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Crop Production Comparison with Spray, LEPA, and Subsurface Drip Irrigation in the Texas High Plains

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Abstract. *Irrigation application method may affect crop yield and water productivity. Crop production was compared for spray, LEPA drag sock, and subsurface drip irrigation (SDI) application methods in the Texas High Plains. Crops included three seasons of grain sorghum, one season of soybean, and four seasons of cotton. Irrigation treatments were 0, 25, 50, 75, and 100% of replacing full crop evapotranspiration, which was measured by neutron probe. For grain sorghum, SDI resulted in the largest grain yield and water use efficiency at the 25 and 50% irrigation treatments, followed by LEPA, but spray outperformed LEPA and SDI at the 75 and 100% treatments. For soybean, the same trend was observed at the 25 and 50% treatments, but SDI performed best at 75%, and spray performed best at 100%. Cotton productivity and gross returns were consistently best for SDI, followed by LEPA, and spray at all irrigation treatments.*

Keywords. Grain sorghum, soybean, cotton, water use efficiency, Ogallala Aquifer, semiarid

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Introduction

Irrigation is practiced on approximately 1.62 million of the 3.4 million ha land area cultivated 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 much of 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 448,000 km^2 across eight Great Plains states, representing 27 percent of U.S. irrigated land (USDA-NASS, 2008). The practice of effective 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 effective 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-Medina et al., 2007; Bordovsky and Porter, 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. 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). During the past decade, cotton production has expanded northward into these regions where well yields have declined because cotton has similar revenue potential but half the irrigation requirement as corn (Howell et al., 2004).

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). Lamm (2009) showed that SDI systems continue to perform as designed after twenty years of service in Western Kansas, which exceeds the 10-15 year service requirement to be competitive with center pivot systems. Despite these 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. Nonetheless, Colaizzi et al. (2004) showed that grain sorghum yield and water productivity were greater with SDI compared with MESA, LESA, and LEPA under deficit irrigation. However, MESA and LESA outperformed SDI and LEPA under full irrigation, suggesting that SDI offered the greatest advantages when declining well yields prevent fully irrigating a crop. Relatively few studies have directly compared the effect of irrigation method for other crops.

The objectives of this paper were to compare crop production and near-surface soil temperatures and soil water contents under MESA, LESA, LEPA, and SDI in a multi-year experiment at Bushland, Tex., USA. Crops included cotton, grain sorghum, and soybean (a catch crop after crop failure in the region). Production parameters measured included crop yield, seasonal water use, water use efficiency (WUE), and irrigation water use efficiency (IWUE), where WUE and IWUE were defined by 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., 1,190 m elevation above MSL). The soil is a Pullman clay loam (fine, superactive, mixed, thermic torrertic Paleustoll; USDA-NRCS, 2010) with slow permeability due to a dense B21t horizon that is 0.15 to 0.50 m below the surface. A calcic horizon begins at approximately 1.2 m 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 treatments ranging from near dryland to meeting full crop evapotranspiration (ET_c) in a strip-split block design. The irrigation 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 ET. 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. 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. Each plot was 9 m wide by 12 m long and contained 12 raised beds with east-west orientation and 0.76-m centers, where each crop was planted in the center of the raised bed. Irrigation treatments were imposed by varying the speed of the lateral. The SDI method consisted of laterals installed with a shank injector beneath alternate furrows at the 0.30-m depth, where irrigation treatments were imposed by varying emitter flow rates and spacing (Table 2).

Cropping seasons included grain sorghum (*Sorghum bicolor* L. *cv.* Moench Pioneer[1] 84G62) (2000, 2001, and 2002; Table 3), soybean (*Glycine max cv.* Pioneer 94M90) (2005; Table 3), and cotton (*Gossypium hirsutum* L. *cv.* Paymaster 2280 BG RR) (2003, 2004, 2006, and 2007; Table 4). Soybean was planted after the 2005 cotton crop was destroyed by hail. Dikes were installed in all furrows between planting and emergence 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).

Volumetric soil water was measured by gravimetric samples to the 1.8-m depth in 0.30-m increments at planting and harvest. Soil water was also measured during the crop season by neutron probe (NP) to the 2.3-m depth in 0.20-m increments (Evett and Steiner, 1995) using a depth control stand, which allowed accurate measurement of soil water at shallow (0.10-m) depths (Evett et al., 2003). The NP meters were field-calibrated and achieved accuracies better

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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.

than 0.005 $m^3 m^{-3}$, including the 0.10-m depth. Both gravimetric and NP were measured near the center of each plot (i.e., sixth row from the south and 12.5 m from plot edge) and in the center of the raised bed. Irrigations for grain sorghum were scheduled when cumulative crop evapotranspiration (ET_c) under full irrigation (I_{100}) reached 25 mm (minus any precipitation), where ET_c was computed using the Texas High Plains Evapotranspiration Network (Porter et al., 2005). Irrigations for soybean and cotton 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 I_{100} treatment reached 25 mm below field capacity, where field capacity was 765 mm in the 2.4-m profile. From second leaf (soybean) and first square (cotton) to termination of irrigations, the appropriate irrigation amount was applied on a weekly basis. 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. The SDI plots had the same amount of water applied as the sprinkler plots except the duration of each irrigation event was longer.

Crop yield (derived from hand sampling a 10 m^2 area in each plot), seasonal water use (irrigation applied + precipitation + change in soil water storage), water use efficiency (WUE), and irrigation water use efficiency (IWUE) were compared using the SAS PROC MIXED procedure (Littell et al., 2006). WUE (kg m^{-3}) was defined as the ratio of economic yield (Y, kg ha^{-1}) to seasonal water use (ET, mm, 0.001 m = 1 kg H_2O m^{-2} at a water density of 1000 kg m^{-3}), or WUE = Y $(ET)^{-1}$. IWUE (kg m^{-3}) was defined as the increase in irrigated yield (Y_i) compared with dryland yield (Y_d) divided by the total seasonal irrigation (IR, mm), or IWUE = $(Y_i\text{-}Y_d)$ IR^{-1} (Bos, 1980). 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).

Soil temperatures and volumetric soil water content were measured near the surface of raised beds using copper-constantan (type-T) thermocouples and time-domain reflectometry (TDR), respectively, during the 2005 soybean and 2006 cotton seasons. Measurements were obtained in the I_{50} and I_{100} irrigation treatments for the MESA, LESA, LEPA, and SDI irrigation methods (eight plots) at three different planted bed locations per plot beneath the center span of the lateral-move irrigation system. The instrumented locations were 4.5 m from the edge of each plot (due to length limitations of the TDR coaxial cable) in rows 5, 6, and 7 from the south edge of the plot. Neutron probe access tubes were installed in row 6 from the south edge of the plot, and 1 m from the instruments, resulting in the access tubes being 5.5 m from the edge of the instrumented plots (instead of 12.5 m from the edge). In each instrumented bed location, the thermocouples and TDR devices were oriented horizontally, parallel to the bed orientation, and installed at 0.05, 0.10, and 0.15 m depths from the soil surface in the center and both sides of the bed. The TDR system consisted of 0.20 m long trifilar probes connected to coaxial multiplexers (Evett, 1998), a cable tester (model 1502C, Tektronix, Inc., Redmond, OR), and an embedded computer running the TACQ supervisory TDR system control and data acquisition program (Evett, 2000a; 2000b). The TACQ program determined bulk electrical conductivity and effective frequency from the recorded waveforms (recorded every 2 h) and used these data in a water content calibration equation that practically eliminates temperature effects (recorded every 1 h) that may occur at greater water contents (Evett et al., 2005). The TDR system accuracy (root mean squared error of calibration) is < 0.01 $m^3 m^{-3}$ in all three main horizons of the Pullman soil (Evett et al., 2006).

Near-surface soil temperatures were compared for MESA, LESA, LEPA, and SDI irrigation methods on the basis of cumulative soil heat units (CSHU) at various times after planting in a similar manner as air temperature-based heat units, except soil temperatures were substituted for air temperature:

$$\mathrm{CSHU} = \sum_{i=1}^{\mathrm{DSP}} \left[\left(\mathrm{T}_{\mathrm{SOIL-MAX,i}} + \mathrm{T}_{\mathrm{SOIL-MIN,i}} \right) / 2 - \mathrm{T}_{\mathrm{BASE}} \right] \tag{1}$$

where DSP is the number of days since planting, $T_{SOIL\text{-}MAX}$ and $T_{SOIL\text{-}MIN}$ are the maximum and minimum, respectively, daily measured soil temperature, T_{BASE} is the crop-specific minimum base temperature at which growth and development occurs, and CSHU and temperatures have the same units (°C). For cotton, T_{BASE} = 15.6 °C is the standard used in computing air temperature-based heat units in the Southern High Plains (Peng et al., 1989) and was therefore also used to compute CSHU. The effect of irrigation method (MESA, LESA, LEPA, or SDI) on CSHU was tested for differences using the SAS mixed model (PROC MIXED, Littell et al., 2006) with least squared differences ($\alpha \leq 0.05$).

Results and Discussion

Grain Sorghum

The relative performance of the irrigation methods changed with the irrigation treatment for grain sorghum (Table 5). For the lower irrigation treatments (I_{25} and I_{50}), grain yield was greatest for SDI, followed by LEPA, MESA, and LESA. For the higher irrigation treatments (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 treatment average (except between I_{75} and I_{100}), and was positively correlated with the irrigation treatment 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 treatment averages. WUE and IWUE followed the same trends observed for grain yield among irrigation treatments and for irrigation method averages. For irrigation treatment 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 (i.e., the proportion of water partitioned to transpiration) was reached around I_{75}, as yield was not much greater at I_{100} and maximum WUE occurred at I_{75}.

We hypothesize that different factors, depending on irrigation treatment, 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 losses 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 treatments (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 may not have been present under LEPA. Grain yield was greater for MESA compared with LESA at all irrigation treatments, 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 0.30 m, whereas it was 1.5 m 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 treatments, 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 1.8- and 2.3-m depths over successive measurements with a neutron probe (NP) 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 76 m. 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 treatments. In the grain sorghum study at Bushland, Tex., the presence of deep percolation suggests that irrigation treatments 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 due to greater evaporation and wind drift that likely occurred under MESA irrigation 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 the NP as the basis for irrigation scheduling.

Soybean

Soybean response was generally more favorable under SDI compared with other irrigation methods at the I_{25}, I_{50}, and I_{75} irrigation treatments (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}, I_{50}, and I_{100}. 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. At I_{100}, SDI did result in the largest WUE, followed by MESA, LESA, and LEPA. As expected, yield and seasonal water use increased significantly as irrigation treatment 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 for SDI was only numerically greater than for MESA). Here, no significant differences were observed for seasonal water use.

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 treatments, 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 treatments, 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, which will be discussed later in this document. 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 SDI irrigated corn.

Cotton

Cotton response was most favorable with SDI, followed by LEPA for all irrigation treatments 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 treatments, followed in decreasing order by LEPA, LESA, and MESA, respectively (an exception occurred at the I_{50} and I_{75} irrigation treatments, 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. Lint yield, seasonal water use, WUE, and IWUE were all significantly greater with increasing irrigation treatment, 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 textile mills 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); and 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. SDI resulted in the largest gross returns for all irrigation treatments, followed by LEPA. Both SDI and LEPA resulted in significantly greater gross returns compared with MESA and LESA when irrigation methods were averaged across treatments.

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 120 km south of Bushland with lower elevation (1,090 m 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 100 km north of Bushland but has similar heat units available for cotton production.

Near-Surface Soil Temperature and Water Content

Soil temperatures were compared based on cumulative soil heat units (CSHU, 15.6 °C base temperature) for the I_{50} and I_{100} irrigation treatments at the 0.05-, 0.10-, and 0.15-m depths during the 2005 soybean (Table 9) and 2006 cotton (Table 10) irrigation seasons. Although soybean has a lower base temperature (usually 7.8 °C) compared with cotton, the cotton base temperature was used to facilitate inter-annual comparison. The dates selected were for the first three weeks after planting, 30 days after planting, and at termination of irrigations. In all but one case, SDI resulted in numerically greater CSHU compared with MESA, LESA, and LEPA, although in only 9 out of 60 total comparisons was CSHU for SDI significantly greater than that for all other irrigation methods. LEPA usually resulted in the least CSHU at the I_{50} treatment, whereas MESA or LESA resulted in the least CSHU at the I_{100} treatment. The relative differences in CSHU among irrigation methods were generally consistent for each number of days since planting, up to 72 and 90 days for soybean and cotton, respectively. These relative differences were also generally consistent among the 0.05-, 0.10-, and 0.15-m depths. The shallower soil depth had slightly greater CSHU compared with deeper depth, which was expected because the diurnal temperature amplitude diminishes as depth increases.

The differences in CSHU were largely correlated with relative differences in volumetric water content measured with time domain reflectometry (TDR), in that greater water content was associated with less CSHU. This may have been related to greater evaporative cooling resulting from greater water content near the surface. In 2006, volumetric soil water at the 0.05-, 0.10-, and 0.15-m depths varied from greater than 0.20 m^3 m^{-3} following a wetting event to less than 0.10 m^3 m^{-3} at the end of the irrigation season (Figure 1). At the I_{50} treatment, volumetric soil water was 0.02 to 0.05 m^3 m^{-3} greater for LEPA compared with the other irrigation methods from planting (DOY 137) to around DOY 195 (Figure 1a). This may have resulted from run on during two irrigation events prior to planting (DOY 121 and 124), before furrow dikes were installed. The was a slight increase in TDR-measured soil water for I_{50} LEPA around DOY 170 that did not occur in the other methods; this may resulted from additional run on as furrow dikes eroded. Volumetric soil water was also measured by NP at the 0.10-m depth approximately 2 m from the TDR/thermocouple location in the bed centers (Figure 1c). Water content for LEPA was greater than other irrigation methods only on the first measurement date, and was less than other methods on the last three measurement dates. At the I_{100} treatment, volumetric water content measured by TDR was around 0.03 m^3 m^{-3} greater for MESA and LESA compared with LEPA and SDI (Figure 1b). A somewhat similar trend resulted with the NP at the 0.10-m depth center, which was also approximately 2 m from the TDR/thermocouple location, where MESA and LESA had greater water contents compared with LEPA and SDI (Figure 1d). For both irrigation treatments, the generally greater volumetric water content measured by the NP at the 0.10-m depth compared with TDR was the result of the larger volume of measurement of the NP.

Considering only measurements made in the I_{100} treatment plots, the MESA and LESA irrigation methods resulted in greater soil water content and cooler soil temperatures compared with LEPA and SDI in the top 0.15 m of the planted bed during the irrigation season. The greater water present near the surface for MESA and LESA would imply that relatively greater water was lost to evaporation compared with LEPA and SDI, especially early in the season. Conversely, relatively greater water would be available for transpiration for LEPA and SDI compared with MESA and LESA. Both the greater partitioning of available water to transpiration and warmer soil temperatures would explain the greater cotton lint yield, water use efficiency, and irrigation water use efficiency observed for SDI, followed by LEPA, compared with MESA and LESA (Table 7).

It is improbable that differences in CSHU between the irrigation methods were enhanced by differences in irrigation water temperature. All water was delivered to the experimental field from a reservoir that was approximately 200 m away, 2 m deep, and 1 ha square. Water was drawn from the reservoir bottom through a screen intake leading to a sump pump, and pressurized in an underground pipe that was buried 1.5 m. Water was applied to the MESA, LESA, and LEPA plots at the same time in the afternoon using the lateral move, and the duration of each irrigation event was usually less than 2.5 h. Irrigation in the SDI plots began at the same time as the lateral move, and were usually finished within one or two hours after midnight. Even if air temperature had decreased substantially during this time, this would not be sufficient to decrease the water temperature much near the reservoir bottom or in the underground pipe.

Summary and Conclusions

Crop production was compared under four irrigation methods and four irrigation treatments 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 mid elevation spray applicators (MESA), low elevation spray applicators (LESA), low energy precision applicators (LEPA), and subsurface drip irrigation (SDI). For each irrigation method, irrigation was applied at treatments of 25, 50, 75, and 100% of meeting the full crop water requirement (i.e., crop evapotranspiration); and an additional near-dryland treatment (0%) was included to compute irrigation water use efficiency.

Grain sorghum and soybean response to irrigation method changed with irrigation treatment, with SDI and LEPA generally outperforming MESA and LESA at low irrigation treatments, and vice-versa at high irrigation treatments. For grain sorghum at high irrigation treatments, deep percolation was observed for SDI and to a lesser extent LEPA. This probably occurred because of over irrigation that resulted from overly large crop coefficient values since crop coefficients were determined under spray irrigation, which has larger evaporative and wind drift losses compared with SDI. The yield depressions at high irrigation treatments 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 treatments. The neutron probe was used to schedule cotton irrigations.

Near surface soil temperature and volumetric water content were compared for the MESA, LESA, LEPA, and SDI irrigation methods at the 50 and 100% irrigation treatments. For the 100% treatment, near surface soil temperatures were greatest for SDI, followed by LEPA, and least for MESA and LESA. For the 50% treatment, SDI resulted in greater soil temperatures compared with MESA and LESA, but LEPA resulted in the lowest soil temperatures possibly due to run on to the instrument site before furrow dikes were installed at planting. As expected, soil temperatures were inversely related to volumetric water content, with greater soil water present near the surface for MESA and LESA compared with SDI. For SDI, this may have resulted in less evaporative loss and more water being partitioned to transpiration; both drier soil conditions and less evaporative cooling may have contributed to warmer soil temperatures. The greater partitioning of available water to transpiration and warmer soil temperatures are both known to promote cotton growth and should result in greater crop productivity, particularly for cotton production in an environment constrained both by water resources and thermal heat units.

This experiment is continuing with production evaluation of 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 their long-term economics under various irrigation treatments. 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.

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

Applicator	Model [b]	Options	Applicator Height from furrow surface (m)
LEPA	Super Spray head	Double-ended drag sock [c]	0
LESA	Quad IV	Flat, medium-grooved spray pad	0.3
MESA	Low-drift nozzle (LDN) spray head	Single, convex, medium-grooved spray pad	1.5

[a] All sprinkler components manufactured by Senninger Irrigation, Inc., Orlando, Florida, except where noted.

[b] All devices equipped with 69 kPa pressure regulators and No. 17 (6.75 mm) plastic spray nozzles, giving a flow rate of 0.412 L s^{-1}.

[c] Manufactured by A. E. Quest and Sons, Lubbock, Texas.

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

Irrigation treatment	Emitter Flow Rate (L h^{-1})	Emitter Spacing (m)	Emitter Application Rate (mm h^{-1})
I_0 [b]	--	--	--
I_{25}	0.68	0.91	0.49
I_{50}	0.87	0.61	0.97
I_{75}	0.87	0.41	1.45
I_{100}	0.87	0.3	1.93

[a] All SDI dripline manufactured by Netafim USA, Fresno, California.

[b] Smooth tubing, no emitters

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

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	30 plants m^{-2}	23 plants m^{-2}	22 plants m^{-2}	45 plants m^{-2}
Planting date	26-May (DOY 146)	22-June (DOY 173) [b]	31-May (DOY 151)	20-Jun (DOY 171)
Harvest date	21-Sep (DOY 264)	29-Oct (DOY 302)	14-Nov (DOY 318)	26-Oct (DOY 299)
Precipitation	139 mm	124 mm	317 mm	140 mm
Fertilizer applied	58 kg ha^{-1} preplant N 76 kg ha^{-1} preplant P 45 kg ha^{-1} irr. N (I_{100}) [a]	179 kg ha^{-1} preplant N 18 kg ha^{-1} irr. N (I_{100}) [a]	160 kg ha^{-1} preplant N 57 kg ha^{-1} preplant P	177 kg ha^{-1} preplant N 114 kg ha^{-1} preplant P
Herbicide applied	4.7 L ha^{-1} Bicep	4.7 L ha^{-1} Bicep	1.6 kg ha^{-1} Atrazine	2.3 L ha^{-1} Treflan
Insecticide applied	0.58 L ha^{-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).

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	17 plants m^{-2}	19 plants m^{-2}	19 plants m^{-2}	15 plants m^{-2}
Planting date	10-Jun (DOY 161) [b]	20-May (DOY 141)	17-May (DOY 137)	29-May (DOY 149)
Harvest date	21-Nov (DOY 325)	14-Dec (DOY 349)	13-Dec (DOY 347)	5-Nov (DOY 309)
Total heat units (15.6 °C base temperature)	1076	865	1268	1099
Precipitation	230 mm [c]	495 mm	362 mm	204 mm
Fertilizer applied	31 kg ha^{-1} preplant N 107 kg ha^{-1} preplant P 48 kg ha^{-1} irr. N (I_{100}) [a]	34 kg ha^{-1} preplant N 114 kg ha^{-1} preplant P 50 kg ha^{-1} irr. N (I_{100}) [a]	18 kg ha^{-1} preplant N 83 kg ha^{-1} preplant P 78 kg ha^{-1} irr. N (I_{100}) [a]	18 kg ha^{-1} preplant N 87 kg ha^{-1} preplant P 135 kg ha^{-1} irr. N (I_{100}) [a]
Herbicide applied	2.3 L ha^{-1} Treflan	2.3 L ha^{-1} Treflan	2.3 L ha^{-1} Treflan	2.3 L ha^{-1} Treflan 2.3 L ha^{-1} Round Up
Insecticide applied	NONE	NONE	1.2 L ha^{-1} Lorsban	1.2 L ha^{-1} Lorsban
Growth regulator applied	NONE	NONE	NONE	NONE
Defoliant applied	NONE	NONE	NONE	1.2 L ha^{-1} Paraquat
Boll opener applied	NONE	NONE	NONE	1.2 L ha^{-1} Gin Star

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

[b] The first planting on 21-May-2003 sustained severe hail damage on 3-June-2003 and was subsequently destroyed and replanted.

[c] Includes all rainfall between gravimetric sampling; 167 mm occurred between replant and harvest.

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

Irrigation treatment [a]	Irrigation method	Grain yield [b] kg ha^{-1}		Seasonal water use mm		WUE [c] kg m^{-3}		IWUE [d] kg m^{-3}	
I_{25} (177 mm)	MESA	3,752	b [e]	459	a	0.92	b	2.08	b
	LESA	3,070	b	469	a	0.75	b	1.55	b
	LEPA	4,033	b	471	a	0.96	b	2.31	b
	SDI	6,144	a	479	a	1.45	a	3.97	a
I_{50} (275 mm)	MESA	7,611	a	562	a	1.49	ab	2.86	a
	LESA	6,747	a	572	a	1.30	b	2.52	a
	LEPA	7,840	a	563	a	1.52	ab	2.97	a
	SDI	8,685	a	568	a	1.71	a	3.34	a
I_{75} (373 mm)	MESA	9,403	a	634	a	1.63	a	2.55	a
	LESA	8,922	a	652	a	1.49	a	2.41	a
	LEPA	8,737	a	643	a	1.48	a	2.34	a
	SDI	8,772	a	629	a	1.54	a	2.32	a
I_{100} (471 mm)	MESA	10,046	a	725	a	1.49	a	2.11	a
	LESA	9,623	a	725	a	1.43	a	2.01	a
	LEPA	9,050	a	710	a	1.38	a	1.87	a
	SDI	8,938	a	727	a	1.33	a	1.82	a
Irrigation treatment averages									
I_0 (79 mm)		1,117	d [f]	379	e	0.39	c	----	
I_{25} (177 mm)		4,250	c	469	d	1.02	b	2.48	ab
I_{50} (275 mm)		7,721	b	566	c	1.50	a	2.92	a
I_{75} (373 mm)		8,959	a	640	b	1.53	a	2.41	bc
I_{100} (471 mm)		9,414	a	722	a	1.41	a	1.95	c
Irrigation method averages									
	MESA	7,703	ab [g]	595	a	1.38	ab	2.40	ab
	LESA	7,091	b	604	a	1.24	b	2.12	b
	LEPA	7,415	ab	597	a	1.33	b	2.37	b
	SDI	8,135	a	601	a	1.51	a	2.86	a

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

[b] Yields were converted from dry mass to 14% moisture content by mass (wet basis).

[c] WUE = Water use efficiency.

[d] IWUE = Irrigation water use efficiency.

[e] Numbers followed by the same letter are not significantly different ($\alpha \leq 0.05$) within an irrigation treatment.

[f] Numbers followed by the same letter are not significantly different ($\alpha \leq 0.05$) between irrigation treatment averages.

[g] Numbers followed by the same letter are not significantly different ($\alpha \leq 0.05$) between irrigation method averages.

Table 6. Soybean response, 2005 season.

Irrigation treatment [a]	Irrigation method	Grain yield [b] kg ha^{-1}		Seasonal water use mm		WUE [c] kg m^{-3}		IWUE [d] kg m^{-3}	
I_0 (0 mm)	-----	1,660		315		0.527		-----	
I_{25} (72 mm)	MESA	2,124	b [c]	373	a	0.573	b	0.642	bc
	LESA	2,019	b	394	a	0.514	b	0.497	c
	LEPA	2,237	ab	384	a	0.583	b	0.799	b
	SDI	2,494	a	373	a	0.671	a	1.154	a
I_{50} (144 mm)	MESA	2,845	b	470	a	0.605	b	0.826	b
	LESA	2,583	b	446	a	0.579	b	0.643	b
	LEPA	2,856	b	455	a	0.627	b	0.834	b
	SDI	3,365	a	457	a	0.737	a	1.188	a
I_{75} (216 mm)	MESA	3,461	ab	543	ab	0.637	ab	0.835	a
	LESA	3,150	b	571	a	0.556	c	0.691	a
	LEPA	3,267	ab	562	a	0.581	bc	0.745	a
	SDI	3,563	a	530	b	0.672	a	0.882	a
I_{100} (287 mm)	MESA	3,957	a	627	a	0.631	ab	0.800	a
	LESA	3,728	ab	616	a	0.605	ab	0.721	a
	LEPA	3,477	b	620	a	0.560	b	0.633	a
	SDI	3,893	a	604	a	0.646	a	0.778	a
Irrigation treatment averages									
I_0 (0 mm)		1,660	e [d]	315	e	0.527	b	-----	
I_{25} (72 mm)		2,219	d	380	d	0.589	b	0.773	a
I_{50} (144 mm)		2,912	c	457	c	0.637	a	0.873	a
I_{75} (216 mm)		3,360	b	552	b	0.612	ab	0.788	a
I_{100} (287 mm)		3,764	a	617	a	0.611	ab	0.733	a
Irrigation method averages									
	MESA	3,097	ab [e]	503	a	0.612	b	0.776	b
	LESA	2,870	b	506	a	0.568	b	0.638	b
	LEPA	2,960	b	505	a	0.588	b	0.753	b
	SDI	3,329	a	491	a	0.682	a	1.001	a

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

[b] Yields were converted from dry mass to 13% moisture content by mass (wet basis).

[c] WUE = Water use efficiency.

[d] IWUE = Irrigation water use efficiency.

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

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

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

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

Irrigation treatment [a]	Irrigation method	Lint yield kg ha^{-1}		Seasonal water use mm		WUE [b] kg m^{-3}		IWUE [c] kg m^{-3}	
I_{25} (67 mm)	MESA	462	a [d]	418	a	0.118	b	0.064	b
	LESA	494	a	426	a	0.122	b	0.082	b
	LEPA	550	a	427	a	0.132	ab	0.113	ab
	SDI	641	a	428	a	0.154	a	0.164	a
I_{50} (111 mm)	MESA	557	b	477	a	0.120	b	0.063	b
	LESA	560	b	474	a	0.120	b	0.061	b
	LEPA	739	ab	493	a	0.152	a	0.162	a
	SDI	800	a	496	a	0.161	a	0.180	a
I_{75} (156 mm)	MESA	781	b	538	a	0.144	bc	0.144	b
	LESA	754	b	538	a	0.139	c	0.130	b
	LEPA	870	ab	526	a	0.165	ab	0.190	ab
	SDI	1020	a	546	a	0.189	a	0.264	a
I_{100} (201 mm)	MESA	871	b	589	a	0.147	b	0.164	b
	LESA	885	ab	588	a	0.150	b	0.168	b
	LEPA	992	ab	592	a	0.165	ab	0.201	ab
	SDI	1065	a	579	a	0.186	a	0.254	a
Irrigation treatment averages									
I_0 (22 mm)		396	e [e]	368	e	0.113	c	----	
I_{25} (67 mm)		537	d	425	d	0.132	bc	0.106	b
I_{50} (111 mm)		664	c	485	c	0.138	b	0.117	b
I_{75} (156 mm)		856	b	537	b	0.159	a	0.182	a
I_{100} (201 mm)		953	a	587	a	0.162	a	0.197	a
Irrigation method averages									
	MESA	668	b [f]	506	a	0.132	c	0.109	c
	LESA	673	b	507	a	0.133	c	0.110	c
	LEPA	788	a	510	a	0.154	b	0.166	b
	SDI	882	a	512	a	0.173	a	0.215	a

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

[b] WUE = Water use efficiency; computed based on lint yield.

[c] IWUE = Irrigation water use efficiency; computed based on lint yield.

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

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

[f] 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 treatment [a]	Irrigation method	Loan value [b] \$ kg^{-1}		Gross return \$ ha^{-1}	
I_{25} (67 mm)	MESA	\$1.02	a [c]	\$474	a
	LESA	\$1.03	a	\$515	a
	LEPA	\$1.07	a	\$592	a
	SDI	\$1.08	a	\$700	a
I_{50} (111 mm)	MESA	\$1.06	ab	\$592	bc
	LESA	\$1.01	b	\$563	c
	LEPA	\$1.09	a	\$825	ab
	SDI	\$1.08	ab	\$874	a
I_{75} (156 mm)	MESA	\$1.08	a	\$858	b
	LESA	\$1.09	a	\$831	b
	LEPA	\$1.09	a	\$962	ab
	SDI	\$1.09	a	\$1,119	a
I_{100} (201 mm)	MESA	\$1.08	a	\$959	a
	LESA	\$1.08	a	\$977	a
	LEPA	\$1.10	a	\$1,116	a
	SDI	\$1.11	a	\$1,187	a
Irrigation treatment averages					
I_0 (22 mm)		\$1.06	ab [d]	\$427	d
I_{25} (67 mm)		\$1.05	b	\$570	d
I_{50} (111 mm)		\$1.06	ab	\$713	c
I_{75} (156 mm)		\$1.09	ab	\$943	b
I_{100} (201 mm)		\$1.09	a	\$1,060	a
Irrigation method averages					
	MESA	\$1.06	a [e]	\$720	b
	LESA	\$1.05	a	\$721	b
	LEPA	\$1.09	a	\$874	a
	SDI	\$1.09	a	\$970	a

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

[b] Base loan value was \$1.1352 kg^{-1} USD 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 treatment.

[d] Numbers followed by the same letter are not significantly different ($\alpha \leq 0.05$) between irrigation treatment averages.

[e] Numbers followed by the same letter are not significantly different ($\alpha \leq 0.05$) between irrigation method averages.

Table 9. Soil and air temperature-based cumulative heat units (15.6 °C base temperature) during the 2005 irrigation season for soybean.

Irrig. tmt.	Soil depth m	Irrig. method	Date	6/27/2005		7/4/2005		7/11/2005		7/20/2005		8/31/2005	
			DOY [a]	178		185		192		201		243	
			DSP [b]	7		14		21		30		72	
			fc (I_{50}) [c]	0		0		0.11		0.29		0.93	
I_{50}	0.05m	MESA		66	b [d]	143	ab	212	a	327	b	703	a
		LESA		65	b	139	b	209	a	324	b	700	a
		LEPA		58	c	128	c	190	b	297	c	603	b
		SDI		74	a	156	a	225	a	348	a	732	a
	0.10m	MESA		63	b	137	a	203	a	313	a	688	a
		LESA		63	b	135	a	203	a	314	a	684	a
		LEPA		57	c	124	b	185	b	290	b	599	b
		SDI		68	a	143	a	207	a	320	a	695	a
	0.15m	MESA		63	ab	134	a	199	a	305	a	670	a
		LESA		61	b	131	a	197	a	305	a	672	a
		LEPA		56	c	121	b	182	b	288	b	602	b
		SDI		65	a	137	a	199	a	308	a	681	a
			fc (I_{100}) [c]	0		0		0.12		0.31		0.96	
I_{100}	0.05m	MESA		65	b	141	b	216	a	336	a	633	c
		LESA		69	b	146	ab	220	a	343	a	659	bc
		LEPA		67	b	143	b	214	a	332	a	676	ab
		SDI		76	a	153	a	224	a	346	a	695	a
	0.10m	MESA		61	b	132	b	202	b	315	a	619	b
		LESA		63	b	136	b	204	b	321	a	633	b
		LEPA		64	b	137	b	204	ab	319	a	660	a
		SDI		71	a	144	a	211	a	326	a	675	a
	0.15m	MESA		62	b	135	a	205	a	320	a	664	a
		LESA		63	b	136	a	204	a	319	a	663	a
		LEPA		67	ab	141	a	210	a	325	a	699	a
		SDI		70	a	144	a	212	a	327	a	700	a
Air temperature heat units				65		140		199		292		639	

[a] DOY = Day of year.

[b] DSP = Days since planting.

[c] fc = Fraction of canopy cover for I_{50} or I_{100} irrigation treatments, average of irrigation methods, measured as the canopy width divided by row spacing.

[d] Numbers followed by the same letter are not significantly different (α ≤ 0.05) within a measurement depth.

Table 10. Soil and air temperature-based cumulative heat units (15.6 °C base temperature) during the 2006 irrigation season for cotton.

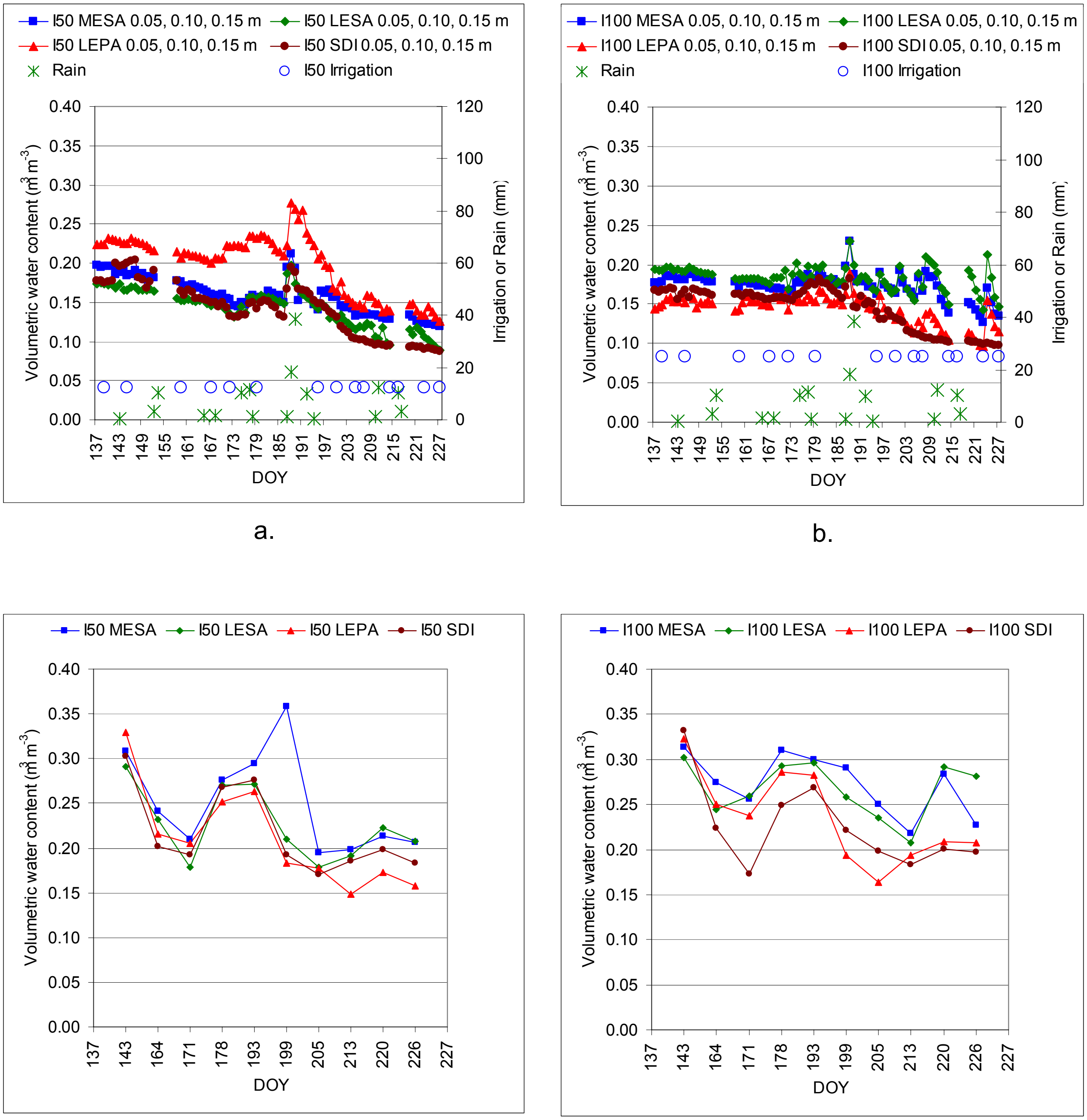
Irrig. tmt.	Soil depth m	Irrig. method	Date	5/25/2006	6/1/2006	6/8/2006	6/17/2006	8/16/2006
			DOY [a]	145	152	159	168	228
			DSP [b]	7	14	21	30	90
			fc (I_{50}) [c]	0	0	0.06	0.09	0.34
I_{50}	0.05m	MESA		70 a [d]	133 a	203 a	296 ab	888 a
		LESA		70 a	133 a	202 a	295 ab	907 a
		LEPA		66 a	127 a	194 a	280 b	870 a
		SDI		71 a	137 a	208 a	307 a	932 a
	0.10m	MESA		67 a	127 a	195 a	268 b	853 b
		LESA		66 a	126 a	194 a	283 ab	877 ab
		LEPA		62 a	121 a	185 a	269 b	848 b
		SDI		66 a	129 a	198 a	293 a	920 a
	0.15m	MESA		61 a	120 ab	185 ab	273 b	844 b
		LESA		61 a	119 ab	185 ab	271 b	853 b
		LEPA		59 a	116 b	178 b	260 b	834 b
		SDI		64 a	126 a	193 a	287 a	916 a
			fc (I_{100}) [c]	0	0	0.05	0.09	0.38
I_{100}	0.05m	MESA		68 ab	130 ab	202 a	294 a	861 ab
		LESA		65 b	127 b	199 a	288 a	804 b
		LEPA		69 ab	130 ab	200 a	292 a	854 ab
		SDI		72 a	138 a	210 a	309 a	912 a
	0.10m	MESA		64 ab	123 ab	191 a	280 ab	825 b
		LESA		61 b	119 b	187 a	273 b	777 c
		LEPA		64 ab	123 ab	191 a	280 ab	826 b
		SDI		66 a	127 a	195 a	288 a	874 a
	0.15m	MESA		61 a	117 ab	184 a	271 a	800 b
		LESA		57 a	112 b	177 b	260 b	766 b
		LEPA		59 a	115 ab	180 ab	265 ab	797 ab
		SDI		62 a	121 a	187 a	278 a	858 a
Air temperature heat units				73	134	204	299	877

[a] DOY = Day of year.

[b] DSP = Days since planting.

[c] fc = Fraction of canopy cover for I_{50} or I_{100} irrigation treatments, average of irrigation methods, measured as the canopy width divided by row spacing.

[d] Numbers followed by the same letter are not significantly different (α ≤ 0.05) within a measurement depth.



a.

b.

c.

d.

Figure 1. Near surface soil water during the 2006 cotton irrigation season measured by time domain reflectometry (TDR) and neutron probe (NP) for a. I_{50} TDR, 0.05, 0.10, and 0.15 m average; b. I_{100} TDR, 0.05, 0.10, and 0.15 m average; c. I_{50} NP, 0.10 m; d. I_{100} NP, 0.10 m.