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CORN PRODUCTION WITH SPRAY, LEPA, AND SDI

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ABSTRACT

Corn is a major irrigated crop in the U.S. Great Plains with a large irrigation requirement making efficient, effective irrigation technology important. The objective of this paper was to compare corn productivity for different irrigation methods and irrigation rates in 2009 and 2010 at Bushland, Texas. Irrigation methods included mid-elevation spray application (MESA), low elevation spray application (LESA), low energy precision application (LEPA), and subsurface drip irrigation (SDI). Each irrigation method was evaluated at four irrigation rates, which were 25, 50, 75, and 100% of meeting the full crop water requirement. There were no significant differences in grain yield and water use efficiency for MESA, LESA, and SDI for the 100% irrigation rate in 2009 and for all irrigation rates in 2010. In 2009, SDI resulted in significantly greater grain yield and water use efficiency compared with all other methods at the 50 and 75% irrigation rates; little measurable grain yield resulted for all methods at the 25% rate. However, 2009 was not a typical production year because an irrigation system failure occurred just before anthesis, and unusually high atmospheric demands followed, resulting in soil water shortages in all plots during the most water-sensitive development stages, with consistent lowering of grain yield. In both years, LEPA resulted in lower yield, soil water content, and water use efficiency compared with the other methods at the 75 and 100% rates, which was partially attributed to furrow dike erosion and plot runoff. The relative response of corn to MESA, LESA, LEPA, and SDI was much different compared with other crops that were evaluated in previous experiments; these included grain sorghum, soybean, and cotton.

INTRODUCTION

Grain corn is a major irrigated crop in the U.S. Great Plains that has been mostly produced for beef cattle feed and more recently as a feedstock for ethanol. In the semiarid Southern High Plains, nearly all corn production requires irrigation and is dependent on pumping from the Ogallala Aquifer, which has been declining since large-scale development of irrigation in the region because pumping has exceeded recharge. Within the Texas portion of the Southern High Plains, approximately 75 percent of the irrigated area is with center pivot sprinklers, with the remaining 20 and 5 percent comprising gravity (i.e., furrow water) and subsurface drip irrigation (SDI), respectively (Colaizzi et al., 2009).

Most SDI has been installed in the cotton producing region centered around Lubbock, Texas. For both full and deficit irrigation rates, cotton lint yield and water use efficiency have been shown to be consistently greater for full and deficit irrigation rates under SDI compared with sprinklers, including both mid elevation spray application (MESA) and low elevation spray application (LESA) configurations. Cotton response to low energy precision application (LEPA) has also been more favorable compared with MESA or LESA, but still not as favorable as SDI (Bordovsky and Porter, 2003; Colaizzi et al., 2010). This is thought to be related to SDI maintaining warmer soil temperatures near the surface because less evaporative cooling occurs relative to MESA, LESA, or LEPA, which apply water directly to the soil surface and/or plant canopy (Colaizzi et al., 2010). Sufficiently warm soil and plant microclimate is critical for cotton production in semiarid regions with high elevations because cool nighttime temperatures usually occur throughout the year. Other studies have shown that SDI resulted in greater grain yield and water use efficiency for grain sorghum (Colaizzi et al., 2004) and soybean (Colaizzi et al., 2010) at deficit irrigation rates because lower evaporative losses for SDI relative to sprinklers resulted in greater soil water being available for plant transpiration, which was also observed for cotton. As irrigation well capacities decline, Great Plains producers are increasingly being forced to adopt deficit irrigation strategies. Since SDI has been shown to increase crop water productivity relative to MESA, LESA, and LEPA at deficit irrigation rates for some crops, there has been continued adoption of SDI in the Great Plains (USDA-NASS, 2008).

Corn response to various rates of deficit and full irrigation has been evaluated in the Great Plains using sprinkler irrigation (Howell et al., 1989; 2002; Payero et al., 2006), LEPA (Howell et al., 1995), and SDI (Howell et al., 1997; Lamm, 2004; Payero et al., 2009). However, it appears that only Schneider and Howell (1998) and Lamm (2004) directly compared corn response to different irrigation methods, where the irrigation system itself was a randomized and replicated treatment. Schneider and Howell (1998) compared spray and LEPA, and Lamm (2004) was limited to SDI vs. simulated LEPA, where water for the simulated LEPA treatment was applied by stationary tubing into furrow basins. No study has directly compared corn production under SDI with moving spray or LEPA packages commonly used with center pivots in the Great Plains. The objective of this research was to compare corn water productivity using MESA, LESA, LEPA, and SDI across a range of irrigation rates.

EXPERIMENTAL PROCEDURE

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., 3,900 ft elevation above mean sea level). The soil is a Pullman clay loam (fine, superactive, mixed, thermic torrertic Paleustoll; USDA-NRCS, 2011) with slow permeability due to a dense B21t horizon that is 6 to 20 inches below the surface. A calcic horizon begins at approximately 4 ft below the surface.

The relative performance of MESA, LESA, LEPA, and SDI were compared for irrigation rate treatments ranging from near dryland to meeting full crop evapotranspiration (ETc) in a strip-split block design. The irrigation rate treatments 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 ETc. The I_0 plots were similar to dryland production, in that they received only enough irrigation around planting to ensure crop establishment; but irrigated fertility and seeding rates were used. Each rain event was measured manually by a gauge located at the field site. Each plot was 30 ft wide by 39 ft long and contained 12 raised beds with east-west orientation and 30-inch centers, with the crop planted in the centers of the raised beds. Dikes were installed in all furrows following emergence to control run on and runoff of irrigation water and rain (Schneider and Howell, 2000; Howell et al., 2002).

The MESA, LESA, and LEPA methods (see Table 1 for details on application devices) were applied with a hose-fed, three-span lateral-move irrigation system, where each span contained a complete block (i.e., a replicate), resulting in three replications for each treatment. The LEPA method used double-ended drag socks in 2009; however, the drag socks were sometimes caught by plants and pulled off as the drop moved through after plants reached heights of about 5 ft, resulting in excessive furrow dike erosion. Several attempts to lower the height and strengthen the drag sock connection were not successful. Therefore, the LEPA treatment used low-impact bubblers without socks in 2010. Irrigation rate treatments were imposed by varying the speed of the lateral-move. The SDI method consisted of drip laterals installed with a shank injector beneath alternate furrows at the 12-inch depth, where irrigation treatments were imposed by varying emitter flow rates and spacing (Table 2).

Corn (Pioneer 33B54 BT, RR[1]) was planted in the 2009 and 2010 seasons. Cultural practices were similar to those practiced in the region for high crop yields (Table 3). 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 probe (NP) to the 10-ft depth in 8-inch increments (Evett and Steiner, 1995) using a depth control stand, which allowed accurate measurement of soil water at shallow (4-inch) depths (Evett et al., 2003). The NP meters were field-calibrated and achieved accuracies better than 0.005 $\text{in.}^3\ \text{in.}^{-3}$, including the 4-inch depth near the surface. Both gravimetric and NP were measured near the center of each plot (i.e., sixth row from the south and 20 ft from plot edge) and in the center of the raised bed.

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[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.

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

Applicator	Model [b]	Options	Applicator height from furrow surface (ft)
LEPA, 2009	Super Spray head	Double-ended drag sock [c]	0
LEPA, 2010	Quad spray	Bubbler	1.0
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-inch) 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}	0.18	36	0.019
I_{50}	0.24	24	0.038
I_{75}	0.24	16	0.057
I_{100}	0.24	12	0.076

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

Irrigations were scheduled based on NP measurements, usually at weekly intervals during the irrigation season. Early in the season, irrigation water was applied when the average soil water deficit in the root zone of the I_{100} treatment reached 1.0 inch below field capacity, where field capacity was 4.0 inches per ft (0.33 in.^{3} in.$^{-3}$) of the soil profile. From about the middle of the vegetative stage (10-leaf) to termination of irrigations, the appropriate irrigation amount was applied on a weekly basis in 1.0-inch increments to avoid over-filling the furrow dike basins. All sprinkler plots were irrigated on the same day, with the deficit (I_{25}, I_{50}, and I_{75}) treatments receiving proportionately less water by increasing the speed of the lateral move system. The SDI plots had the same amount of water applied as the sprinkler plots except the duration of each irrigation event was longer.

Table 3. Agronomic and irrigation data for the 2009 and 2010 seasons.

Variable	2009	2010
Fertilizer applied	150 lb ac^{-1} preplant N 130 lb ac^{-1} preplant P 240 lb ac^{-1} irr N (I_{100}) [a]	150 lb ac^{-1} preplant N 65 lb ac^{-1} preplant P 150 lb ac^{-1} irr N (I_{100}) [a] 90 lb ac^{-1} preplant S
Herbicide applied	2.0 qt ac^{-1} Bicep	1.5 lb ac^{-1} Atrazine
Insecticide applied	NONE	NONE
Gravimetric soil water samples	30-Apr 5-Nov	20-May 6-Oct
Corn variety	Pioneer 33B54 BT, RR	Pioneer 33B54 BT, RR
Plant density	35,000 seeds ac^{-1}	35,700 seeds ac^{-1}
Planting date	29-Apr	12-May
Harvest date	15-Sep	15-Sep
Preplant irrigation	3.0 inches	0.8 inches
First treatment irrigation	1-Jun	11-Jun
Last irrigation	28-Aug	26-Aug
I_0 irrigation [b]	3.0 inches	1.8 inches
I_{25} irrigation [b]	7.2 inches	7.1 inches
I_{50} irrigation [b]	11.4 inches	12.2 inches
I_{75} irrigation [b]	15.6 inches	17.5 inches
I_{100} irrigation [b]	19.7 inches	22.8 inches
Precipitation	10.0 inches	8.7 inches

[a] Liquid urea 32-0-0 injected into irrigation water; deficit irrigation treatments received proportionately less.
[b] Includes preplant irrigation

Grain yield, final plant population, kernel mass, number of ears, and kernels per ear were determined by hand harvesting two adjacent rows along a 21.5 ft length in the center of each plot (resulting in a 107.5 ft^2 sample area). Ears were shelled by hand and kernels were oven dried at 160°F for 5 days. Dry yield mass was converted to 15.5 percent moisture (wet basis), and reported as volume (i.e., 56.0 lb. per bu at 15.5% wet basis). Kernel mass was determined from three 500-kernel subsamples, and kernels per ear was calculated as yield mass per area divided by kernel mass divided by ears per area. Yield components, seasonal water use (irrigation applied + precipitation + change in soil water storage), and water use efficiency were compared using the SAS PROC MIXED procedure (Littell et al., 2006). Water use efficiency (bu ac^{-1} in.$^{-1}$) was defined as the ratio of economic yield (Y, bu ac^{-1}) to seasonal water use (ETc, inches) (Bos, 1980). 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

The 2009 season began with planting on April 29, reaching anthesis on July 8, and black layer by September 3 (Table 4). Hand samples used to determine yield and yield components were obtained on September 15.On June 3 (8 leaf stage), some hail damage occurred, which the plants appeared to have outgrown in two weeks. The tassel and silk stages coincided with high temperatures, high wind speeds, and low relative humidity, resulting in crop evapotranspiration approaching almost 0.50 in. d^{-1} for several days. The unusually high temperatures during silking are believed to have affected pollen viability. Rainfall during the 2009 season totaled 10.0 inches (Table 3), which was somewhat below the 12.3-inch average from April 29 to September 15. In 2010, planting was delayed until May 12 because of cold and wet conditions during the El Niño winter and spring (Table 4). Very warm conditions during May and June resulted in rapid growing degree day accumulation, and the 2010 crop reached anthesis near the same time as the 2009 crop. The 2010 crop reached black layer by September 8, and hand samples were obtained on September 15. Total rainfall during the season was 8.7 inches (Table 3), which was also below average.

Table 4. Dates and cumulative growing degree days (GDD) for corn development stages, where GDD were computed using baseline and maximum temperatures of 50 and 86 °F, respectively.

	2009		2010	
	Date	GDD (°F)		GDD (°F)
Plant	29-Apr	0	12-May	0
Emerged	13-May	158	28-May	258
4-leaf	21-May	277	3-Jun	387
5-leaf	25-May	339	5-Jun	433
6-leaf	28-May	378	8-Jun	515
8-leaf	3-Jun	484	11-Jun	591
10-leaf	12-Jun	668	14-Jun	664
12-leaf	15-Jun	739	17-Jun	737
14-leaf	4-Jul	1206	5-Jul	1184
Tassel	8-Jul	1298	10-Jul	1290
Silk	15-Jul	1481	15-Jul	1422
Blister	21-Jul	1626	23-Jul	1630
Milk	30-Jul	1817	28-Jul	1753
Dough	4-Aug	1929	6-Aug	1981
Dent	11-Aug	2109	12-Aug	2137
Black layer	3-Sep	2623	8-Sep	2758

Grain yields in 2009 were much lower than expected except for the MESA, LESA, and SDI methods at the I_{100} irrigation rate (Table 5). There was essentially no yield for all irrigation methods at the I_0 and I_{25} rates, and only SDI resulted in more than 10 bu ac^{-1} at the I_{50} rate. At the I_{75} rate, MESA, LESA, and LEPA resulted in less than 100 bu ac^{-1}, and SDI only 188.8 bu ac^{-1}. Previous studies at our location using LEPA at the I_{80} rate and SDI at the I_{67} rate resulted in 200 to 235 bu ac^{-1} (Howell et al., 1995; 1997). Grain yield was reduced in 2009 mainly from failure of ears to produce kernels, as numerous blank cobs were observed. Final plant population and kernel mass, however, were as expected and were similar to those reported at Bushland, Texas (Howell et al., 1995; 1997) and at Colby, Kansas (Lamm, 2004). Seasonal water use was less for SDI at I_{25} and I_{50} compared with the other methods, resulting in greater water use efficiency. At I_{75}, there were no differences in seasonal water use; at I_{100}, LEPA used 1.5 to 2.0 inches more than the other methods. Overall, seasonal water use was similar to that reported in previous studies (Howell et al., 1995; 1997), but since grain yield was relatively low, water use efficiency was also relatively low except for MESA, LESA, and SDI at I_{100} and SDI at I_{75}.

In 2010, most grain yields were similar to previous studies (Howell et al., 1995; 1997) at the I_{75} and I_{100} rates, and greater than expected at the I_{25} and I_{50} rates (Table 6). However, grain yield using LEPA was significantly less compared with the other methods at the I_{75}, and I_{100} rates. The low grain yield using LEPA was inconsistent with previous studies at our location (e.g., Howell et al., 1995; Schneider and Howell, 1998). As discussed later, although soil water depletion in the LEPA method was greater compared with the other methods, it did not appear to be enough in the I_{100} rate to cause yield-reducing water stress. At I_{50}, grain yield for MESA was similar to LEPA. Grain yield differences were related to both kernel mass and kernels per ear; these yield components were within the expected ranges. Plant population was slightly greater for LEPA at I_{50}, I_{75}, and I_{100} rates. For each irrigation rate, there were no differences in seasonal water use among irrigation methods. Therefore, water use efficiency followed nearly the same trends as grain yield, with LEPA having less water use efficiency compared with the other irrigation methods.

The kernel set failure observed in 2009 was likely the result of water shortages in the soil profile during anthesis, which coincided with very high atmospheric demand and high temperatures. The soil water shortages were due to irrigation system operational problems followed by unusually high crop water demand. The combination of greater sensitivity to water stress during anthesis (e.g., Payero et al., 2009) and greater atmospheric demand would both serve to decrease the readily available soil water in the root zone (RAW), as defined by FAO 56 (Allen et al., 1998). If soil water depletion in the root zone exceeds RAW, the crop experiences water stress, which may reduce yield. This is illustrated by comparing RAW with measured soil water depletion in the root zone during the season (Fig. 1). Also shown is the total available soil water in the root zone

Table 5. Corn response for 2009 season.

Irrig. rate [a]	Irrig. method	Grain yield 15.5% wb [b] bu ac^{-1}	Final plant pop. plants ac^{-1}	Kernel mass mg	Kernels per ear	Seasonal water use inches	Water use efficiency bu ac^{-1} in^{-1}
I_{25} (7.2)	MESA	0.0 a [c]	34,143 a	0 b	0 b	15.3 ab	0.0 a
	LESA	0.0 a	33,603 a	0 b	0 b	15.7 ab	0.0 a
	LEPA	0.3 a	32,793 a	0 b	0 b	16.6 a	0.0 a
	SDI	3.6 a	33,198 a	105 a	567 a	14.8 b	0.2 a
I_{50} (11.4)	MESA	7.5 b	33,333 a	322 a	26 b	19.9 ab	0.4 b
	LESA	8.8 b	32,928 a	307 a	29 b	20.7 ab	0.4 b
	LEPA	8.9 b	34,008 a	301 a	50 b	21.4 a	0.4 b
	SDI	70.9 a	33,738 a	310 a	186 a	19.8 b	3.6 a
I_{75} (15.6)	MESA	37.5 c	34,278 a	341 a	89 c	24.1 a	1.5 c
	LESA	77.3 b	32,659 a	347 a	186 b	24.7 a	3.1 b
	LEPA	30.1 c	33,873 a	312 a	96 c	25.2 a	1.2 c
	SDI	188.8 a	33,468 a	357 a	433 a	25.4 a	7.4 a
I_{100} (19.7)	MESA	214.9 a	34,683 a	348 a	477 ab	28.0 b	7.7 a
	LESA	235.5 a	33,873 a	349 a	525 a	28.5 b	8.3 a
	LEPA	103.0 b	33,198 a	349 a	256 b	30.2 a	3.4 b
	SDI	233.0 a	34,413 a	348 a	527 a	28.5 b	8.2 a
Irrigation rate averages							
I_0 (3.0)		0.0 c [d]	30,769 b	0 c	0 b	10.5 e	0.0 c
I_{25} (7.2)		1.0 c	33,434 a	26 c	142 b	15.6 d	0.1 c
I_{50} (11.4)		24.0 c	33,502 a	310 b	73 b	20.4 c	1.2 c
I_{75} (15.6)		83.4 b	33,570 a	339 a	201 b	24.8 b	3.3 b
I_{100} (19.7)		196.6 a	34,042 a	349 a	446 a	28.8 a	6.9 a
Irrigation method averages							
	MESA	65.0 bc [e]	34,109 a	253 ab	148 b	21.8 b	2.4 bc
	LESA	80.4 b	33,266 a	251 ab	185 b	22.4 ab	3.0 b
	LEPA	35.5 c	33,468 a	240 b	100 b	23.3 a	1.3 c
	SDI	124.1 a	33,704 a	280 a	428 a	22.1 b	4.9 a

[a] Numbers in parenthesis are seasonal irrigation totals for each irrigation rate (inches).

[b] Yields were converted from dry mass to 15.5 percent moisture content by mass (wet basis) and 56.0 lb bu^{-1}.

[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.

Table 6. Corn response for 2010 season.

Irrig. rate [a]	Irrig. method	Grain yield 15.5% wb [b] bu ac^{-1}		Final plant pop. plants ac^{-1}		Kernel mass mg		Kernels per ear		Seasonal water use inches		Water use efficiency bu ac^{-1} in^{-1}	
I_{25}	MESA	90.1	a [c]	35,088	a	207	bc	328	a	18.2	a	5.0	a
(7.1)	LESA	101.9	a	34,548	a	217	ab	363	a	18.2	a	5.6	a
	LEPA	90.7	a	35,088	a	228	a	309	a	18.1	a	5.0	a
	SDI	82.6	a	34,008	a	193	c	349	a	17.8	a	4.7	a
I_{50}	MESA	180.1	b	35,223	a	274	b	484	a	22.6	a	8.0	ab
(12.2)	LESA	196.9	ab	34,683	a	284	ab	522	a	22.4	a	8.8	a
	LEPA	175.1	b	35,493	a	276	b	461	a	23.0	a	7.6	b
	SDI	202.3	a	34,278	a	296	a	522	a	22.6	a	9.0	a
I_{75}	MESA	233.5	a	33,603	b	316	a	574	a	27.7	a	8.5	a
(17.5)	LESA	231.0	a	34,008	ab	322	a	556	a	27.1	a	8.5	a
	LEPA	194.3	b	36,167	a	309	a	453	b	28.0	a	7.0	b
	SDI	237.5	a	35,088	ab	316	a	562	a	26.9	a	8.8	a
I_{100}	MESA	246.7	a	34,008	ab	326	b	575	a	31.6	a	7.8	a
(22.8)	LESA	235.4	a	32,659	b	348	a	557	ab	32.1	a	7.3	a
	LEPA	195.3	b	35,762	a	291	c	489	b	32.2	a	6.1	b
	SDI	249.1	a	34,278	ab	333	ab	565	a	32.1	a	7.8	a
Irrigation rate averages													
I_0 (1.8)		18.5	d [d]	33,828	a	194	c	140	c	13.3	e	1.4	d
I_{25} (7.1)		91.3	c	34,683	a	211	c	337	b	18.1	d	5.1	c
I_{50} (12.2)		188.6	b	34,919	a	282	b	497	a	22.6	c	8.3	a
I_{75} (17.5)		224.1	a	34,717	a	316	a	536	a	27.4	b	8.2	a
I_{100} (22.8)		231.6	a	34,177	a	325	a	547	a	32.0	a	7.2	b
Irrigation method averages													
	MESA	187.6	a [e]	34,481	a	281	ab	490	ab	25.0	a	7.3	a
	LESA	191.3	a	33,974	a	293	a	500	a	24.9	a	7.6	a
	LEPA	163.9	b	35,628	a	276	b	428	b	25.4	a	6.4	b
	SDI	192.9	a	34,413	a	284	ab	500	a	24.8	a	7.6	a

[a] Numbers in parenthesis are seasonal irrigation totals for each irrigation rate (inches).

[b] Yields were converted from dry mass to 15.5 percent moisture content by mass (wet basis) and 56.0 lb bu^{-1}.

[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.

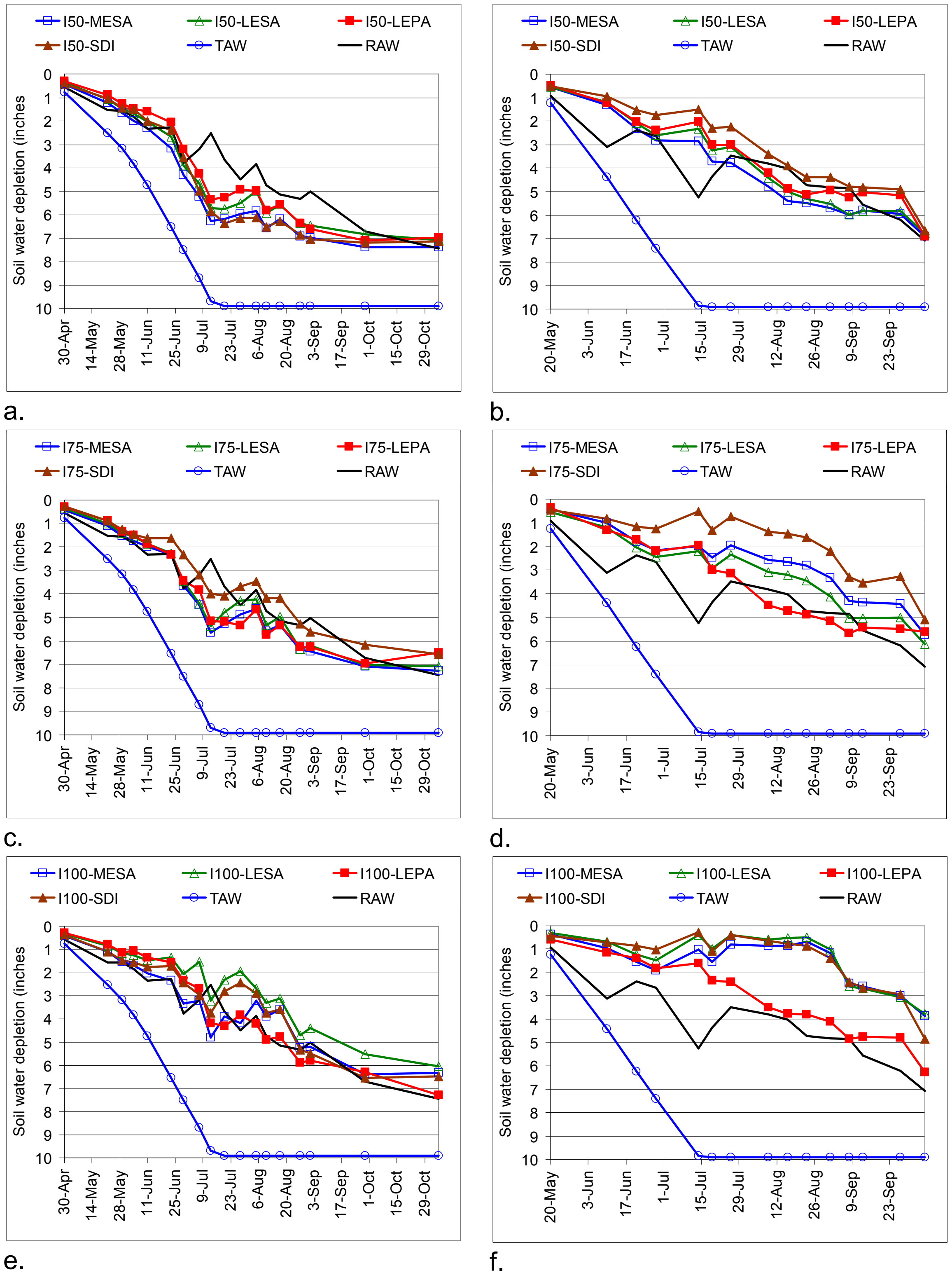

Figure 1. Soil water depletion, total available soil water (TAW), and readily available soil water (RAW) in the root zone for (a) 2009 I_{50}; (b) 2010 I_{50}; (c) 2009 I_{75}; (d) 2010 I_{75}; (e) 2009 I_{100}; (f) 2010 I_{100}.

(TAW). Assuming a maximum root depth of 6 ft, the Pullman clay loam soil at the study location has about 10.0 inches of maximum TAW, with the lower and upper limits of plant extractable water at 14.0 (~0.19 in.^{3} in.$^{-3}$) and 24.0 inches (~0.33 in.^{3} in.$^{-3}$), respectively (USDA-NRCS, 2011). RAW is generally around 50 percent of TAW for most crops including corn during the growing season. However, RAW depends on crop species and the soil water – matric potential relationship, and varies with time according to crop growth stage and atmospheric demand. RAW can be adjusted from a base value in terms of ETc, which accounts for the crop growth stage and atmospheric demand. The FAO 56 procedure recommends that RAW be increased if ETc exceeds 0.20 in. d^{-1}, and decreased if ETc is below this value. The resulting RAW was computed using a daily soil water balance based on FAO 56 procedures, and shown on days when soil water contents were measured in 2009 and 2010 (Fig. 1).

Soil water depletion and RAW were different in the two seasons evaluated (Fig. 1). In 2009, soil water depletion generally increased throughout the season. Soil water depletion in the I_{100} irrigation rate was below RAW until around silking (July 15), but then increased (Fig. 1e). At that time, high temperatures (over 100°F) and winds (40 mph gusts) resulted in ETc reaching almost 0.50 in. d^{-1} (data not shown). Consequently, the adjustment to RAW using the FAO 56 procedure resulted in RAW decreasing from almost 4.0 to 2.5 inches. Since soil water depletion was greater than RAW, the crop would have experienced water stress that likely reduced yield, especially since the water stress occurred during anthesis. Later in July, the unusually high atmospheric demand abated, and soil water depletion fell below RAW in all irrigation methods except LEPA. As expected, soil water depletion in the I_{75} (Fig. 1c) and I_{50} (Fig. 1a) irrigation rates were even greater compared with I_{100}. In 2010, soil water depletion in the I_{100} irrigation rate was well below RAW throughout the season except for LEPA (Fig. 1f). In contrast to 2009, RAW increased to over 5.0 inches around anthesis (July 10) in 2010 due to low atmospheric demand from relatively cool and wet conditions. Soil water depletion at I_{100} in 2010 (MESA, LESA, and SDI; Fig. 1f) generally varied about the 1.0-inch level until irrigations were terminated (August 26). This reflected the intended full irrigation treatment, which unfortunately was not achieved in 2009 due to irrigation system operational problems followed by high atmospheric demand coinciding with anthesis. Total rainfall plus irrigation for the I_{100} rate in 2009 and 2010 was 29.7 and 31.5 inches, respectively (Table 3, or 1.8 inches less in 2009).

The LEPA grain yield and water use efficiency depressions relative to the other methods may have resulted from runoff from the hand sample areas in the I_{75} and I_{100} rates, which were sometimes indicated by increases in LEPA soil water depletion (Fig. 1). In 2010, the LEPA soil water contents declined below the other methods from July 14 to the end of the season (Figs. 1d and 1f); as noted previously, LEPA grain yields were also significantly less than the other methods at I_{75} and I_{100} (Table 6). Greater furrow dike erosion was observed for the LEPA bubblers (used in 2010) compared with the drag socks (used in 2009). In 2009, initial soil water content for the I_{100} LEPA treatment was greater than the other methods, but this fell below the other methods (i.e., soil water depletion increased) by August (Fig. 1e). Also as noted previously, seasonal water use was significantly greater, but grain yield was significantly less than the other methods (Table 5). This may have also resulted from runoff from the hand sample and neutron access tube areas of the plots. Drag socks were sometimes caught on plants and were pulled from the applicator as the lateral move passed through, resulting in erosion of furrow dikes.

Differences in grain yield and water use efficiency were sometimes correlated to differences in soil water content. The SDI method resulted in the least soil water depletion compared with the other methods for the I_{75} rate in 2009 and the I_{50}, I_{75}, and I_{100} rates in 2010, which was not surprising since losses to evaporation should be minimized with SDI (Fig. 1). However, SDI resulted in significantly greater grain yield compared with the other methods only for I_{50} and I_{75} in 2009, and SDI grain yield was similar to MESA and/or LESA for I_{50} and I_{75} in 2010 and I_{100} in 2009 and 2010 (Tables 5 and 6). One anomalous result that could not be explained in terms of soil water content occurred in 2009 for the I_{50} rate. Here, soil water depletion was the least for LEPA during most of the season, but soil water depletion for SDI was similar to or greater than MESA and LESA (Fig. 1a). However, only SDI had appreciable grain yield (Table 5). Also, at the I_{25} rate in 2010 (Table 6), there were no significant differences in grain yield or water use efficiency among irrigation methods, and SDI resulted in numerically the least grain yield and water use efficiency compared with the other methods as kernel mass was significantly the least. The only apparent differences in soil water depletion for the I_{25} rate were observed for MESA, which was around 0.75 inches greater than the other methods by the end of the season (data not shown). This was in sharp contrast to other crops, where SDI consistently resulted in greater yield and water use efficiency compared with other methods at the I_{25} rate, as described next.

Corn response to different irrigation methods was vastly different from the responses of grain sorghum, soybean, and cotton, which were evaluated in previous experiments (Colaizzi et al., 2004; 2010). To review, there were three main aspects of grain yield differences for corn, including 1) yield being much lower than expected in 2009 for deficit irrigation rates; 2) yield depressions for LEPA relative to the other irrigation methods; and 3) yield being much greater for SDI compared with the other methods for I_{50} and I_{75} (2009 only). These differences could be explained mostly in terms of differences in soil water contents and the timing of soil water shortages (except for SDI at the I_{50} rate in 2009). Four seasons of cotton were also evaluated in a previous experiment (Colaizzi et al., 2010). At all irrigation rates, SDI consistently resulted in the largest lint yield compared with all other methods, and LEPA consistently out-yielded MESA and LESA. For three seasons of grain sorghum and one season of soybean (planted after cotton was destroyed by hail), SDI also resulted in significantly greater yield and water use efficiency compared with all other methods, but only at the I_{25} and I_{50} rates. Also at these rates, grain sorghum and soybean responses were nearly the same for MESA and LEPA, but numerically less for LESA. At the I_{75} and I_{100} rates, however, grain sorghum yield was greater for MESA and LESA compared with LEPA and SDI, which appeared to be related to over irrigation in some years. The grain sorghum, soybean, and cotton evaluations all used LEPA drag socks, and no consistent yield depressions were observed for LEPA compared with the other irrigation methods as were observed for corn. Furthermore, the yield depressions were inconsistent with previous studies of corn irrigated with LEPA at our location (Howell et al., 1995; Schneider and Howell, 1998). The consistently greater lint yield response of cotton for SDI was most likely related to reductions in evaporative cooling of the soil surface compared with the spray methods, as indicated by near-surface soil temperature measurements (Colaizzi et al., 2010). The greater grain yield for sorghum and soybean with SDI compared with the other methods at low (I_{25} and I_{50}) irrigation rates was more likely related to reductions in evaporative losses, as SDI resulted in greater soil water content that could be partitioned to plant transpiration, and these crops are not as thermally-sensitive as cotton.

Finally, although SDI did not result in consistently better corn water productivity compared with the other irrigation methods, it should be noted that small plot studies have limitations in that they cannot represent every situation inherent in large-scale operations. For example, there is anecdotal evidence from producers, extension personnel, and crop consultants that SDI results in field environments less favorable to weeds, pests, and other diseases, which may greatly reduce the costs of herbicides, pesticides, and other inputs, which are significant, especially in light of increasingly stringent environmental regulations. Therefore, although crop water productivity is a key criterion in selecting the most profitable irrigation method, numerous other factors apply. In addition, the results of this study were based on only two seasons using a single corn variety, and the first season clearly represented a worst-case scenario in terms of the sequence of irrigation, crop development, and weather events. As new seed varieties are introduced that are more drought tolerant and disease resistant, it is plausible that they will have different responses in terms of crop water productivity, which will warrant continued field studies in irrigation system comparison.

CONCLUSION

Corn grain yield and water use efficiency were not significantly different among mid-elevation spray application (MESA), low elevation spray application (LESA), and subsurface drip irrigation (SDI) for the full irrigation rate in 2009 and all irrigation rates (I_{25}, I_{50}, I_{75}, and I_{100}, where the subscript is the percentage of full irrigation) in 2010. The SDI method sometimes resulted in greater soil water content compared with MESA or LESA, but this did not always translate to differences in grain yield, apparently because in some cases the soil water contents were sufficient to avoid water stress. The SDI method resulted in significantly greater grain yield and water use efficiency compared with all other irrigation methods only for the I_{50} and I_{75} rates in 2009; however, the 2009 season was not representative of typical conditions because several events resulted in soil water shortages during anthesis, and crop yields were much lower than expected. The low energy precision application (LEPA) method resulted in reduced yield, soil water contents, and water use efficiency compared with the other methods at the I_{75} and I_{100} rates, which appeared to result from furrow dike erosion and runoff from the hand sample and soil water measurement areas of the plots. Corn response to the different irrigation methods was very different from other crops evaluated in previous experiments, which included grain sorghum, soybean, and cotton. In particular, cotton lint yield and water use efficiency were significantly greater for all irrigation rates for SDI compared with all other methods, and LEPA also resulted in consistently better response compared with MESA or LESA.

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