CROP PRODUCTION COMPARISON UNDER VARIOUS IRRIGATION SYSTEMS[1]

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SUMMARY

Studies on crop productivity for major irrigated crops in the Great Plains were reviewed for different types of modern pressurized irrigation systems. Crops included corn, cotton, grain sorghum, winter wheat, and preliminary data on soybean and sunflower. Irrigation systems consisted of spray and LEPA devices commonly found on center pivots, and drip irrigation (usually SDI). Spray, LEPA, and SDI were compared at Halfway and Bushland, TX, and simulated LEPA and SDI were compared at Colby, KS. Nearly all studies involved varying the irrigation capacity (fixed application per unit time) or irrigation rate (percentage of soil water replenishment). Yield response in terms of irrigation method could usually be described as SDI ≥ LEPA ≥ SPRAY for low irrigation capacities (or rates), and SPRAY ≥ LEPA ≥ SDI for full (or nearly full) capacities or rates. In some cases, yield response was more consistent across irrigation rates. Although additional data are lacking that would explain these differences, it appears that LEPA, and to a greater extent SDI, result in greater partitioning of

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water to plant transpiration relative to spray for low irrigation rates. At greater irrigation rates, the yield depressions observed for SDI and/or LEPA relative to spray were less clear, although these may be the result of poor aeration and nutrient leaching by deep percolation.

INTRODUCTION

The U.S. Great Plains produces a major portion of the nation's corn, wheat, sorghum, soybeans, sunflower, and in the southern and central portions, cotton. High yields are possible with irrigation, and roughly 8 Mha (out of 20 Mha in the U.S.) are presently irrigated in an eight state area that includes South Dakota, Nebraska, southeastern Wyoming, eastern Colorado, Kansas, the Oklahoma Panhandle, northwestern Texas, and eastern New Mexico (Howell, 2001; Lamm and Brown, 2004). The region is mostly semiarid, with extremely variable precipitation (both temporally and spatially), high evaporative demand due to high solar radiation, high vapor pressure deficit, and periods of high regional advection, especially in the southern portion (Howell et al., 1997b). The primary water resource for this eight state area is the Ogallala Aquifer, one of the largest freshwater aquifers in the world. The Ogallala has been declining in most areas because withdrawals have exceeded recharge after intensive irrigation began in the late 1930s, when internal-combustion engines and rural electrification first became widely available for pumping. However, the rate of decline has abated in some areas such as the High Plains of Texas (Musick et al., 1990) due to either reductions in irrigated area, conversion to more efficient irrigation systems, or both.

The earliest irrigation systems in the Great Plains were generally graded furrow, and these were most suitable for land with small slopes (<1%). Musick et al. (1988) mentions improvements in sprinkler systems after World War II allowed expansion of irrigation to land otherwise unsuitable for furrow systems. This was followed by center pivots in the 1960s and 1970s. Earlier center pivot sprinkler configurations were high-pressure impact, but these were replaced by low-pressure spray and low-pressure precision applicators (LEPA) since the 1980s (Lyle and Bordovsky, 1983). Spray heads are commonly positioned above the crop (variously termed overhead spray or mid-elevation spray applicator – MESA) or within the crop canopy (in-canopy spray or low-elevation spray applicator – LESA). In the mid-1980s, surface and subsurface drip irrigation (SDI) became adopted by cotton producers in the Trans Pecos region of Texas (Henggeler, 1995), and SDI has been used successfully for corn production in Kansas (Lamm et al., 1995; Lamm and Trooien, 2003).

Center pivots with modern sprinkler packages (e.g., MESA, LESA, or LEPA) can be highly efficient in terms of uniformity and application efficiency (Schneider, 2000), as can SDI (Camp, 1998), and numerous studies have documented high crop productivity using either type of system. With declining water resources and escalating energy costs, total irrigated area in the Great Plains will likely decrease; however, remaining irrigated land will likely see greater adoption of efficient irrigation technology and techniques, including deficit irrigation, irrigated-dryland rotations (Stewart et al., 1983; Unger and Wiese, 1979), and careful irrigation scheduling (Howell et al., 1998a). Studies in Texas, Kansas, and elsewhere indicate that relative performance of different irrigation systems in terms of crop productivity often changes with irrigation rate (i.e., level of deficit irrigation) and climate, among other factors, which should be considered in selecting an irrigation system.

The objectives of this paper are to review studies of crop productivity under various irrigation systems, with an emphasis on how crop productivity is affected by types of systems across a range of irrigation rates. The scope will be limited to major crops irrigated in the Great Plains, including corn, cotton, grain sorghum, winter wheat, and some preliminary data on soybean and sunflower (we plan to expand this paper to include other crops such as peanuts, fresh market vegetables, and additional data on soybean and sunflower as they become available). Data presented will be limited to pressurized irrigation systems (i.e., sprinkler, LEPA, and drip) from studies conducted at the USDA-Agricultural Research Service in Bushland, TX, the Texas Agricultural Experiment Station in Halfway, TX, and the Kansas State University Northwest Research-Extension Center in Colby, KS. Soils at these locations are generally deep, well drained, and loam to clay loam in texture. Consequently, results presented herein may not be applicable to locations having coarser or finer soils, or for shallow-rooted crops. Some additional references are given for studies conducted outside the Great Plains, and a few involve comparisons with furrow irrigation. This review is by no means comprehensive and does not contain rigorous statistical analyses, but is intended to highlight major findings that appear common to different crops at the three locations.

SOME EFFICIENCY AND ECONOMIC ASPECTS OF SPRAY, LEPA, AND SDI

Schneider (2000) reviewed published research of application efficiencies and uniformity coefficients for spray and LEPA systems. Reported application efficiencies for spray methods generally exceeded 90% and were from 95% to 98% for the LEPA methods. Reported uniformity coefficients in the direction of travel ranged from 0.75 to 0.90 for spray and from 0.75 to 0.85 for LEPA; along the mainline (perpendicular to travel) these were from 0.75 to 0.85 for spray and from 0.94 to 0.97 for LEPA. The review noted that measured application efficiencies for spray were sensitive to the device used, and because of the start and stop movement of most irrigation systems, measured uniformities of LEPA were sensitive to the length of basin checks, irrigation system span alignment, and distance from the tower where system speed was controlled. Water is usually applied to alternating interrows with LEPA; thus, the high reported LEPA uniformities along the mainline are the result of measuring water only where it is actually applied, disregarding the rows and nonirrigated interrows. The review also discussed potential water loss pathways and concluded that runoff is generally the greatest potential loss for both LEPA and spray; hence, some form of runoff control such as basin tillage (furrow dikes) or reservoir tillage is required to achieve these high efficiencies and uniformities.

Schneider and Howell (2000) measured surface runoff from a slowly permeable Pullman clay loam soil with a 0.25% slope over two seasons of irrigated grain sorghum production. Treatments consisted of the spray and LEPA methods with and without basin tillage (furrow dikes) for five levels of soil water replenishment, or irrigation rate IR (0%, 40%, 60%, 80%, and 100%). They observed no runoff for the spray method using furrow dikes for all IR, and no runoff for any sprinkler-tillage method combination for the 40% IR. Grain yields and water use efficiencies were significantly reduced with increasing runoff. For 100% IR, runoff losses averaged 12% for spray without dikes, 22% for LEPA with dikes, and 52% for LEPA without dikes. They noted that as the seasons progressed, the furrow dikes eroded, decreasing soil water storage capacity on the soil surface and increasing the potential for runoff. Howell et al. (2002) reported that furrow dikes improved corn yield for both full and limited spray irrigation compared to flat and bed tillage (no dikes), but did not observe runoff due to dike erosion. Schneider (2000) discussed other potentially large water loss pathways, including deep percolation, wind drift, and surface evaporation (Tolk et al., 1995) and emphasized that both LEPA and spray can be highly efficient, provided that these pathways are carefully evaluated in order to select the most appropriate sprinkler package.

Water loss pathways described for spray and LEPA can potentially be eliminated with SDI through proper design, maintenance, and management, which is likely to also conserve expensive fertilizer and chemicals commonly injected into irrigation water (Lamm and Trooien, 2003). We further postulate that furrow dikes may be more effective for rainfall capture for SDI than LEPA or spray because of reduced erosion (Jones and Clark, 1987). Camp (1998) reviewed published research on SDI and noted that crop yields were equal to or exceeded those of other irrigation systems, and water use was significantly less. However, adoption of SDI in the Great Plains remains low relative to center pivots primarily because of capital costs but also due to greater maintenance and management requirements, among other factors. If preplant rainfall is sparse and unreliable, crop germination can be difficult with SDI (Howell et al., 1997a; Enciso et al., 2005).

O'Brien et al. (1998) showed that SDI can be more economical than center pivots for decreased field sizes (~20 ha or less), provided system life was at least 10 years (preferably 15-20 years) for continuous corn production. SDI is particularly suited to small and oddly-shaped fields; furthermore, center pivots quickly lose their cost advantage where they cannot make a complete circle. On the other hand, Segarra et al. (1999) reported that SDI was not always competitive with LEPA for continuous cotton, despite SDI having greater lint yields. But they noted that economic outcomes were also sensitive to system life, as well as installation costs, pumping lift requirements, and hail damage to crops. Enciso et al. (2005) reported that net returns of SDI in a cotton production system were sensitive to lateral spacing (alternate interrows vs. every row), lateral installation depth, and crop germination, where lateral spacing (i.e., amount of drip tape required) was a tradeoff between capital cost and risks assumed in crop germination.

These varying results illustrate the difficulty in making general guidelines for SDI (a conclusion also reached by Camp, 1998), and suitability of SDI should, at minimum, be assessed on a crop-, site-, and producer-specific basis. The following sections review productivity for different pressurized irrigation systems according to crop, and selected publications are summarized for corn, cotton, grain sorghum, and winter wheat in Tables 1, 2, 3, and 4, respectively.

CORN, SOYBEAN, AND SUNFLOWER

Subsurface drip irrigation (SDI) research has been conducted at the Kansas State University Northwest Research-Extension Center in Colby, KS since 1989 on a deep, medium textured, well-drained Keith silt loam soil (Lamm and Trooien, 2003). Lamm (2004) compared seven years (1998-2004) of corn productivity at this location for SDI and simulated LEPA, where the effects of LEPA were mimicked by delivering precise amounts of water to furrow diked basins through pressure regulated flow dividers and flexible supply tubes. Irrigation capacity for simulated LEPA was varied by applying 25 mm (1 in) of water at 4, 6, and 8 day intervals. Irrigation was applied daily with SDI at 2.5, 3.3, 4.3, and 6.4 mm per day (0.10, 0.13, 0.17, and 0.25 in per day; see Table 5 for SI to English unit conversions). This resulted in a range of seasonal irrigations applied relative to meeting the full irrigation requirement. Grain yield vs. seasonal irrigation were grouped for years having average or greater rainfall (1998, 1999, 2004; Fig. 1a) or significant drought (2000-2003; Fig. 1b) for simulated LEPA and SDI, where yield and seasonal irrigations were averaged for each group of years. For average to wet years, grain yield with SDI was slightly greater than simulated LEPA, but *vice versa* for drought years. In average to wet years, differences in grain yields were primarily due to kernel weight, but in drought years, this was due to the number of kernels per ear (see Lamm, 2004 for actual yield component data).

Soybean and sunflower production were also compared between simulated LEPA and SDI at Colby, KS (Figs 2 and 3, respectively). Irrigation rates (IR) were varied according to 60%, 80%, and 100% of meeting the full irrigation requirement (i.e., in Fig. 2, 178, 305, and 356 mm average seasonal irrigation totals, respectively). For both crops, relative yields between simulated LEPA and SDI again varied by IR, with SDI resulting in greater production at the lower IR, but less production at the higher IR. Although only a single season is represented for each crop, it is interesting that production patterns were somewhat similar to corn in that 2005 received less rainfall than 2004. We presently do not have data

Table 1: Selected studies of crop productivity with pressurized irrigation systems for corn.

Irrigation Methods	Additional factors	Location	Reference
Impact sprinklers	Irrigation rate	Bushland, TX	Howell et al. (1989)
LEPA sock	Irrigation rate	Bushland, TX	Howell et al. (1995a)
MESA	Short and full season hybrids, crop ET	Bushland, TX	Howell et al. (1998b)
MESA	Irrigation rate, tillage (furrow dikes, clean raised beds, flat planting)	Bushland, TX	Howell et al. (2002)
MESA, LESA, LEPA bubble, LEPA sock	Irrigation rate	Bushland, TX	Schneider and Howell (1998)
SDI	Review article	Colby, KS	Lamm and Trooien (2003)
SDI	lateral spacing, lateral depth	Colby, KS	Lamm et al. (1997)
SDI	Irrigation rate, irrigation frequency, lateral depth	Colby, KS	Lamm et al. (1995)
Simulated LEPA, SDI	Irrigation capacity	Colby, KS	Lamm (2004)
Surface drip, SDI	Irrigation rate, irrigation frequency	Bushland, TX	Howell et al. (1997a)

Table 2: Selected studies of crop productivity with pressurized irrigation systems for cotton.

Irrigation Methods	Additional factors	Location	Reference
Furrow, level basin, sprinkler, surface drip, SDI	Review article, crop ET, water use efficiency, water value	AZ and CA, also references worldwide	Grismer (2002)
Furrow, solid set sprinklers, surface drip	Irrigation rate	Sanliurfa, Turkey	Cetin and Bilgel (2002)
Furrow, surface drip	Irrigation rate, irrigation frequency	Five Points, CA	Howell et al. (1987)
LEPA sock	Irrigation capacity, irrigation frequency	Halfway, TX	Bordovsky et al. (1992)
LEPA sock, SDI	Irrigation capacity, irrigation frequency (LEPA only)	Halfway, TX	Segarra et al. (1999)
LESA, LEPA sock, SDI	Irrigation capacity, preplant irrigation rate	Halfway, TX	Bordovsky and Porter (2003)
MESA	Irrigation rate, crop ET	Bushland, TX	Howell et al. (2004)
MESA, LESA, LEPA sock, SDI	Irrigation rate	Bushland, TX	Colaizzi et al. (2005)
SDI	Irrigation frequency	St. Lawrence, TX	Enciso et al. (2003)
SDI	Preplant irrigation, lateral spacing, lateral depth	St. Lawrence, TX	Enciso et al. (2005)
Surface drip	Irrigation timing by canopy temperature, irrigation rate, irrigation frequency, initialization of irrigation season, plant dates	Lubbock, TX	Wanjura et al. (2002)
Surface drip, LEPA sock	Irrigation rate, irrigation frequency	Koruklu, Turkey	Yazar et al. (2002)

Table 3: Selected studies of crop productivity with pressurized irrigation systems for grain sorghum.

Irrigation Methods	Additional factors	Location	Reference
LEPA sock	Irrigation rate, irrigation frequency	Halfway, TX	Bordovsky and Lyle (1996)
MESA, LEPA sock	Irrigation rate, tillage (furrow dikes, clean raised beds)	Bushland, TX	Schneider and Howell (2000)
MESA, LESA, LEPA bubble, LEPA sock	Irrigation rate	Bushland, TX	Schneider and Howell (1995)
MESA, LESA, LEPA sock, SDI	Irrigation rate	Bushland, TX	Colaizzi et al. (2004)

Table 4: Selected studies of crop productivity with pressurized irrigation systems for winter wheat.

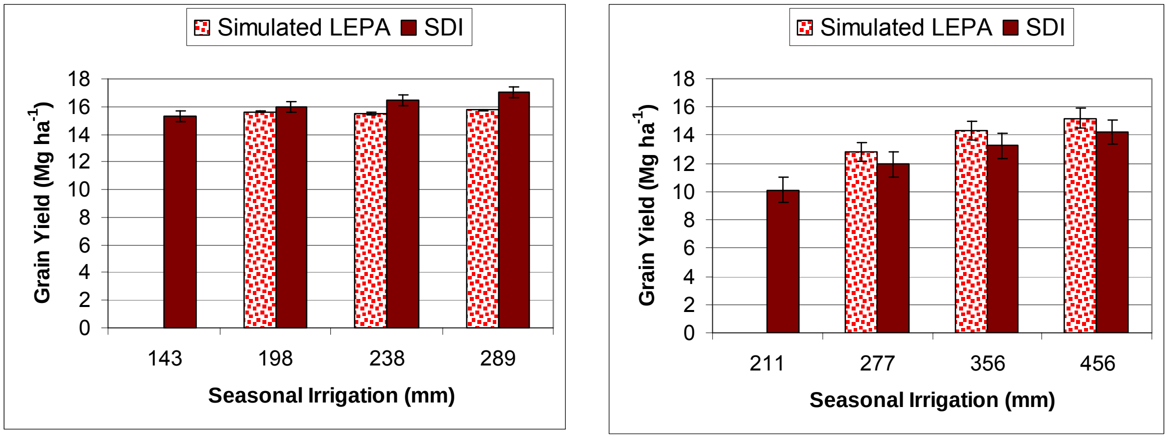
Irrigation Methods	Additional factors	Location	Reference
MESA, impact sprinklers (end of season 1 year only)	Crop ET	Bushland, TX	Howell et al. (1995b)
MESA, LEPA bubble, LEPA sock	Irrigation rate, irrigation timing, irrigation termination	Bushland, TX	Schneider and Howell (1997)
MESA, LESA, LEPA bubble, LEPA sock	Irrigation rate	Bushland, TX	Schneider and Howell (2001)

Table 5: Unit conversions. Conversions from weight (lbs) to volume (bu) based on dry and standard moisture contents for selected crops taken from Hirning et al. (1987).

	dry weight		standard weight		
Crop	**lb bu^{-1}**	**bu ac^{-1} per Mg ha^{-1}**	**percent moisture**	**lb bu^{-1}**	**bu ac^{-1} per Mg ha^{-1}**
corn	47.32	18.8	15.50	56.00	15.9
grain sorghum	47.00	19.0	14.00	55.00	16.2
soybean	52.20	17.1	13.00	60.00	14.8
sunflower	90.00	9.9	10.00	100.00	8.9
wheat	51.90	17.2	13.50	60.00	14.8

1 mm = 0.03937 in
1 ha = 2.47 ac
1 kg = 2.2 lb
1 kg ha^{-1} = 0.8907 lb ac^{-1}
1 Mg ha^{-1} = 890.7 lb ac^{-1}

that would explain these production differences, but tentatively offer several hypotheses. When water supply is limited, SDI likely results in greater partitioning of water to transpiration and less to soil evaporation, which would result in slightly less water stress. At greater IR, the greater concentration of SDI-delivered water and nutrients in the root zone may result in poor aeration or nutrient leaching, which may limit yields (Lamm et al., 1995; Colaizzi et al., 2004). Payero et al. (2005) investigated the deficit irrigation for soybeans using surface drip at Curtis, NE (2002), and solid set sprinklers at North Platte, NE (2003 and 2004). They used a greater range of IR than at Colby, but relative performance drip and sprinkler could not be compared because these were at different locations and different years.



a) b)

Figure 1: Corn yield and seasonal irrigation averages for simulated LEPA and SDI for a) three average to wet years (1998, 1999, 2004); and b) four dry years (2000, 2001, 2002, 2003) at Colby, KS (Lamm, 2004).

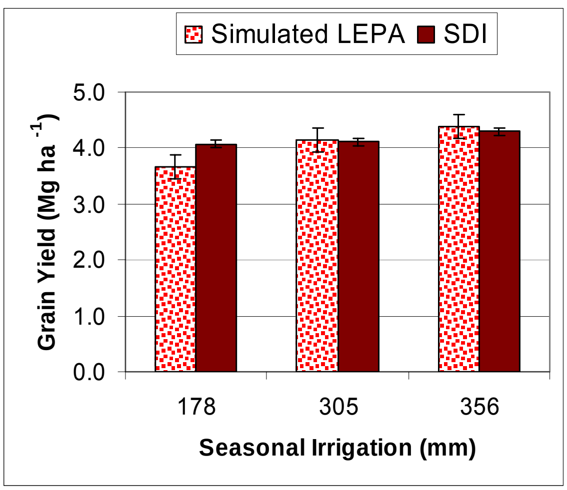


Figure 2: Soybean yield and seasonal irrigation (2005) at Colby, KS (F. R. Lamm, preliminary data).

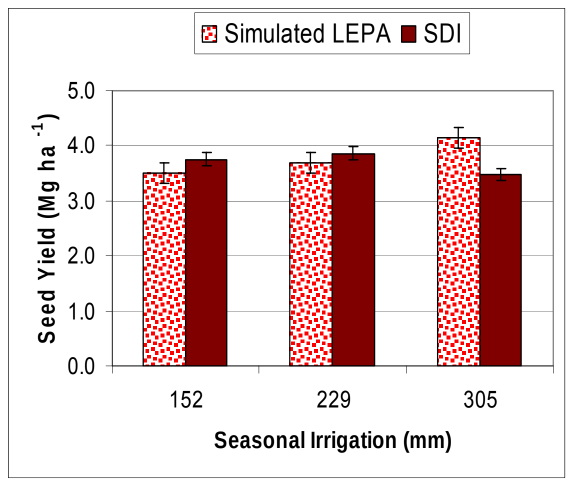


Figure 3: Sunflower yield and seasonal irrigation (2004) at Colby, KS (F. R. Lamm, preliminary data).

Corn yields for various irrigation systems across a range of IR were also investigated by the USDA-Agricultural Research Service at Bushland, TX. The Bushland location contains a slowly permeable Pullman clay loam (fine, mixed, superactive, thermic torrertic Paleustoll), with a dense B21t later 0.15- to 0.40-m below the surface, and a calcic horizon beginning about 1.2 m below the surface. Schneider and Howell (1998) compared MESA, LESA, LEPA Bubble, and LEPA sock (Fig. 4), and Howell et al. (1997) compared surface drip and SDI at daily and weekly intervals (Fig. 5). In both studies, seasonal irrigation totals were the result of variable IR (0%, 25%, 50%, 75%, and 100% in Fig. 4; 0%, 33%, 66%, and 100% in Fig. 5). The 0% IR represents actual, or in some years nearly

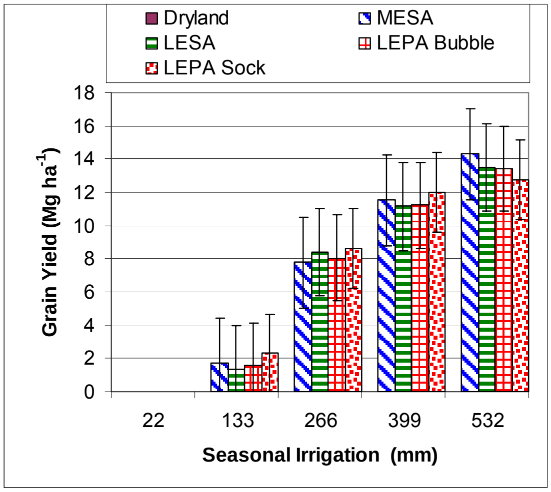


Figure 4: Corn yield and seasonal irrigation averages (1994, 1995) at Bushland, TX (Schneider and Howell, 1998).

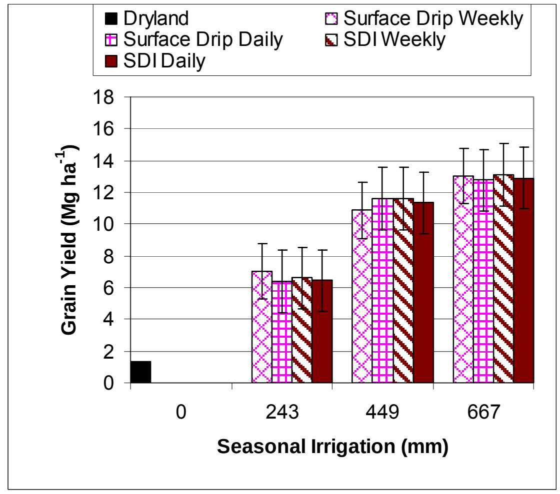


Figure 5: Corn yield and seasonal irrigation averages (1993, 1994) at Bushland, TX (Howell et al., 1997).

actual, dryland conditions, as uniform spray irrigations were sometimes given to all experimental plots to ensure adequate germination. Corn yields were much more sensitive to IR than the irrigation method. In Fig. 4, zero corn yields resulted for 0% IR (22 mm average seasonal irrigation). Slight differences in grain yields resulted between spray and LEPA configurations, with the LEPA sock having a small advantage over all other methods under deficit irrigation (< 100% IR), whereas MESA resulted in the greatest corn yields at full irrigation (532 mm). In Fig. 5, grain yield was insensitive to drip irrigation frequency (weekly or daily) and lateral installation (at or below the surface), probably because these factors were buffered by the relatively large soil water holding capacity and rooting depth. Although yield per irrigation applied appeared to be less with drip than with spray or LEPA (from a side-by-side comparison of Fig. 4 and 5), it should be noted that these represent averages of different years and were conducted on different experimental plots, and identical yield response to water should not be expected for different years or locations (Howell et al., 1995a).

WINTER WHEAT

Irrigated winter wheat production was documented in two studies with various configurations of spray and LEPA at Bushland, TX (Schneider and Howell, 1997; 2001; see also Schneider and Howell, 1999 for a summary of winter wheat, grain sorghum, and corn). Grain yields were less responsive to IR than corn as winter wheat has much greater drought tolerance. Grain yield response to irrigation method were numerical only (statistically insignificant), but these are nonetheless discussed. Grain yield trends in the first study (Fig. 6) were similar to those for corn (Fig. 4), where LEPA sock had a slight advantage at 33% IR (168 mm average), and MESA had a slight advantage at the 67% and 100% IR (289 and

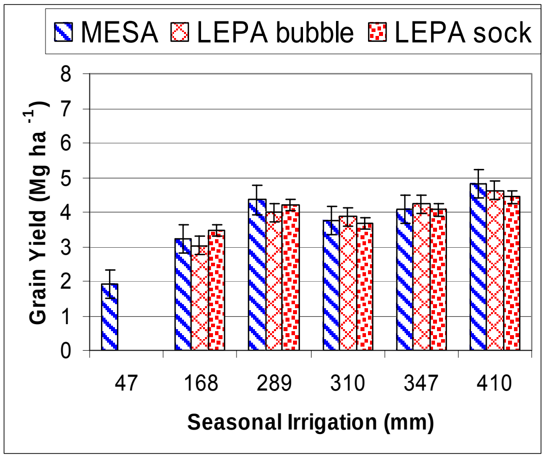


Figure 6: Winter wheat yield and seasonal irrigation averages (1994, 1995) at Bushland, TX (Schneider and Howell, 1997).

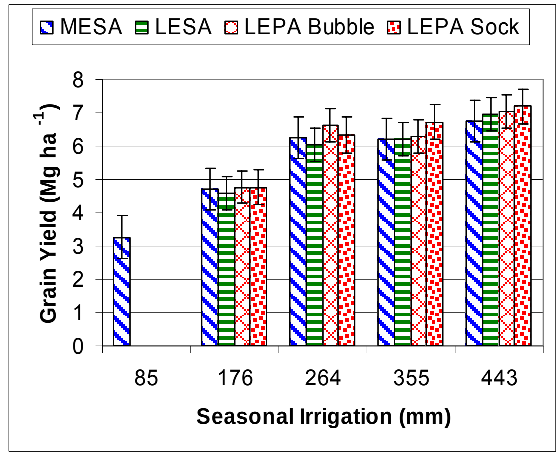


Figure 7: Winter wheat yield and seasonal irrigation averages (1998, 1999) at Bushland, TX (Schneider and Howell, 2001).

410 mm seasonal irrigation averages, respectively). The 310 and 347 mm seasonal irrigation averages also represent 100% IR, except initial irrigations were delayed until early boot (310 mm), or irrigations were terminated at early grain filling (347 mm), and the LEPA bubble had a slight advantage with these treatments. In the second study (Fig. 7), the LEPA methods resulted in equal or slightly greater wheat yield than spray (MESA or LESA); with the LEPA sock resulting in the greatest yield at 75% and 100% IR (355 mm and 443 mm, respectively). The slight yield advantages of MESA and LEPA noted in each study could not be correlated to differences in rainfall patterns (data not shown), as was the case for the simulated LEPA-SDI study for corn at Colby, KS (Fig. 1). Schneider and Howell (2001) concluded that reducing irrigation rates to 50% of the full requirement only resulted in 5- to 14% yield reductions for spray or LEPA methods, with yields exceeding 6.0 Mg ha^{-1}. Direct comparisons of wheat production between spray/LEPA and SDI have not been published to our knowledge, but winter wheat has been produced successfully with SDI on a commercial farm in Coolidge, AZ, with grain yield exceeding 6.0 Mg ha^{-1} with approximately 300 mm of water.

GRAIN SORGHUM

Grain sorghum is commonly rotated with cotton (Bordovsky and Lyle, 1996) or winter wheat (Stewart et al., 1983), and has a considerably less water requirement than corn. Bordovsky and Lyle (1996) investigated the effect of irrigation interval (3.5, 7.0, 10.5, and 14 days) on grain sorghum with LEPA equipped with double-ended drag socks and using furrow dikes. The study was conducted on an Olton loam soil (fine, mixed, thermic Aridic Paleustolls) in Halfway, TX, with 40%, 70%, 100%, and 130% IR. The 3.5-day interval resulted in greater grain sorghum yields than longer intervals for all irrigation rates (Fig. 8), but this was significant only when grain yield was averaged for all rates and years. Yields were not significantly different for 70% IR (251 mm average seasonal irrigation) and above.

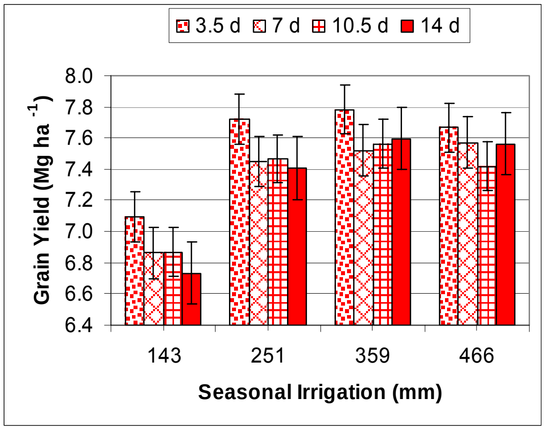


Figure 8: Grain sorghum yield and seasonal irrigation averages (1992, 1993, 1994) for LEPA at Halfway, TX (Bordovsky and Lyle, 1996).

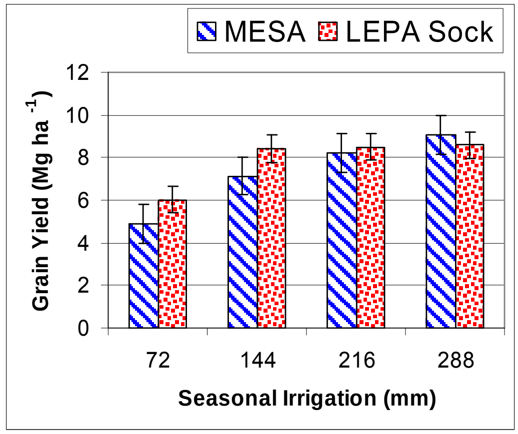


Figure 9: Grain sorghum yield and seasonal irrigation averages (1992, 1993) at Bushland, TX (Schneider and Howell, 1995).

Schneider and Howell (1995) evaluated grain sorghum response to MESA and LEPA sock for 25%, 50%, 75%, and 100% IR in Bushland, TX (Fig. 9). Average grain yields were greater with LEPA than MESA for 25% and 50% IR (72 and 144 mm in Fig. 9); however, MESA outperformed LEPA at 100% IR (288 mm in Fig. 9). The authors postulated that LEPA resulted in greater partitioning of water to transpiration at low irrigation rates. This trend was similar to that observed for soybean and sunflower in Colby, KS (Figs. 2 and 3, respectively) for simulated LEPA and SDI.

Colaizzi et al. (2004) also reported results of grain sorghum at Bushland, TX, where the study of Schneider and Howell (1995) was modified to include SDI in place of the LEPA bubbler. Grain yields with SDI were significantly greater than MESA, LESA, or LEPA at 25% and 50% IR, but this trend was reversed for 75% and 100% IR (Fig. 10; respective average seasonal irrigations of 79, 177, 275, 373, and 471 mm). In two out of three years, grain yields were significantly less with SDI and LEPA compared to MESA (data not shown). Deep percolation was evident for the fully irrigated SDI (and sometimes LEPA) plots, based on successive measurements of the volumetric soil water profile by neutron scattering. This could conceivably result in nutrient leaching and poor aeration. In a study with corn under SDI in Colby, KS (1989, 1990, 1991) Lamm et al. (1995) reported yield depressions in two out of three years (1989 and 1990) for 125% IR and attributed this to poor aeration or leaching of nutrients. Darusman et al. (1997) deduced deep percolation from tensiometer measurements for the 1990 and 1991 seasons of that study and reported greater soil water flux below the root zone for 100% and 125% IR. In Fig. 10, enhanced yields with spray at 75% and 100% IR could also be linked to greater partitioning of water to evaporation from droplets intercepted by the crop canopy. Larger humidity values within the

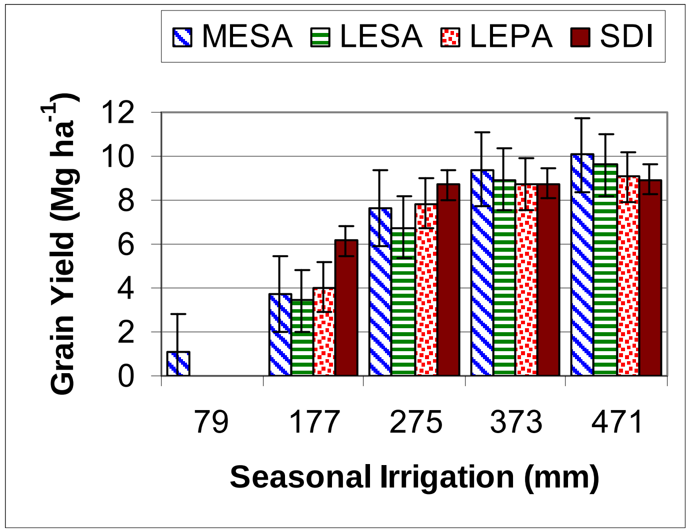


Figure 10: Grain sorghum yield and seasonal irrigation averages (2000, 2001, 2002) at Bushland, TX (Colaizzi et al., 2004).

canopy following spray irrigation would minimize stomatal closure under the heat and strong winds common in the region and enhance plant respiration while suppressing transpiration. Tolk et al. (1995) observed significant transpiration reduction of corn for several hours following daytime irrigation by overhead impact sprinklers, but very little transpiration reduction following irrigation by LEPA.

COTTON

Cotton has traditionally been produced at the southern portion of the Great Plains in an area centered at Lubbock, TX. In recent years, cotton production has expanded northward into Kansas as an alternative to corn because it has similar revenue potential for about half the water requirement (Howell et al., 2004). However, cotton production in thermally-limited climates pose some risk as both lint quantity and quality are correlated to accumulated heat units (Wanjura et al., 2002). Crop water productivity (marketable yield per unit water consumed) tends to increase with vapor pressure deficit, and irrigated cotton is particularly suited to arid and semiarid environments (Grismer, 2002; Zwart and Bastiaanssen, 2004).

Cotton may have been the first row crop to be drip-irrigated in Texas (Henggeller, 1995), and presently, it probably accounts for most of the SDI-irrigated land area in the Great Plains, simply based on casual observations and the number of published studies. Some cotton producers perceive SDI to result in enhanced seedling emergence and earlier crop maturity due to the absence of evaporative cooling associated with LEPA and to a greater extent spray irrigation. This is a critical consideration in thermally-limited climates, and may trigger greater adoption of SDI as cotton production migrates northward. There is presently, however, little direct evidence in support of this view, as next to air temperature, soil water depletion in the root zone appears most responsible for inducing earliness (Mateos et al., 1991; Orgaz et al., 1992). In fact, the reduced evaporative cooling thought to be associated with SDI could also be countered by the greater cooling effect of increased irrigation frequency (Wanjura et al., 1996). In consideration of these confounding factors, detailed studies of near-surface soil water and temperature for spray, LEPA, and SDI are currently underway at Bushland, TX. There have been many interesting observations of cotton under spray, LEPA, and SDI, and some studies conducted at Halfway and Bushland, TX are summarized next.

Segarra et al. (1999) analyzed four years of continuous cotton at Halfway, TX under LEPA and SDI (Fig. 11). Irrigation capacities were 2.5, 5.1, and 7.6 mm d^{-1}, which were typical of well capacities in the region; seasonal irrigation amounts were not given. LEPA irrigation frequencies were varied at 1, 2, and 3 days, but SDI frequency was daily. For all irrigation capacities, average lint yields were greater with SDI than LEPA, and these differences increased as irrigation capacity decreased. Average lint yields did not show a consistent response to LEPA irrigation frequency. Bordovsky and Porter (2003) investigated the influence of preplant irrigation amount and irrigation capacity for spray, LEPA, and SDI at the same location (Fig. 12). Both factors resulted in different seasonal irrigation amounts, but lint yield was consistently greatest with SDI, and LEPA was consistently greater than spray. For both irrigation capacities, full preplant irrigation resulted in greater lint yield than limited preplant irrigation (despite

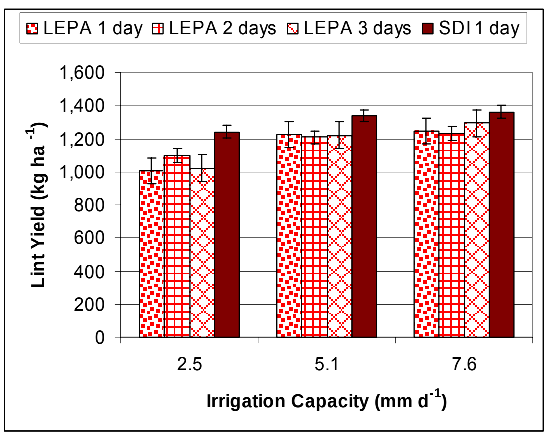


Figure 11: Cotton lint yield averages (1995, 1996, 1997, 1998) and irrigation capacities and frequencies (i.e., 1-3 days) at Halfway, TX. Seasonal irrigation amounts were not given (Segarra et al., 1999).

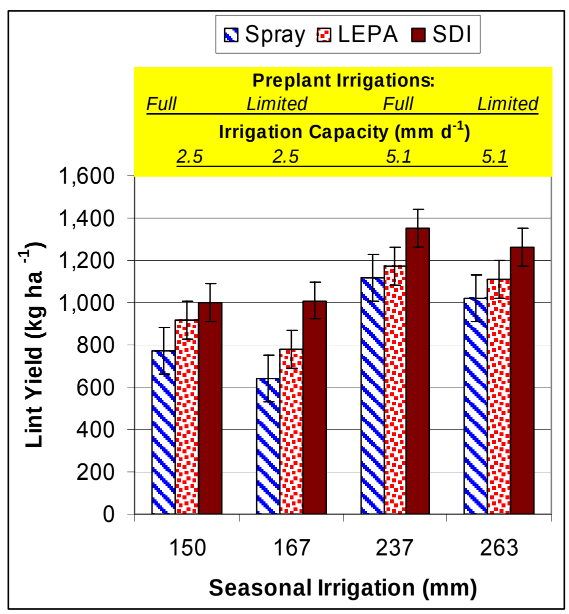
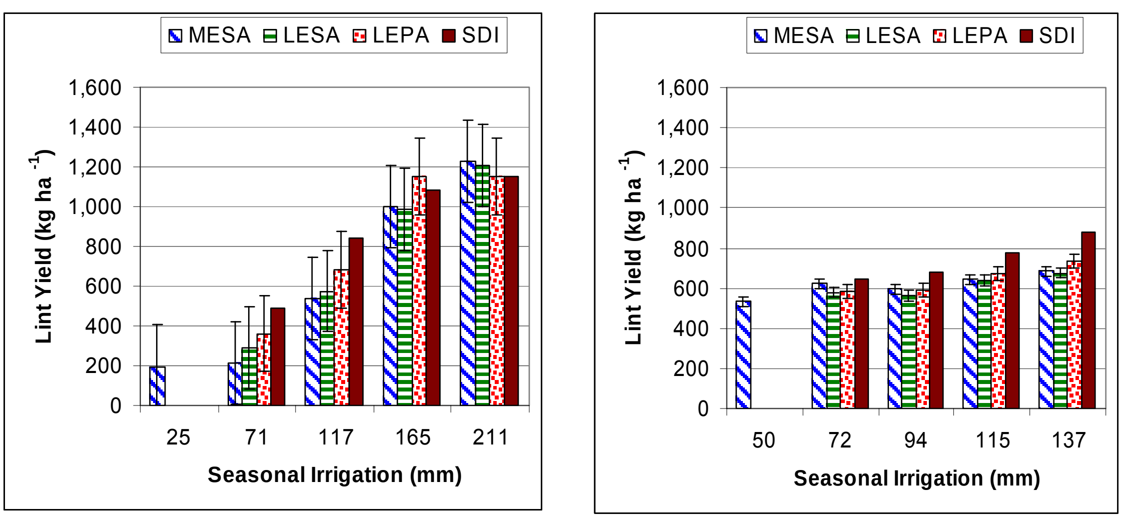


Figure 12: Cotton lint yield and seasonal irrigation averages (1999, 2000, 2001) at Halfway, TX. Additional factors were preplant irrigation amounts (full and limited) and irrigation capacities (2.5 and 5.1 mm d^{-1}) (Bordovsky and Porter, 2003).

greater seasonal irrigation being applied), implying early season water deficits likely occurred.

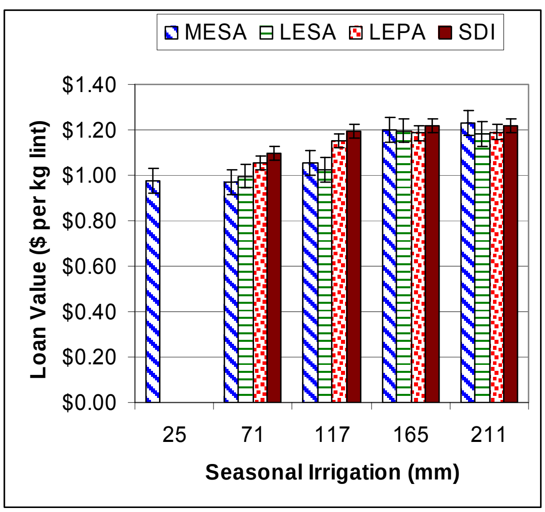
The Halfway, TX climate has sufficient heat units to produce cotton reliably; however, limited heat units in Bushland, TX make cotton production less reliable. Colaizzi et al. (2005) present the results of two contrasting cotton seasons in Bushland, where 2003 was hot and dry, whereas 2004 was relatively cool and wet. The experimental design was identical to the grain sorghum study (Colaizzi et al., 2004), where MESA, LESA, LEPA, and SDI were compared at 0%, 25%, 50%, 75%, and 100% IR. In 2003 (Fig. 13a), lint yield for SDI was significantly greater at 25% and 50% IR (71 and 117 mm seasonal irrigation, respectively) than all other methods, and LEPA was significantly greater than MESA or LESA. At 75% IR (165 mm seasonal irrigation), LEPA and SDI were greater than MESA and LESA, with lint yield under LEPA the greatest. At 100% IR (211 mm seasonal irrigation), MESA and LESA were slightly greater than LEPA and SDI, which were nearly equal. This result contradicts those of Burke (2003), who postulated that sprinklers induced pollen bursting, flower loss, and subsequent yield reductions. He reported greater lint yield under LEPA than spray, especially when irrigations occurred later in the afternoon; however, IR could not be determined from irrigation information given. Lint yield trends observed at Bushland in 2003 were very similar to those discussed previously for soybeans, sunflower, and grain sorghum. In 2004 (Fig. 13b), lint yield with SDI was significantly greater than all other methods except at 25% IR (72 mm seasonal irrigation). The patterns between wet and dry seasons were similar to those observed for corn in Colby, KS (Fig. 1; Lamm, 2004); however, lint yield was more responsive to IR in 2003 than in 2004.



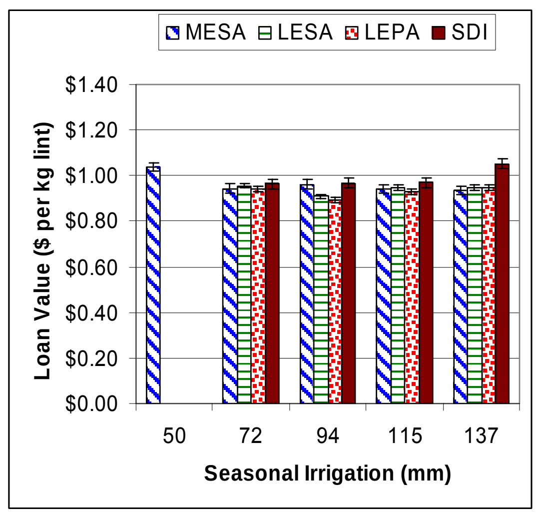
a) 2003
b) 2004

Figure 13: Cotton lint yield and seasonal irrigation for a) 2003, a relatively hot and dry year; and b) 2004, a relatively cool and wet year at Bushland, TX (Colaizzi et al., 2005).

The fiber quality of lint is becoming increasingly important in the world market; for example, many textiles are adopting high-spin technologies that require longer and stronger fibers (e.g., Yu et al., 2001). Fiber quality is comprised of several parameters (length, strength, uniformity, color, micronaire, etc.). Cotton producers will receive a premium or discount relative to a base price for overall fiber quality, and the final price is termed the *loan value* (units of $ per kg lint). Loan values in 2003 (Fig. 14a) were greater for SDI at 25% and 50% IR (71 and 117 mm seasonal irrigation, respectively) than all other methods, and LEPA was greater than the spray methods. Loan values were nearly equal at 75% IR (165 mm seasonal irrigation), but MESA was significantly greater than all other methods at 100% IR (211 mm seasonal irrigation). The poor growing conditions in 2004 resulted in poorer fiber quality, as reflected by the generally lower loan values (Fig. 14b). Loan values were greatest for SDI at 100% IR (137 mm seasonal irrigation), followed by 0% IR (simulated dryland treatment with 50 mm seasonal irrigation). Overall fiber quality trends (Fig. 14) were somewhat similar to those for lint yield (Fig. 13), where fiber quality appeared responsive to IR up to 75% in 2003 but were relatively insensitive to IR in 2004. Cotton maturity did not appear responsive to irrigation method; maturity was most correlated to IR as soil water depletion progressed through increasing IR at the end of the season. However, SDI did enhance lint yield at low IR in the dry year and regardless of IR in the wet year. In many cases SDI was correlated to higher fiber quality, as reflected by slightly greater loan values relative to LEPA or spray.



a) 2003



b) 2004

Figure 14: Cotton loan value and seasonal irrigation for a) 2003, a relatively hot and dry year; and b) 2004, a relatively cool and wet year at Bushland, TX (Colaizzi et al., 2005).

CONCLUSIONS

Relative yield response between different irrigation methods usually changed with irrigation capacity (fixed application per unit time) or irrigation rate (percentage of soil water replenishment), and these were often similar for different crops and locations. Yield response in terms of irrigation method could usually be described as SDI ≥ LEPA ≥ SPRAY for low irrigation capacities (or rates), and SPRAY ≥ LEPA ≥ SDI for full (or nearly full) capacities or rates. In some cases, yield response was more consistent across irrigation rates, which may be related to rainfall patterns. For example, corn grain yield in Colby, KS was SDI ≥ LEPA when rainfall was average or above average, but LEPA ≥ SDI for below average rainfall. In Bushland, TX, cotton lint yield during a relatively cool and wet season was SDI ≥ (LEPA or SPRAY). SDI is thought to enhance cotton earliness due to reduced evaporative cooling compared to LEPA or spray. This was not observed for the two years of data at Bushland, TX; however, SDI sometimes resulted in better fiber quality.

There is a lack of existing data to conclusively explain the similar yield response trends observed for SDI, LEPA, and spray; that these occurred for different crops and locations implies that certain processes might dominate for a given irrigation method. It does appear that LEPA, and to a greater extent SDI, result in greater partitioning of water to plant transpiration relative to spray for low irrigation rates. At greater irrigation rates, the yield depressions observed for SDI and/or LEPA relative to spray were less clear, although these may be the result of poor aeration and nutrient leaching by deep percolation. The type of data required to further investigate these processes are presently very difficult to obtain. Nonetheless, some examples include near-surface soil water and temperature (which are presently being acquired at Bushland, TX), separate measurements of evaporation and transpiration, and careful studies of plant development and nutrient uptake.

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