irrigation quantity within VR strips. All UR strips and the VR areas of soil EC < 35 dS/m received 100% BI. Evaluations of VR vs. UR application were based on total irrigation WUE.

Cotton (Stoneville 2454RR) was planted in the test area on 7 May 2002 and the crop maintained using normal cultural practices. Seasonal irrigation was initiated on 17 May and continued through 28 August. Rain, from the day of planting until 28 August, totaled 1.4 inches. Irrigations in UR treatments were ~80% of ET. Seasonal irrigation amounts of 3.7 inches were uniformly applied across the entire 15.4-acre area from 17 June to 16 July. From 16 July through 28 August, irrigations totaled 8.5 and 10.2 inches in the VR strips of the "normal" and "high" productive areas, respectively.

Results

Equipment Evaluation

The mechanical evaluation of the VR system included tests of the hydraulic and positioning systems. Figure 6 displays hydraulic performance data of the VR system on 4 August 2001 and, again, following several modifications on 30 August 2001. These charts show comparisons of desired, achievable, and actual flow rates of applicators within each of nine manifold units of spans 6, 7, and 8. Flow rates of individual manifold systems were offset from adjacent manifolds due to programmed differences in flow rates relative to the location in the field. Data from the initial date indicate actual applicator flow rates were somewhat higher and more scattered than the achievable flow rates. System improvements were made by increasing and stabilizing inlet water pressure at the pivot, renozzling the VR applicators, modifying plumbing components to prevent flow restrictions, and eliminating low-pressure drain valves. Hydraulic performance tests were conducted in 2002 following additional VR manifold installation on span 5 and redesign of stepwise flow rates of all manifolds. Actual applicator flow rates were within 5% of achievable flow rates by the time VR experiments began.

To date, the controller, remote terminal units, and solenoid valves have worked flawlessly, however, the positioning system used to actuate valves at appropriate locations in the field failed to perform as precisely as desired. An evaluation was conducted that compared actual pivot location to the pivot location sensor outputs of both the VR positioning sensor and the pivot manufactures sensor. Output data was systematically recorded as the pivot rotated around the field in both clockwise and counter-clockwise directions. Comparisons of pivot and VR sensor response to actual position are shown in Figure 7. The pivot and VR sensors showed deviations of up to 6^0 from the actual field location at $0/360^0$ (true north). This represents a positioning error at the outer edge of the pivot of ~140 feet. As the pivot rotated through the 120 to 200^0 arc, the output signals of both sensors were consistently within a few degrees of the actual pivot position. Position data were generally similar in both pivot directions after multiple revolutions. The systematic difference between pivot and VR outputs indicates possible mechanical problems with the rack portion of the rack and pinion sensor mechanisms. This error may be reduced by replacing pivot parts or by reprogramming the count sequence within the VR controller. Error of up to 2^0 may be acceptable for most irrigation or chemical applications in this setting.

Cotton Lint Yield Response

Cotton lint yields were determined by three methods: 1) using stripper harvested, boll buggy weights from each of the treatment strips under the manifold units; 2) hand harvesting 870 ft^2 areas at 64 (2001) and 65 (2002) geo-referenced sites; and 3) harvesting the entire area using a cotton stripper equipped with a yield monitor. No significant statistical differences in total yield or total irrigation WUE were evident between VR and UR treatments in 2001 or differences in WUE between VR and UR treatments in 2002. Table 1 includes weighted irrigation amounts, lint yield based on burr cotton weights (boll buggy), average hand harvested lint weights, and integrated hand harvest lint weights; and total irrigation WUE for VR and UR irrigation treatments for the 2001 crop year. Yield based on boll buggy weights were 719 vs. 713 lb/ac for VR vs. UR treatments. Yield based on average hand samples were 966 lb/ac (981 lb/ac, integrated) from the VR irrigation treatment compared to 1004 lb/ac (1015 lb/ac, integrated) from the UR treatment. Estimates of WUE were similar for the two treatments. Table 2 gives cotton lint yield by manifold strip and harvest method for the VR and UR treatments for the 2002 experiment. Average lint yields are slightly higher in the VR than UR treatments due, in part, to the larger total water volume applied within the VR plots (16.1 and 15.23 inches, respectively). VR yields were 2.8, 2.7, and 4.6% higher than UR yields when determined from boll buggy, hand sample, and yield monitor yields, respectively. Table 3 shows WUE of VR and UR treatment areas as a function of harvest. Although yields were higher in VR than UR strips, WUE was higher in UR than VR areas.

Although average lint yields were similar, spatial distribution of yields were quite different depending on irrigation treatment. Figure 8 represents the integration of hand harvest data obtained at the 32 sites in the UR treatments as well as VR sites that received the UR irrigation quantity in 2001. This represents the yield response from uniformly irrigating the entire 12-acre area. This map shows two general areas of lower yields, an area with no slope and high clay content (west side) and a sloping area (> 0.5%) with low clay content (southeast corner). For comparison, the VR map shown in Figure 9 used only the yield data from the 32 VR sites. This map indicates that shifting water from the west side of the field to the east side reduced lint yield in the low water zone and increased yield in the high water zone. High yields seen on the far west side of the VR map may be due to irrigation from the adjacent field (VR controller not actuating valves at the precise location).

The 2002 spatial distribution of cotton lint yield from VR and UR treatments (hand harvested data) is shown in Figure 10. The UR yield shows generally higher yields in the "more productive" zones (EC > 35 dS/m). Applying additional water to these areas further increased yield in the "more productive" zone on the west (zone 3) as depicted by the darker shades in the VR graph. Integrated yields for this area were 1604 lb/ac for UR vs. 1679 lb/ac for VR irrigation. The potential value of VR irrigation is the prospect of improving irrigation WUE. This did not occur by adding additional water to areas with high EC values in 2002. The spatial distribution of WUE was more uniform by using VR rather than UR irrigation (Figure 11), however, the integrated WUE of the UR treatment was higher at 104 lb/ac-in compared to the WUE of 101 lb/ac-in of the VR treatment in the same area.

The small yield and WUE differences between VR and UR applications in 2001 were not unexpected. Irrigation treatments were started late in the growing season, initial irrigations were being made with VR equipment that had not been fully optimized, data used to base VR irrigation transition zones were limited, and the strategy for creating the zones was based on normal rainfall. In 2002, using 1-m soil EC as the criterion to establish management zones for VR irrigation resulted in higher lint yield with additional water inputs, but lower total irrigation WUE. These preliminary results illustrate that the in-season, site-specific water management of a cotton crop is complex. Further, due to the indeterminate growth habit of cotton in combination with the short growing season in the Texas High Plains strategies to optimize the allocation of finite water resources may need to consider additional factors other than slope and soil water holding capacity.

Acknowledgments

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Table 1. Cotton lint yield and total irrigation water use efficiency from VR and UR irrigation treatments TAES, Helms Farm, 2001.

		Variable Rate Irrigation						Uniform Rate Irrigation					
Span	**Manifold Unit**	**Irr. Amt. (in)**	**Yield Boll Buggy (lb/ac)**	**Yield Hand Harvest (lb/ac)**	**Yield Integrated Hand (lb/ac)**	**WUE Boll Buggy (lb/ac-in)**	**WUE Hand Harvest (lb/ac-in)**	**Irr. Amt. (in)**	**Yield Boll Buggy (lb/ac)**	**Yield Hand Harvest (lb/ac)**	**Yield Integrated Hand (lb/ac)**	**WUE Boll Buggy (lb/ac-in)**	**WUE Hand Harvest (lb/ac-in)**
6	a	10.17	758	861		74.5	84.6						
	b							10.74	812	1034		75.6	96.3
	c	10.50	747	1069		71.2	101.9						
7	a							10.74	693	1028		64.5	95.7
	b	11.01	761	991		69.1	90.0						
	c							10.74	692	964		64.4	89.8
8	a	11.01	700	940		63.6	85.4						
	b							10.74	653	990		60.8	92.2
	c	11.20	628	968		56.1	86.4						
Averages	10.78	719	966	981	66.9	89.7		10.74	713	1004	1015	66.3	93.5

Table 2. Cotton lint yields (lb/ac) and weighted irrigation quantities of areas where variable and uniform irrigation applications occurred, TAES, Helms Farm, 2002.

		Variable Rate				Uniform Rate			
Span	**Manifold Unit**	**Wt. Irr. Amt. (in)**	**Boll Buggy**	**Hand Harvest**	**Yld Monitor**	**Wt. Irr. Amt. (in)**	**Boll Buggy**	**Hand Harvest**	**Yld Monitor**
5	a					15.23	1456	1540	1403
	b	16.93	1476	1865	1512				
	c					15.23	1389	1392	1422
6	a	16.68	1672	1673	1625				
	b					15.23	1545	1648	1484
	c	15.83	1469	1620	1542				
7	a					15.23	1471	1724	1459
	b	15.57	1439	1447	1532				
	c					15.23	1504	1608	1539
8	a	15.49	1470	1571	1562				
	b					15.23	1373	1694	1595
	c	16.08	1453	1694	1546				
Average		16.10	1497	1645	1553	15.23	1456	1601	1484

Table 3. Total irrigation water use efficiency (lb/ac-in) and weighted irrigation quantities of areas where variable and uniform irrigation applications occurred, Helms Farm, 2002.

		Variable Rate			Uniform Rate		
Span	**Manifold. Unit**	**Boll Buggy**	**Hand Harvest**	**Yld Monitor**	**Boll Buggy**	**Hand Harvest**	**Yld Monitor**
5	a				95.6	101.1	92.1
	b	87.2	110.2	89.3			
	c				91.2	91.4	93.4
6	a	100.2	100.3	97.4			
	b				101.4	108.2	97.5
	c	92.8	102.3	97.4			
7	a				96.9	113.2	95.8
	b	92.4	92.9	98.4			
	c				98.8	105.6	101.1
8	a	94.9	101.4	100.8			
	b				90.2	111.2	104.7
	c	90.4	105.3	96.1			
Avg.		93.0	102.1	96.6	95.6	105.1	97.4

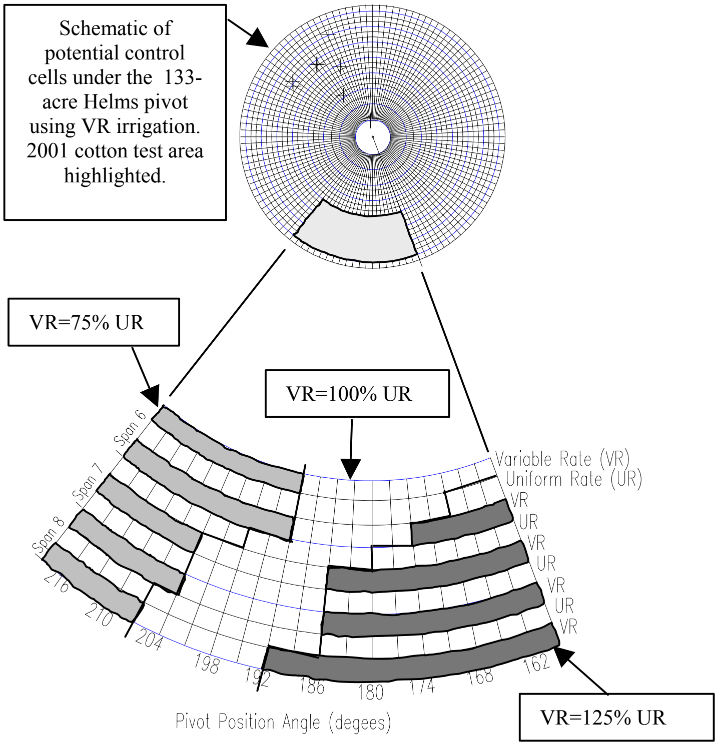

Figure 1. Schematic of the VR control cells of the Helms pivot and the 12-acre area used in the VR irrigation cotton study. In 2001, the control cells were divided into three target irrigation areas based on slope down the furrow and clay content in the top 15-cm of the profile.

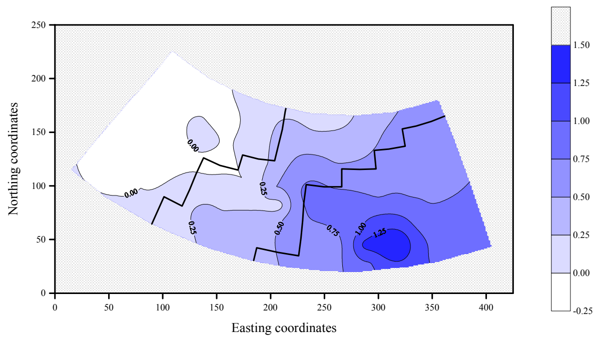

Figure 2. Furrow slope of 12-acre area used in the VR cotton irrigation study, 2001.

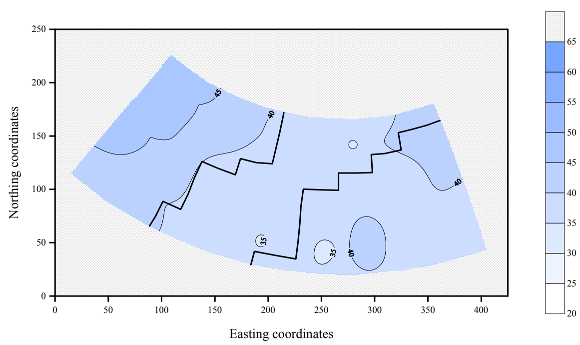

Figure 3. Percentage of clay in the top 16-in of the soil profile.

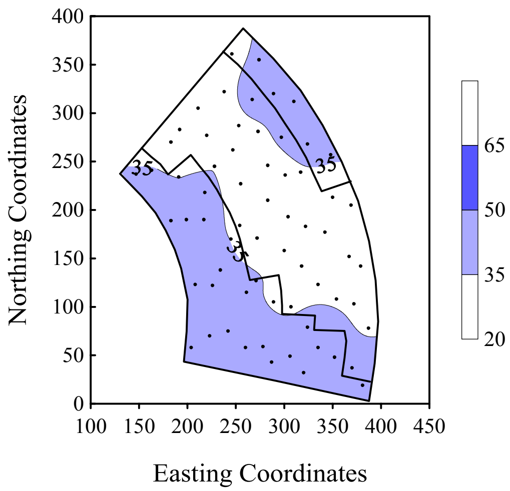

Figure 4. Soil electrical conductivity at one-meter depth used to determine management zones for VR cotton irrigation, 2002. Also shown are geo-referenced locations where harvest data was acquired.

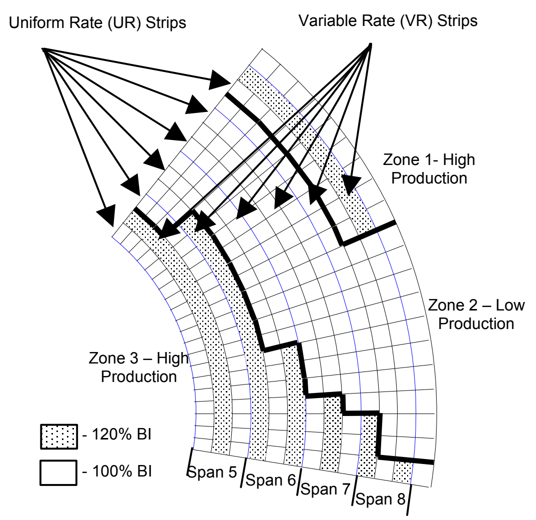

Figure 5. Map of VR and UR irrigation control cells, irrigation quantities, and boundaries between management zones, Helms, 2002.

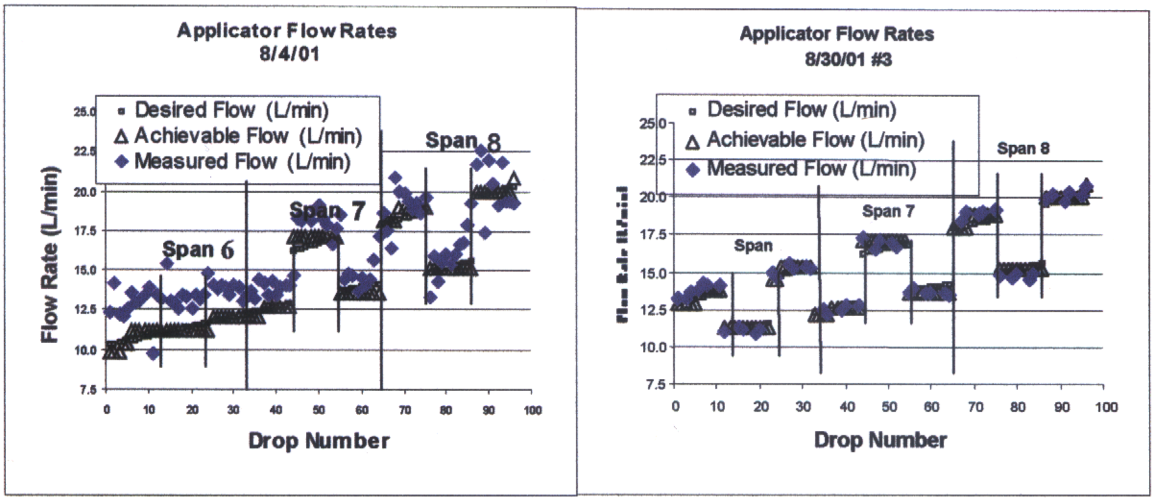

Figure 6. Comparisons of desired, achievable, and actual flow rates of applicators within each of the nine manifold units of spans 6, 7, and 8 on August 4 and August 30, 2001, Helms Farm.

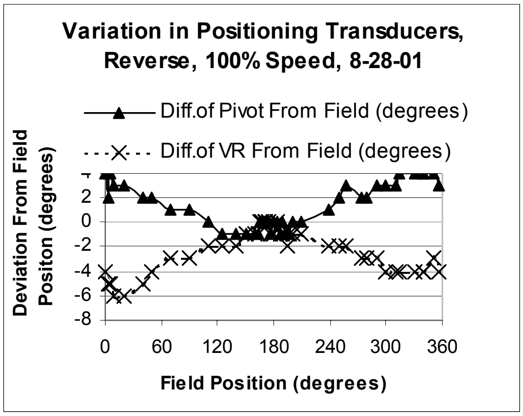

Figure 7. Deviations from actual field position of pivot and VR sensor indicators during one revolution of the Helms pivot.

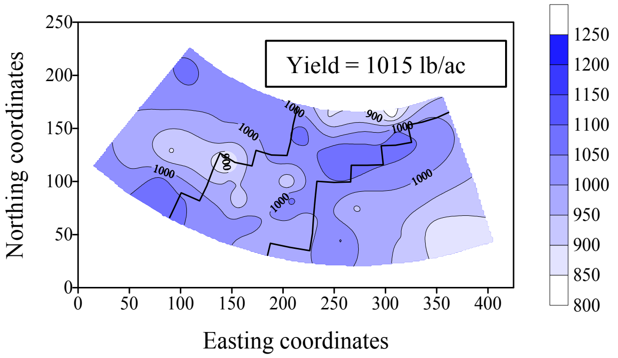

Figure 8. Yield map constructed from hand harvested cotton yields in uniform irrigated areas at Helm, 2001.

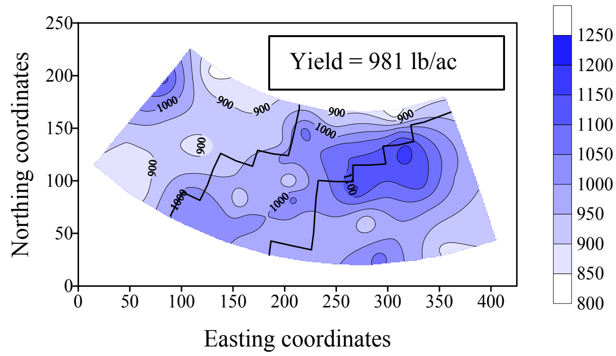

Figure 9. Yield map constructed from hand harvested cotton yields in variable rate irrigated areas at Helm, 2001.

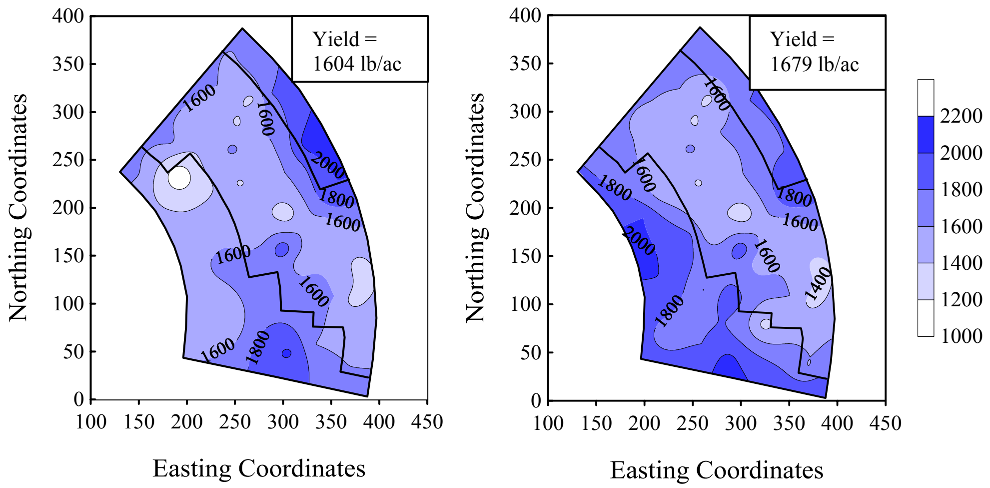

Figure 10. Yield map constructed from hand-harvested data representing uniform irrigation (left) and variable rate irrigation (right)of an indenrical area at Helms Farm, 2002.

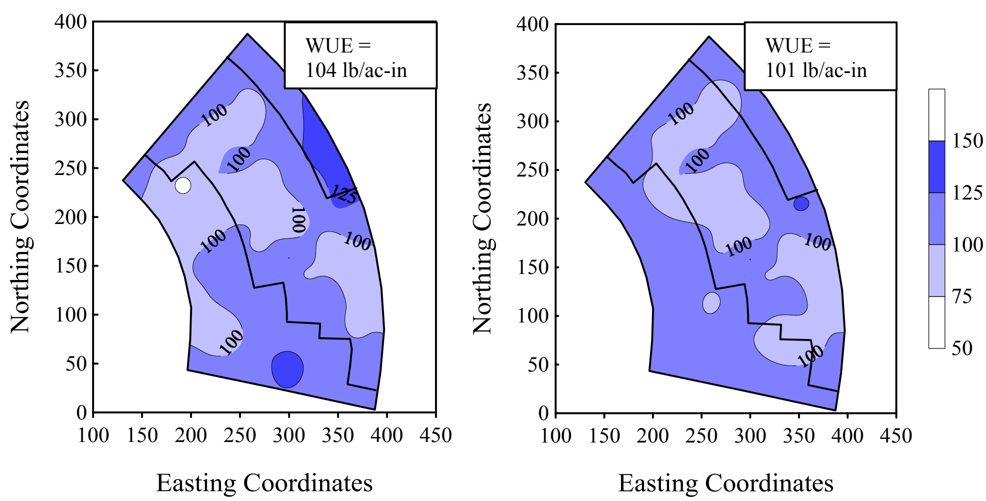

Figure 11. Spatial distribution of total irrigation water use efficiency (WUE) constructed from hand-harvested data representing uniform irrigation (left) and variable rate irrigation (right) of an identical area at Helms Farm, 2002.