Proceedings of the 21st Annual Central Plains Irrigation Conference, Colby Kansas, February 24-25, 2009
Available from CPIA, 760 N. Thompson, Colby, Kansas

COMPARISON OF GRAIN SORGHUM, SOYBEAN, AND COTTON PRODUCTION UNDER SPRAY, LEPA, AND SDI

Paul D. Colaizzi
Agricultural Engineer
Phone: 806-356-5763
paul.colaizzi@ars.usda.gov

Steven R. Evett
Research Soil Scientist
Phone: 806-356-5775
steve.evett@ars.usda.gov

Terry A. Howell
Research Leader (Agric. Engr.)
Phone: 806-356-5746
terry.howell@ars.usda.gov

R. Louis Baumhardt
Research Soil Scientist
Phone: 806-356-5766
r.louis.baumhardt@ars.usda.gov

USDA-ARS
P.O. Drawer 10
Bushland, Texas 79012-0010
FAX: 806-356-5750

ABSTRACT

Crop production was compared under subsurface drip irrigation (SDI), low energy precision applicators (LEPA), low elevation spray applicators (LESA), and mid elevation spray applicators (MESA) at the USDA-Agricultural Research Service Conservation and Production Research Laboratory, Bushland, Tex., USA. Each irrigation method was compared at irrigation rates meeting 25, 50, 75, and 100% of full crop evapotranspiration (ET_c). Crops included three seasons of grain sorghum, one season of soybean (planted following a cotton crop that was destroyed by hail), and four seasons of upland cotton. For grain sorghum, SDI followed by LEPA, MESA, and LESA resulted in greater grain yield, water use efficiency, and irrigation water use efficiency at the 25- and 50% irrigation rates, whereas MESA followed by LESA outperformed LEPA and SDI at the 75- and 100% irrigation rates. For soybean, the same trend was observed at the 25- and 50% irrigation rates, whereas SDI followed by MESA, LEPA, and LESA resulted in the best crop response at the 75% irrigation rate, and MESA followed by SDI, LESA, and LEPA resulted in the best crop response at the 100% irrigation rate. Cotton response was consistently best for SDI, followed by LEPA, and either MESA or LESA at all irrigation rates. Within each irrigation rate, few significant differences were observed among irrigation methods in total seasonal water use for all crops.

INTRODUCTION

Irrigation is practiced on approximately 4 million of the 8.5 million cultivated acres in the semiarid Texas High Plains. Irrigation results in substantially greater crop productivity and water use efficiency compared with dryland production where precipitation is limited or sporadic (Howell, 2001). The Ogallala Aquifer is the primary water resource for irrigated agriculture in the U.S. Great Plains, including the Texas High Plains, and is one of the largest freshwater resources in the world. However, the Ogallala Aquifer has been declining in many areas because withdrawals (the vast majority being for irrigation) have greatly exceeded recharge. The Ogallala is the major part of the High Plains aquifer, which underlies 175,000 square miles across eight Great Plains states, representing 27 percent of U.S. irrigated land. The practice of efficient irrigation is therefore imperative to simultaneously prolong the life of the Ogallala and High Plains aquifers, conserve energy used for pumping, and sustain rural economies.

Center pivot irrigation systems equipped with low-pressure application packages and subsurface drip irrigation (SDI) can be highly efficient in terms of uniformity, application efficiency, and crop water productivity compared with gravity irrigation (Schneider, 2000; Camp, 1998). In the Texas High Plains, about 75 percent of the irrigated area is by center pivot, with gravity and SDI comprising about 20 and 5 percent, respectively (Colaizzi et al., 2009). Center pivot application packages initially included impact sprinklers, but these have been supplanted by packages that operate at lower pressure and hence reduce energy consumption, including mid elevation spray applicators (MESA), low elevation spray applicators (LESA), and low energy precision applicators (LEPA) (Lyle and Bordovsky, 1983). Surface and subsurface drip irrigation were first adopted in Texas during the mid-1980s for cotton production (Henggeler, 1995); SDI has greatly expanded in the Trans Pecos and Southern High Plains cotton producing regions (Enciso et al., 2007; Bordovsky et al., 2008).

There is anecdotal evidence that SDI results in greater crop yield, greater water use efficiency, and earlier cotton maturity relative to center pivot systems equipped with spray or LEPA packages. Cotton earliness under SDI is thought to be related to reduced evaporative cooling from the soil surface and plant canopy relative to that under center pivot systems. Reduced evaporation could result in warmer soil temperatures and encourage more vigorous early-season plant development. However, this may be countered somewhat by the greater cooling effect on the soil from the more frequent irrigation inherent with SDI (Wanjura et al., 1996). In any case, warmer soil temperatures would be a critical advantage for cotton production in thermally-limited climates where corn is traditionally produced, such as the northern Texas Panhandle and southwestern Kansas (Howell et al., 2004; Colaizzi et al., 2005). In addition, SDI has been shown to be technically feasible and economically advantageous over center pivot under certain circumstances for corn production in western Kansas (Lamm et al., 1995; Lamm and Trooien, 2003; O’Brien et al., 1998). Despite these apparent advantages, the initial capital expense, greater maintenance and management requirements, and difficulty with crop germination in dry soil (Bordovsky and Porter, 2003; Enciso et al., 2005; Thorburn et al., 2003), have been persistent barriers to greater adoption of SDI.

The objective of this paper was to compare crop production under MESA, LESA, LEPA, and SDI in a multi-year experiment at Bushland, Tex., USA. Crops included grain sorghum, soybean, and cotton. Production parameters measured included crop yield, seasonal water use (irrigation applied + rain + change in soil water storage), water use efficiency (WUE), and irrigation water use efficiency (IWUE). WUE was defined as the ratio of economic yield (Y) to seasonal water use, or WUE = Y $(ET)^{-1}$. IWUE was defined as the increase in irrigated yield (Y_i) over dryland yield (Y_d) due to irrigation (IR), or IWUE = $(Y_i - Y_d)\ IR^{-1}$ (Bos, 1980). Loan value and gross returns were also reported for cotton.

MATERIALS AND METHODS

This research was conducted at the USDA Agricultural Research Service Conservation and Production Research Laboratory at Bushland, Texas (35° 11′ N lat., 102° 06′ W long., 3,894 ft elevation above MSL). The soil is a Pullman clay loam (fine, superactive, mixed, thermic torrertic Paleustoll; USDA-NRCS, 2009) with slow permeability due to a dense B21t horizon that is 6- to 20-in. below the surface. A calcic horizon begins at approximately 4 ft below the surface.

The relative performance of mid elevation spray applicators (MESA), low elevation spray applicators (LESA), low energy precision applicator (LEPA), and subsurface drip irrigation (SDI) were compared for irrigation rates ranging from near dryland to meeting full crop evapotranspiration (ET_c) in a strip-split block design. The irrigation rates were designated I_0, I_{25}, I_{50}, I_{75}, and I_{100}, where the subscripts were the percentage of irrigation applied relative to meeting full ET. The I_0 plots were similar to dryland production, in that they received only enough irrigation around planting to ensure crop establishment, except irrigated fertility and seeding rates were used. The MESA, LESA, and LEPA methods (see Table 1 for details on application devices) were applied with a hose-fed, three-span Valmont[1] lateral-move irrigation system, where each span contained a complete block (i.e., a replicate). Irrigation rates were imposed by varying the speed of the lateral. The SDI method consisted of laterals chiseled beneath alternate furrows at the 12-in. depth, where irrigation rates were imposed by varying emitter flow rates and spacing (Table 2).

Cropping seasons included grain sorghum (2000, 2001, and 2002; Table 3), soybean (2005; Table 3), and cotton (2003, 2004, 2006, and 2007; Table 4). Soybean was planted after the 2005 cotton crop was destroyed by hail. All crops

---

[1] 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.

were planted in east-west oriented raised beds on 30-in. centers. Dikes were installed in all furrows after crops had developed true leaves to control run on and runoff of irrigation water and rain (Schneider and Howell, 2000; Howell et al., 2002). Crop varieties and cultural practices were similar to those practiced in the region for high crop yields (Tables 3 and 4).

Table 1. Sprinkler irrigation application device information [a].

Applicator	Model [b]	Options	Applicator height from furrow surface (ft)
LEPA	Super Spray head	Double-ended drag sock [c]	0
LESA	Quad IV	Flat, medium-grooved spray pad	1.0
MESA	Low-drift nozzle (LDN) spray head	Single, convex, medium-grooved spray pad	5.0

[a] All sprinkler components manufactured by Senninger Irrigation, Inc., Orlando, Fla., except where noted.
[b] All devices equipped with 10 psi pressure regulators and No. 17 (0.27-in) plastic spray nozzles, giving a flow rate of 6.5 gpm.
[c] Manufactured by A. E. Quest and Sons, Lubbock, Tex.

Table 2. Subsurface drip irrigation (SDI) dripline information [a].

Irrigation rate	Emitter Flow Rate (gph)	Emitter Spacing (in.)	Emitter Application Rate (in. h^{-1})
I_0 [b]	--	--	--
I_{25}	2.6	36	0.019
I_{50}	3.3	24	0.038
I_{75}	3.3	16	0.057
I_{100}	3.3	12	0.076

[a] All SDI dripline manufactured by Netafim USA, Fresno, Calif.
[b] Smooth tubing, no emitters

Volumetric soil water was measured by gravimetric samples to the 6 ft depth in 1-ft increments at planting and harvest. Soil water was also measured during the crop season by neutron scattering to the 7.5-ft depth in 8-in. increments (Evett and Steiner, 1995) using a depth control stand (Evett et al., 2003). Neutron moisture meters were field-calibrated and achieved accuracies better than 0.005 $m^3 m^{-3}$ (or 0.06 in. ft^{-1}). Near-surface soil water and temperatures were also measured with time-domain reflectometry and copper-constantan thermocouples, respectively (Evett et al., 2006) during the soybean and last two cotton seasons (Colaizzi et al., 2006a; 2006b). Irrigations for grain sorghum were scheduled using the Texas High Plains Evapotranspiration Network (Porter et al., 2005). Irrigations for soybean and cotton were scheduled when measured soil water deficit (by neutron scattering) averaged 1 in. in the I_{100} plots. The I_{100} plots received sufficient irrigation to bring the soil profile to field capacity; the I_{75}, I_{50}, and I_{25} plots received proportionately less. In some years, all plots received a uniform 1-in. spray application to ensure germination.

Table 3. Agronomic data for grain sorghum (2000, 2001, and 2002 seasons; Colaizzi et al., 2004) and soybean (2005 season; Colaizzi et al., 2006a).

Year	2000	2001	2002	2005
Crop	Grain sorghum	Grain sorghum	Grain sorghum	Soybean [c]
Variety	Pioneer 84G62	Pioneer 8966	Pioneer 84G62	Pioneer 94M90
Plant density (seeds ac^{-1})	121,000	93,000	89,000	182,000
Planting date	26-May	22 June[b]	31-May	20-Jun
Harvest date	21-Sep	29-Oct	14-Nov	26-Oct
Precipitation (in.)	5.5	4.9	12.5	5.5
Fertilizer applied	68 lb ac^{-1} preplant P		51 lb ac^{-1} preplant P	102 lb ac^{-1} preplant P
	52 lb ac^{-1} preplant N	160 lb ac^{-1} preplant N	143 lb ac^{-1} preplant N	158 lb ac^{-1} preplant N [c]
	40 lb ac^{-1} irr. N (I_{100}) [a]	16 lb ac^{-1} irr. N (I_{100}) [a]		
Herbicide applied	2.0 qt ac^{-1} Bicep	2.0 qt ac^{-1} Bicep	1.4 lb ac^{-1} Atrazine	1.0 qt ac^{-1} Treflan
Insecticide applied	0.25 qt ac^{-1} Lorsban	None	None	None

[a] Liquid urea 32-0-0 injected into irrigation water; deficit irrigation treatments received proportionately less.
[b] Two previous plantings on 22 May and 5 June failed to emerge.
[c] Replaced cotton that was destroyed by hail.

Table 4. Agronomic data for cotton (2003, 2004, 2006, and 2007 seasons; Colaizzi et al., 2005; 2006b).

Year	2003	2004	2006	2007
Crop	Cotton	Cotton	Cotton	Cotton
Variety	Paymaster 2280 BG, RR	Paymaster 2280 BG, RR	Paymaster 2280 BG, RR	Paymaster 2280 BG, RR
Plant density (seeds ac^{-1})	70,000	80,000	80,000	60,000
Planting date	10-Jun [a]	20-May	17-May	29-May
Harvest date	21-Nov	14-Dec	13-Dec	5-Nov
Total heat units (DD60's, F)	1940	1560	2280	1980
Precipitation (in.)	6.6	19.5	14.3	8.0
Fertilizer applied	95 lb ac^{-1} preplant P	102 lb ac^{-1} preplant P	74 lb ac^{-1} preplant P	78 lb ac^{-1} preplant P
	28 lb ac^{-1} preplant N	30 lb ac^{-1} preplant N	16 lb ac^{-1} preplant N	17 lb ac^{-1} preplant N
	43 lb ac^{-1} irr N (I_{100}) [b]	45 lb ac^{-1} irr N (I_{100}) [b]	70 lb ac^{-1} irr N (I_{100})[b]	120 lb ac^{-1} irr N (I_{100}) [b]
Herbicide applied	1.0 qt ac^{-1} Treflan	1.0 qt ac^{-1} Treflan	1.0 qt ac^{-1} Treflan	1.0 qt ac^{-1} Treflan
				1.0 qt ac^{-1} Round Up
Insecticide applied	NONE	NONE	0.5 qt ac^{-1} Lorsban	0.5 qt ac^{-1} Lorsban
Growth regulator applied	NONE	NONE	NONE	NONE
Defoliant applied	NONE	NONE	NONE	0.5 qt ac^{-1} Paraquat
Boll opener applied	NONE	NONE	NONE	0.5 qt ac^{-1} Gin Star

[a] The first planting on 21-May sustained severe hail damage on 3-Jun.
[b] Liquid urea 32-0-0 injected into irrigation water; deficit irrigation treatments received proportionately less.

Crop yield (derived from hand sampling a 108 ft^2 area in each plot), seasonal water use, water use efficiency (WUE), and irrigation water use efficiency (IWUE) were compared using the SAS PROC MIXED procedure (Littell et al., 2006). Loan value and gross return were also compared for cotton. Any differences in these parameters were tested using least squared differences ($\alpha \leq 0.05$), and means were separated by letter groupings using a macro by Saxton (1998).

RESULTS AND DISCUSSION

Grain Sorghum

The relative performance of the irrigation methods changed with the irrigation rate for grain sorghum (Table 5). For the lower irrigation rates (I_{25} and I_{50}), grain yield was greatest for SDI, followed by LEPA, MESA, and LESA. For the higher irrigation rates (I_{75} and I_{100}), grain yield was greatest for MESA, followed by LESA. The only significant difference ($\alpha \leq 0.05$) occurred at I_{25}, where grain yield under SDI was significantly greater than for the other irrigation methods. The other differences were only numerical, although some additional significant differences did occur within individual seasons (Colaizzi et al., 2004). Grain yield was significantly different for each irrigation rate average (except between I_{75} and I_{100}), and was positively correlated with the irrigation rate as expected. For irrigation method averages, grain yield was greatest for SDI, followed by MESA, LEPA, and LESA, where the only significant difference was observed between SDI and LESA. For seasonal water use, the only significant differences observed were between irrigation rate averages. WUE and IWUE followed the same trends observed for grain yield among irrigation rates and for irrigation method averages. For irrigation rate averages, however, WUE was greatest at I_{75}, followed by I_{50}, I_{100}, I_{25}, and I_0, and IWUE was greatest at I_{50}, followed by I_{25}, I_{75}, and I_{100}. The least WUE occurred at I_0, which was only about 38 percent of WUE at I_{50}, and shows the impact of irrigation on WUE (Howell, 2001). It appears that diminishing crop response to water was reached around I_{75}, as yield was not much greater at I_{100} and maximum WUE occurred at I_{75}.

We speculate that different factors, depending on irrigation rate, may have influenced the relative performance of the irrigation methods that were observed for grain sorghum. One rationale of SDI and LEPA is that evaporative losses from the plant canopy and air above the canopy and losses to wind drift are virtually eliminated, and that evaporative looses from the soil are greatly reduced (because of less soil wetting) compared with spray applicators. This would allow a greater proportion of irrigation water to be available for plant transpiration (assuming no other losses occurred such as runoff or deep percolation) and hence increase crop productivity. This hypothesis was supported by the greater grain yield observed for SDI compared with the other methods at the I_{25} and I_{50} irrigation rates (Table 5). Grain yield with LEPA was only slightly greater than MESA, suggesting both had similar total evaporative losses. However, MESA loss pathways may have also included evaporation from the canopy and overlying air and wind drift (which probably were not present under LEPA), but less loss pathways by soil water evaporation compared with LEPA. Grain yield was greater for MESA compared with LESA at all irrigation rates, but more so at I_{25} and I_{50}. This may have been caused by greater erosion of furrow dikes and runoff away from the center of the plot (where grain yield was measured by hand samples) under LESA. The spray applicator height of LESA was 1 ft, whereas it was 5 ft for MESA (Table 3). Therefore, the plant canopy would be expected to intercept more irrigation water with MESA, whereas greater risk of furrow dike erosion may result with the low applicator height of LESA, which does not divert water away from furrow dikes like the double-ended drag sock used with LEPA.

At the I_{75} and I_{100} irrigation rates, the lack of soil aeration and nutrient leaching by deep percolation may have reduced grain sorghum yield for SDI (and to a lesser extent LEPA) compared with MESA and LESA (Table 5). Colaizzi et al. (2004) observed increases in volumetric soil water between the 6- and 10-ft depths over successive measurements with neutron scattering for SDI at I_{75} and I_{100}, LEPA at I_{100}, but not for MESA or LESA. This was attributed to deep percolation rather than upward capillary movement, since the depth to saturated thickness of the Ogallala Aquifer was approximately 250 ft. Lamm et al. (1995) reported that corn yield with SDI was lower at 125% of full ET compared with 100% ET in two out of three years in a study at Colby, Kan., and also attributed this to poor soil aeration and leaching of nutrients by deep percolation. In that study, Darusman et al. (1997) deduced deep percolation using tensiometer measurements for the 100% and 125% irrigation rates. In the grain sorghum study at Bushland, Tex., the presence of deep percolation suggests that irrigation rates exceeded 100% in some cases for LEPA and SDI. The irrigations were scheduled using the Texas High Plains Evapotranspiration (TXHPET) Network (Porter et al., 2005), which used crop coefficients derived from large weighing lysimeters (Marek et al., 1988; Howell et al., 1995) for several crops including grain sorghum (Howell et al., 1997). The crop coefficients reflect crops irrigated with MESA, and probably have larger values (to compensate for greater evaporation and wind drift) compared with crop coefficients that might have resulted had the coefficients been determined using LEPA or SDI. Consequently, the subsequent studies with soybean and cotton used neutron scattering as the basis for irrigation scheduling.

Table 5. Grain sorghum response, average of 2000, 2001, and 2002 seasons; Colaizzi et al., 2004.

Irrigation Rate [a]	Irrigation method	Grain yield [b] (bu ac^{-1})		Seasonal water use (in.)		WUE (bu ac^{-1} $in.^{-1}$)		IWUE (bu ac^{-1} $in.^{-1}$)	
I_{25}	MESA	60.8	b [c]	18.1	a	3.80	b	8.57	b
(7.0 in.)	LESA	49.7	b	18.5	a	3.07	b	6.37	b
	LEPA	65.3	b	18.5	a	3.97	b	9.49	b
	SDI	99.5	a	18.9	a	5.96	a	16.32	a
I_{50}	MESA	123.3	a	22.1	a	6.12	ab	11.77	a
(10.8 in.)	LESA	109.3	a	22.5	a	5.36	b	10.36	a
	LEPA	127.0	a	22.2	a	6.24	ab	12.23	a
	SDI	140.7	a	22.3	a	7.02	a	13.74	a
I_{75}	MESA	152.3	a	25.0	a	6.71	a	10.48	a
(14.7 in.)	LESA	144.5	a	25.7	a	6.12	a	9.92	a
	LEPA	141.5	a	25.3	a	6.09	a	9.63	a
	SDI	142.1	a	24.8	a	6.33	a	9.55	a
I_{100}	MESA	162.7	a	28.6	a	6.14	a	8.69	a
(18.6 in.)	LESA	155.9	a	28.5	a	5.90	a	8.26	a
	LEPA	146.6	a	28.0	a	5.67	a	7.69	a
	SDI	144.8	a	28.6	a	5.47	a	7.47	a
Irrigation rate averages									
I_0 (3.1 in.)		18.1	d [d]	14.9	e	1.59	c	----	
I_{25} (7.0 in.)		68.8	c	18.5	d	4.20	b	10.19	ab
I_{50} (10.8 in.)		125.1	b	22.3	c	6.19	a	12.03	a
I_{75} (14.7 in.)		145.1	a	25.2	b	6.31	a	9.90	bc
I_{100} (18.6 in.)		152.5	a	28.4	a	5.80	a	8.03	c
Irrigation method averages									
	MESA	124.8	ab [e]	23.4	a	5.69	ab	9.88	ab
	LESA	114.9	b	23.8	a	5.11	b	8.73	b
	LEPA	120.1	ab	23.5	a	5.49	b	9.76	b
	SDI	131.8	a	23.6	a	6.20	a	11.77	a

[a] Numbers in parenthesis are average seasonal irrigation totals for each irrigation rate.
[b] Yields were converted from dry mass to 14% moisture content by mass; 1 bu = 55 lb.
[c] Numbers followed by the same letter are not significantly different ($\alpha \leq 0.05$) within an irrigation rate.
[d] Numbers followed by the same letter are not significantly different ($\alpha \leq 0.05$) between irrigation rate averages.
[e] Numbers followed by the same letter are not significantly different ($\alpha \leq 0.05$) between irrigation method averages.

Soybean

Soybean response was generally more favorable under SDI compared with other irrigation methods at the I_{25}, I_{50}, and I_{75} irrigation rates (Table 6). At I_{25}, SDI resulted in significantly greater crop yield, WUE, and IWUE compared with MESA and LESA; at I_{50}, these parameters were all significantly greater for SDI compared with MESA, LESA, and LEPA. Seasonal water use was not significantly different among irrigation methods at I_{25}; however, seasonal water use was significantly greater for MESA compared with LESA at I_{50} due to an outlying value in a MESA plot, the cause of which could not be determined. At I_{75}, SDI also resulted in the largest yield, WUE, and IWUE values, followed by MESA, LEPA, and LESA, whereas the ranks of greatest seasonal water use were in opposite order (i.e., SDI had the least but LESA had the most seasonal water use). At I_{100}, however, MESA resulted in the largest yield and IWUE, followed by SDI, LESA, and LEPA. SDI did result in the largest WUE at I_{100}, followed by MESA, LESA, and LEPA. As expected, yield and seasonal water use increased significantly as irrigation rate increased, but maximum WUE and IWUE both occurred at I_{50}, and the smallest WUE occurred at I_0. For irrigation method averages, SDI resulted in significantly greater yield, WUE, and IWUE compared with other methods (except yield with SDI was only numerically greater than MESA). Here, no significant differences were observed for seasonal water use; however, SDI resulted in numerically less seasonal water use compared with other methods.

Soybean yield, WUE, and IWUE followed the same trends as those observed for grain sorghum at I_{25}, I_{50}, and irrigation method averages. At all irrigation rates, MESA outperformed LESA, a result also observed for grain sorghum. These results suggest that similar loss pathways occurred for soybeans as did for grain sorghum, except that poor soil aeration and nutrient leaching may not have been as prevalent at the I_{75} and I_{100} irrigation rates, since irrigations were scheduled using direct measurements of the soil water profile, and no increases in volumetric soil water were observed below the root zone (data not shown). In addition, soil temperatures were greater with SDI compared with other methods during early development stages (Colaizzi et al., 2006a). This may have promoted pod development, and further suggests that SDI results in less evaporative loss (by lack of evaporative cooling) from the soil, a result that was predicted by Evett et al. (1995) for corn.

Table 6. Soybean response, 2005 season; Colaizzi et al., 2006a.

Irrigation Rate [a]	Irrigation method	Yield [b] (bu ac^{-1})		Seasonal water use (in.)		WUE (bu ac^{-1} $in.^{-1}$)		IWUE (bu ac^{-1} $in.^{-1}$)	
I_{25}	MESA	31.4	b [c]	14.7	a	2.15	b	2.41	bc
(2.8 in.)	LESA	29.9	b	15.5	a	1.93	b	1.87	c
	LEPA	33.1	ab	15.1	a	2.19	b	3.00	b
	SDI	36.9	a	14.7	a	2.52	a	4.34	a
I_{50}	MESA	42.1	b	19.2	a	2.20	b	3.11	b
(5.7 in.)	LESA	38.2	b	17.6	b	2.18	b	2.42	b
	LEPA	42.3	b	17.9	ab	2.36	b	3.14	b
	SDI	49.8	a	18.0	ab	2.77	a	4.47	a
I_{75}	MESA	51.2	ab	21.4	ab	2.39	ab	3.14	a
(8.5 in.)	LESA	46.6	b	22.5	a	2.09	c	2.60	a
	LEPA	48.4	ab	22.1	ab	2.18	bc	2.80	a
	SDI	52.7	a	20.9	b	2.53	a	3.32	a
I_{100}	MESA	58.6	a	24.7	a	2.37	ab	3.01	a
(11.3 in.)	LESA	55.2	ab	24.3	a	2.27	ab	2.71	a
	LEPA	51.5	b	24.4	a	2.11	b	2.38	a
	SDI	57.6	a	23.8	a	2.43	a	2.92	a
Irrigation rate averages									
I_0 (0 in.)		24.6	e [d]	12.4	e	1.98	b	----	
I_{25} (2.8 in.)		32.8	d	15.0	d	2.21	b	2.91	a
I_{50} (5.7 in.)		43.1	c	18.2	c	2.38	a	3.28	a
I_{75} (8.5 in.)		49.7	b	21.7	b	2.30	ab	2.96	a
I_{100} (11.3 in.)		55.7	a	24.3	a	2.30	ab	2.76	a
Irrigation method averages									
	MESA	45.8	ab [e]	20.0	a	2.28	b	2.92	b
	LESA	42.5	b	19.9	a	2.14	b	2.40	b
	LEPA	43.8	b	19.9	a	2.21	b	2.83	b
	SDI	49.3	a	19.3	a	2.56	a	3.76	a

[a] Numbers in parenthesis are average seasonal irrigation totals for each irrigation rate.

[b] Yields were converted from dry mass to 13% moisture content by mass; 1 bu = 60 lb.

[c] Numbers followed by the same letter are not significantly different (α ≤ 0.05) within an irrigation rate.

[d] Numbers followed by the same letter are not significantly different (α ≤ 0.05) between irrigation rate averages.

[e] Numbers followed by the same letter are not significantly different (α ≤ 0.05) between irrigation method averages.

Cotton

Cotton response was most favorable with SDI, followed by LEPA for all irrigation rates and irrigation method averages (Table 7). SDI resulted in the largest lint yield, WUE, and IWUE values compared with all other irrigation methods for all irrigation rates, followed by LEPA, LESA, and MESA (a minor exception occurred at the I_{50} and I_{75} irrigation rates, where MESA resulted in slightly greater WUE and IWUE compared with LESA). In many cases these differences were significant, with SDI usually being significantly greater than MESA and/or LESA. Seasonal water use, however, was not significantly different among irrigation methods, although SDI resulted in slightly greater numerical values. Preliminary soil temperature data during the 2006 season indicated that SDI maintained warmer soil temperatures early in the season compared with LEPA, LESA, or MESA, which was probably due to reduced evaporative cooling, and supported the hypothesis that SDI may enhance early cotton establishment and growth compared with other irrigation methods (Colaizzi et al., 2006b). Lint yield, seasonal water use, WUE, and IWUE were all significantly greater with increasing irrigation rate, with the largest values observed at I_{100}. This result for WUE and IWUE differed from those for soybean and grain sorghum, where maximum WUE and IWUE occurred below I_{100}.

The fiber quality of cotton has become increasingly important as textiles have adopted high spin technology that requires longer and stronger fibers (e.g., Yu et al., 2001). Fiber quality is comprised of several parameters (micronaire, length, strength, uniformity, color, etc.), and cotton producers receive a premium or discount, called *loan value*, based on overall fiber quality. The irrigation method generally did not result in significant differences in loan value (except at I_{50} where LEPA was significantly greater than LESA); for irrigation amount only I_{100} was significantly greater than I_{25} (Table 8). This would result in gross returns being mostly correlated to lint yield rather than loan value, and SDI resulted in the largest gross returns for all irrigation rates, followed by LEPA. Both SDI and LEPA resulted in significantly greater gross returns compared with MESA and LESA when irrigation methods were averaged.

The relative performance of SDI, LEPA, and spray for cotton were consistent with results of studies at Halfway, Tex. (Segarra et al., 1999; Bordovsky and Porter, 2003). Halfway is approximately 75 miles south of Bushland with lower elevation (3569 ft above MSL), and typically has greater heat units during the cotton season, resulting in greater lint yield and loan value compared with Bushland. Lint yield and loan values herein were similar to those reported by Marek and Bordovsky (2006), who evaluated several cotton varieties (including Paymaster 2280 BG/RR) at Etter, Tex., which is approximately 60 miles north of Bushland but has similar heat units available for cotton production.

Table 7. Cotton response, average of 2003, 2004, 2006, and 2007 seasons; Colaizzi et al., 2005; Colaizzi et al., 2006b.

Irrigation Rate [a]	Irrigation method	Lint yield ($lb\ ac^{-1}$)		Seasonal water use (in.)		WUE [b] ($lb\ ac^{-1}\ in.^{-1}$)		IWUE [b] ($lb\ ac^{-1}\ in.^{-1}$)	
I_{25}	MESA	413	a [c]	16.4	a	14.5	b	26.7	b
(2.6 in.)	LESA	441	a	16.8	a	18.6	b	27.6	b
	LEPA	492	a	16.8	a	25.6	ab	29.9	ab
	SDI	572	a	16.9	a	37.1	a	34.8	a
I_{50}	MESA	497	b	18.8	a	14.2	b	27.1	b
(4.4 in.)	LESA	500	b	18.7	a	13.8	b	27.0	b
	LEPA	660	ab	19.4	a	36.7	a	34.4	a
	SDI	715	a	19.5	a	40.8	a	36.4	a
I_{75}	MESA	697	b	21.2	a	32.5	b	32.6	bc
(6.2 in.)	LESA	674	b	21.2	a	29.5	b	31.3	c
	LEPA	777	ab	20.7	a	42.9	ab	37.3	ab
	SDI	911	a	21.5	a	59.6	a	42.8	a
I_{100}	MESA	778	b	23.2	a	37.2	b	33.3	b
(7.9 in.)	LESA	791	ab	23.2	a	37.9	b	33.9	b
	LEPA	885	ab	23.3	a	45.3	ab	37.2	ab
	SDI	951	a	22.8	a	57.3	a	42.1	a
Irrigation rate averages									
I_0 (0.9 in.)		354	e [d]	14.5	e	25.6	c	----	
I_{25} (2.6 in.)		479	d	16.7	d	29.8	bc	23.9	b
I_{50} (4.4 in.)		593	c	19.1	c	31.2	b	26.4	b
I_{75} (6.2 in.)		765	b	21.1	b	36.0	a	41.1	a
I_{100} (7.9 in.)		851	a	23.1	a	36.6	a	44.4	a
Irrigation method averages									
	MESA	596	b [e]	19.9	a	29.9	c	24.6	c
	LESA	601	b	19.9	a	30.0	c	24.9	c
	LEPA	703	a	20.1	a	34.7	b	37.6	b
	SDI	787	a	20.2	a	39.0	a	48.7	a

[a] Numbers in parenthesis are average seasonal irrigation totals for each irrigation rate.
[b] WUE and IWUE were computed based on lint yield.
[c] Numbers followed by the same letter are not significantly different (α ≤ 0.05) within an irrigation rate.
[d] Numbers followed by the same letter are not significantly different (α ≤ 0.05) between irrigation rate averages.
[e] Numbers followed by the same letter are not significantly different (α ≤ 0.05) between irrigation method averages.

Table 8. Cotton loan value and gross return, average of 2003, 2004, 2006, and 2007 seasons.

Irrigation Rate [a]	Irrigation method	Loan Value [b] (cents lb^{-1})		Gross return ($ ac^{-1})	
I_{25} (2.6 in.)	MESA	46.39	a [c]	$192	a
	LESA	46.96	a	$209	a
	LEPA	48.59	a	$240	a
	SDI	49.23	a	$284	a
I_{50} (4.4 in.)	MESA	48.13	ab	$240	bc
	LESA	45.77	b	$228	c
	LEPA	49.53	a	$334	ab
	SDI	49.29	ab	$354	a
I_{75} (6.2 in.)	MESA	49.20	a	$347	b
	LESA	49.41	a	$336	b
	LEPA	49.40	a	$390	ab
	SDI	49.45	a	$453	a
I_{100} (7.9 in.)	MESA	48.94	a	$388	a
	LESA	49.29	a	$395	a
	LEPA	50.05	a	$452	a
	SDI	50.35	a	$481	a
Irrigation rate averages					
I_0 (0.9 in.)		48.11	ab [d]	$173	d
I_{25} (2.6 in.)		47.79	b	$231	d
I_{50} (4.4 in.)		48.18	ab	$289	c
I_{75} (6.2 in.)		49.37	ab	$382	b
I_{100} (7.9 in.)		49.65	a	$429	a
Irrigation method averages					
	MESA	48.16	a [e]	$292	b
	LESA	47.86	a	$292	b
	LEPA	49.39	a	$354	a
	SDI	49.58	a	$393	a

[a] Numbers in parenthesis are average seasonal irrigation totals for each irrigation rate.
[b] Base loan value was 51.60 cents lb^{-1} for all years, from International Textile Center, Lubbock, Texas
[c] Numbers followed by the same letter are not significantly different ($\alpha \leq 0.05$) within an irrigation rate.
[d] Numbers followed by the same letter are not significantly different ($\alpha \leq 0.05$) between irrigation rate averages.
[e] Numbers followed by the same letter are not significantly different ($\alpha \leq 0.05$) between irrigation method averages.

SUMMARY AND CONCLUSIONS

Crop production was compared under four irrigation methods and four irrigation rates in the Southern High Plains, Tex., USA. Crops included three seasons of grain sorghum, one season of soybean (planted after a cotton crop was destroyed by hail), and four seasons of upland cotton. Irrigation methods included subsurface drip irrigation (SDI), low energy precision applicators (LEPA), low elevation spray applicators (LESA), and mid elevation spray applicators (MESA). For each irrigation method, irrigation was applied at rates of 25, 50, 75, and 100% of meeting the full crop water requirement (i.e., crop evapotranspiration), and an additional near-dryland rate (0%) was included to compute irrigation water use efficiency.

Grain sorghum and soybean response to irrigation method changed with irrigation rate, with SDI and LEPA generally outperforming MESA and LESA at low irrigation rates, and vice-versa at high irrigation rates. For grain sorghum at high irrigation rates, deep percolation was observed for SDI and to a lesser extent LEPA. The yield depressions at high irrigation rates may have resulted from nutrient leaching and lack of soil aeration. Cotton response was consistently best for SDI, followed by LEPA, and either MESA or LESA at all irrigation rates. Preliminary soil temperature data for soybean and cotton indicated that SDI maintained warmer soil temperatures compared with the other irrigation methods early in the season. Warmer soil temperatures may have been the result of less soil water evaporation. Thus, SDI may have partitioned more soil water to plant transpiration, which enhanced crop yields, especially at low irrigation rates. Warmer soil temperatures would make SDI advantageous for cotton production in thermally-limited climates. LEPA may also result in greater partitioning to plant transpiration compared with MESA or LESA, as crop response to LEPA was generally almost as favorable as SDI. Despite possible differences in evaporation pathways, there were few significant differences in total seasonal water use among irrigation methods within an irrigation rate for all crops. This, along with the potential for deep percolation and other losses (e.g., runoff), underscores the need for proper irrigation management if the full benefits of advanced irrigation technology are to be realized.

Beginning in the 2009 season, this experiment will continue with corn, which is also a major crop in the Southern Great Plains. The cost and return of crop production under each irrigation method will be assessed to determine the long-term economics of SDI, LEPA, LESA, and MESA with various irrigation rates. It is hoped that these results will assist producers in selecting the irrigation technology that will result in the greatest profit potential while prolonging the life of the Ogallala Aquifer.

ACKNOWLEDGEMENTS

This research was supported by the Ogallala Aquifer Program and USDA-ARS National Program 211, Water Availability and Watershed Management. We thank the numerous biological technicians and student workers for their meticulous and dedicated efforts in executing experiments and obtaining and processing data. Thanks also to Dr. Arland Schneider, USDA-ARS, Ret., for initiating the grain sorghum study, and to Drs. Sara Duke and Kathy Yeater, USDA-ARS, Statisticians, for their assistance with the statistical analysis.

REFERENCES

Bordovsky, J. P., and D. Porter. 2008. Effect of subsurface drip irrigation system uniformity on cotton production in the Texas High Plains. *Applied Engineering in Agriculture.* 24(4): 465-472.

Bordovsky, J. P., and D. Porter. 2003. Cotton response to pre-plant irrigation level and irrigation capacity using spray, LEPA, and subsurface drip irrigation. Presented at the 2003 ASAE International Meeting, Las Vegas, NV, 27-30 July. ASAE Paper No. 032008.

Bos, M. G. 1980. Irrigation efficiencies at crop production level. *ICID Bull.* 29: 18-25, 60.

Camp, C. R. 1998. Subsurface drip irrigation: A review. *Trans. ASAE* 41(5): 1353-1367.

Colaizzi, P. D., P. H. Gowda, T. H. Marek, and D. O. Porter. 2009. Irrigation in the Texas High Plains: A brief history and potential reductions in demand. *In press, Irrig. and Drain.* DOI:10.1002/ird.418.

Colaizzi, P. D., A. D. Schneider, S. R. Evett, T. A. Howell. 2004. Comparison of SDI, LEPA, and spray irrigation performance for grain sorghum. *Trans. ASAE.* 47(5):1477-1492.

Colaizzi, P. D., S. R. Evett, and T. A. Howell. 2005. Cotton production with SDI, LEPA, and spray irrigation in a thermally-limited climate. CD-ROM. Irrigation Association Annual Meeting, 6-8 Nov, Phoenix, AZ.

Colaizzi, P. D., S. R. Evett, and T. A. Howell. 2006a. Crop emergence and near-surface soil temperature for SDI, LEPA, and spray irrigation. Paper Number: 062278. 2006 ASABE Annual International Meeting, Sponsored by American Society of Agricultural and Biological Engineers, 9-12 July, Portland, OR.

Colaizzi, P. D., S. R. Evett, and T. A. Howell. 2006b. Near-surface soil water and temperature for SDI, LEPA, and spray irrigation. CD-ROM. Irrigation Association Annual Meeting, 5-7 Nov, San Antonio, TX.

Darusman, A. H. Khan, L. R. Stone, W. E. Spurgeon, and F. R. Lamm. 1997. Water flux below the root zone vs. irrigation amount in drip-irrigated corn. *Agron. J.* 89(3): 375-379.

Enciso-Medina, J. M., P. D. Colaizzi, W. L. Multer, and C. R. Stichler. 2007. Cotton response to phosphorus fertigation using subsurface drip irrigation. *Applied Engineering in Agriculture.* 23(3): 299-304.

Enciso, J. M., P. D. Colaizzi, and W. L. Multer. 2005. Economic analysis of subsurface drip irrigation lateral spacing and installation depth for cotton. *Trans ASAE.* 48(1):197-204.

Evett, S. R., T. A. Howell, and A. D. Schneider. 1995. Energy and water balances for surface and subsurface drip irrigated corn. pp. 135-140. In F. R. Lamm (ed.) *Microirrigation for a Changing World: Conserving Resources/Preserving the Environment. Proc. Fifth International Microirrigation Congress.* Am. Soc. Agric. Engr., St. Joseph, MI.

Evett, S. R., J. A. Tolk, and T. A. Howell. 2003. A depth control stand for improved accuracy with the neutron probe. *Vadose Zone J.* 2(4): 642-649.

Evett, S. R., and J. L. Steiner. 1995. Precision of neutron scattering and capacitance-type soil water content gauges from field calibration. *Soil Sci. Soc. Am. J.* 59(4): 961-968.

Evett, S. R., J. A. Tolk, and T. A. Howell. 2006. Soil profile water content determination: Sensor accuracy, axial response, calibration, temperature dependence, and precision. *Vadose Zone J.* 5: 894-907.

Henggeler, J. C. 1995. A history of drip-irrigated cotton in Texas. In *Microirrigation for a Changing World: Conserving Resources/Preserving the Environment. Proc. Fifth International Microirrigation Congress.* F. R. Lamm (ed.). pp. 669-674. ASAE, St. Joseph, MI.

Howell, T. A., A. D. Schneider, D. A. Dusek, T. H. Marek, and J. L. Steiner. 1995. Calibration and scale performance of Bushland weighing lysimeters. *Trans. ASAE* 38(4): 1019-1024.

Howell, T. A., J. L. Steiner, A. D. Schneider, S. R. Evett, and J. A. Tolk. 1997b. Seasonal and maximum daily evapotranspiration of irrigated winter wheat, sorghum, and corn: Southern High Plains. *Trans. ASAE* 40(3): 623-634.

Howell, T. A. 2001. Enhancing water use efficiency in irrigated agriculture. *Agron. J.* 93(2): 281-289.

Howell, T. A., A. D. Schneider, and D. A. Dusek. 2002. Effects of furrow diking on corn response to limited and full sprinkler irrigation. *Soil Sci. Soc. Am. J.* 66(1): 222-227.

Howell, T. A., S. R. Evett, J. A. Tolk, and A. D. Schneider. 2004. Evapotranspiration of full-, deficit-irrigation, and dryland cotton on the Northern Texas High Plains. *J. Irrig. Drain. Engrg., Am. Soc. Civil Engrs.* 130(4): 277-285.

Lamm, F. R., and T. P. Trooien. 2003. Subsurface drip irrigation for corn production: a review of 10 years of research in Kansas. *Irrig. Sci.* 22: 195-200.

Lamm, F. R., H. L. Manges, L. R. Stone, A. H. Khan, and D. H. Rogers. 1995. Water requirement of subsurface drip-irrigated corn in northwest Kansas. *Trans. ASAE* 38(2): 441-448.

Littell, R. C., G. A. Milliken, W. W. Stroup, R. D. Wolfinger, and O. Schabenberger. 2006. SAS® for Mixed Models, 2nd ed. Cary, N.C.: SAS Institute, Inc.

Lyle, W. M., and J. P. Bordovsky. 1983. LEPA irrigation system evaluation. *Trans. ASAE* 26(3): 776-781.

Marek, T. H., and D. Bordovsky. 2006. Performance of ten cotton varieties in the Northern Texas High Plains. *Texas Journal of Agricultural and Natural Resources.* 19: 48-61.

Marek, T. H., A. D. Schneider, T. A. Howell, and L. L. Ebeling. 1988. Design and construction of large weighing monolithic lysimeters. *Trans. ASAE* 31(2):477-484.

O'Brien, D. M., D. H. Rogers, F. R. Lamm, and G. A. Clark. 1998. An economic comparison of subsurface drip and center pivot irrigation systems. *Applied Engineering in Agriculture.* 14(4): 391-398.

Porter, D. O., T. H. Marek, T. A. Howell, and L. L. New. 2005. The Texas High Plains Evapotranspiration Network (TXHPET) User Manual v. 1.01. Texas A&M University Agricultural Research and Extension Centre Rep. 03-37. Available at: http://txhighplainset.tamu.edu/usermanual.pdf (accessed 23 January 2009).

Saxton, A. M. 1998. A macro for converting mean separation output to letter groupings in proc mixed. In *Proc. 23rd SAS Users Group Intl*., 1243-1246. Cary, N.C.: SAS Institute, Inc.

Schneider, A. D. 2000. Efficiency and uniformity of the LEPA and spray sprinkler methods: A review. *Trans. ASAE* 43(4): 937-944.

Schneider, A. D., and T. A. Howell. 2000. Surface runoff due to LEPA and spray irrigation of a slowly permeable soil. *Trans. ASAE* 43(5): 1089-1095.

Segarra, E., L. Almas, and J. P. Bordovsky. 1999. Adoption of advanced irrigation technology: LEPA vs. drip in the Texas High Plains. In *Proc. Beltwide Cotton Conf.*,1:324-328. Memphis, Tenn.: National Cotton Council.

Thorburn, P. J., F. J. Cook, and K. L. Bristow. 2003. Soil-dependent wetting from trickle emitters: implications for system design and management*. Irrig. Sci.* 22: 121-127.

USDA-Natural Resources Conservation Service. 2009. Web Soil Survey, Soil Survey TX375, Potter County, Texas. Available at: http://websoilsurvey.nrcs.usda.gov. (accessed 23 January 2009).

Wanjura, D. F., J. R. Mahan, and D. R. Upchurch. 1996. Irrigation starting time effects on cotton under high-frequency irrigation. *Agron. J.* 88(4): 561-566.

Yu, J., Kohel, R. J., and Zhang, T. 2001. Evaluation of cotton fiber quality QTLs for molecular breeding. In *Proc. Genetic Control Of Cotton Fiber And Seed Quality Workshop*, 5-6 Dec. 2000, San Antonio, TX, 175-180.