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Comparison of SDI, LEPA, and spray efficiency for grain sorghum

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Abstract. *A three-year study was conducted at Bushland, Texas (Southern High Plains) to compare SDI, LEPA, and spray irrigation on grain sorghum. Parameters compared were grain yield, seed mass, soil water depletion, seasonal water use, water use efficiency (WUE), and irrigation water use efficiency (IWUE). Parameters using each irrigation method were compared within five irrigation levels consisting of full irrigation and 0-, 25-, 50-, and 75% of full irrigation.*

In all three years, SDI had greater yield, WUE, and IWUE than other irrigation methods at the 50% level and especially at the 25% level, whereas spray outperformed SDI and LEPA at the 75% and full irrigation levels. Differences in seed mass, soil water depletion, and seasonal water use were usually insignificant at the 25% and 50% levels and inconsistent at the 75% and full levels. Parameters were most sensitive to irrigation level, then year, then irrigation method, although relative rankings of parameters for each method within a level were consistent across years.

Keywords. Microirrigation, sprinkler irrigation, LEPA, subsurface drip irrigation, grain, sorghum

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Introduction

The Southern High Plains region of Texas produces over half of all grain crops including one-fifth of grain sorghum in the state. Much of this production is due to irrigation, with 150% yield increases over dryland typical (TASS, 2002). Irrigated agriculture in the region, however, is dependent on groundwater withdrawals from the Ogallala aquifer, a finite water resource which is declining because withdrawals have exceeded natural recharge. The rate of water table decline has been reduced in recent decades, principally from reductions in irrigated area, but also by conversion from furrow (gravity) to more efficient center pivot sprinkler irrigation systems (Musick et al., 1990). The earlier sprinkler configurations were high-pressure impact, but these have been replaced by low-pressure spray since the early 1980s and low energy precision applicators (LEPA, Lyle and Bordovsky, 1983) since the later 1980s (Musick et al., 1988).

Numerous studies have been conducted to document and compare the performance of various sprinkler application methods. 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 (0, 40, 60, 80, and 100% of crop evapotranspiration, or ET). They observed no runoff for the spray method using furrow dikes for all irrigation levels, and no runoff for any sprinkler-tillage method combination for the 40% irrigation level. Grain yields and water use efficiencies were significantly reduced with increasing runoff. For full irrigation (100% replenishment), runoff losses averaged 12% for spray without dikes, 22% for LEPA with dikes, and 52% for LEPA without dikes. They pointed out that as the seasons progressed, the furrow dikes eroded, decreasing soil water storage capacity on the 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 these pathways are carefully evaluated in order to select the most appropriate sprinkler package.

Microirrigation is another irrigation technology that can be highly efficient, with subsurface drip irrigation (SDI) being the most common form of microirrigation for row crops.

With proper design, maintenance, and management, many of the water loss pathways described for spray and LEPA may be eliminated using SDI. Camp (1998) reviewed published research on SDI and noted that crop yields were equal or exceeded those of other irrigation systems, and water use was significantly less. Ayars et al. (1999) reviewed fifteen years of SDI research at the USDA-ARS Water Management Research Laboratory in Fresno, CA and also noted significant increases in water use efficiency (WUE), either from increased yield, reduced water use, or both, although they only compared SDI with furrow systems. In the Southern High Plains of Texas, Bordovsky and Lyle (1998) reported that both lint yields and WUE for three seasons of cotton were significantly greater for SDI than LEPA and attributed this difference to greater soil evaporative losses for LEPA; however, Segarra et al. (1999) report economic returns were greater for LEPA because of the greater capital costs of SDI. Later, Bordovsky (2001) compared WUE for two additional seasons of cotton using spray, LEPA, and SDI and reported that average WUE for SDI was 19% greater than LEPA and 22% greater than spray. These cotton studies were conducted on a moderately permeable Olton loam soil.

Yields, water use efficiency (WUE), and irrigation water use efficiency (IWUE) for various spray and LEPA configurations with full and deficit irrigation have been compared for several grain crops in the Southern High Plains at the USDA Conservation and Production Research Laboratory in Bushland, Texas. In these studies, WUE is defined as the ratio of the economic yield (Y) to seasonal water use (irrigation applied + rain + change in soil water storage), or WUE = $Y\ (ET)^{-1}$. The irrigation water use efficiency (IWUE) is defined as the increase in irrigated yield (Y_i) over dryland yield (Y_d) due to irrigation (IR), or IWUE = $(Y_i - Y_d)\ IR^{-1}$ (Bos, 1980). The studies documented corn (Schneider and Howell, 1998), winter wheat (Schneider and Howell, 1997, 2001), and grain sorghum (Schneider and Howell, 1995) and are summarized in Schneider and Howell (1999). The responses of corn and winter wheat generally did not differ significantly between spray and LEPA methods within an irrigation level, but did vary significantly across irrigation levels. For grain sorghum, the LEPA response was more favorable, especially with increasing irrigation deficits (i.e., 25 and 50% of full irrigation). These studies were all conducted on a slowly permeable Pullman clay loam soil. Microirrigation research (both surface and subsurface drip) has also been conducted at this location and soil but only for corn and soybean (Howell et al., 1997a; Evett et al., 2001); however, SDI has not been directly compared with the spray or LEPA methods.

The objectives of this research were to compare grain sorghum yield response, seasonal water use, WUE, and IWUE using two spray configurations (mid- and low-elevation spray application, MESA and LESA, respectively), LEPA, and SDI across four levels of irrigation capacities.

Procedure

Site Description

The research was conducted at the USDA Conservation and Production Research Laboratory in Bushland, TX (35º 11' N lat., 102º 06' W long., 1170 m elevation M.S.L.), during the 2000, 2001, and 2002 seasons. The soil was a Pullman clay loam (fine, mixed, thermic torrertic Paleustolls) with slow permeability, having a dense B21t layer from about 0.15- to 0.40-m depth and a calcic horizon that begins at about 1.2- to 1.5-m depth (Taylor et al., 1963; Unger and Pringle, 1981). Respective upper and lower limits of plant available water in the 1.8-m profile have been reported as 623- and 350-mm (Taylor et al., 1963), 575- and 362-mm (Musick and Sletten, 1966), and 603- and 387-mm (J.A. Tolk, unpublished data). The field had uniform slopes of 0.0025 m m^{-1} or less parallel and perpendicular to the rows.

The climate is semi-arid with a high evaporative demand of about 2600 mm per year (Class A pan evaporation) and low precipitation of 470 mm per year (63-year average). Most evaporative demand and precipitation occurs during the growing season (May to September) and are 1550 mm and 320 mm, respectively. Strong advection of heat energy from the South and Southwest is typical, especially during March through June when average 24-hr wind runs at a 2-m height exceed 460 km.

Agronomy

Agronomic practices were similar to those used for high-yield grain sorghum production on commercial farms in the Southern High Plains and are described in table 1. Grain sorghum (*Sorghum bicolor* (L.) Moench Pioneer 84G62) was planted in the 2000, 2001, and 2002 growing seasons on east-west oriented raised beds spaced 0.76 m. In 2001, two plantings (22 May and 5 June) of this variety failed to emerge, so a shorter season variety (Pioneer 8966) was planted on 22 June and emerged by 2 July. In all years, spray (mid-elevation spray applicator, MESA) irrigations were applied uniformly to the entire field after planting to ensure germination and prevent soil crusting that would inhibit emergence. It is thought that the first two plantings in 2001 failed to emerge because of excessive herbicide residual from the previous year, so in 2002 a different herbicide that was successful in earlier studies (Schneider and Howell, 1999), was used.

Prior to planting, beds were formed using a disk bedder followed by a rolling cultivator (to incorporate preplant fertilizer and herbicide) and were firmed using a bed roller. After the last cultivation, all furrows were diked using a Sunco (Sunco Marketing, North Platte, NE) propeller diker that formed dikes at a 45° angle with the furrows. This design allows easier movement of harvesting equipment through the field. A 25-mm irrigation using the MESA spray heads was applied to settle and firm the furrow dikes.

Preplant fertilizers containing nitrogen and phosphorous (10-34-0 or 32-0-0) were applied at rates based on soil samples tested by a commercial soils testing laboratory, and herbicide was applied for weed control. Additional nitrogen (liquid urea 32-0-0) was injected into the irrigation water between flag leaf and boot stage in 2000 and 2001. Deficit irrigation plots received proportionately less. The low nitrogen application in 2000 reflects high residual nitrogen in the previously fallowed soil, and only preplant nitrogen was necessary in 2002. Phosphorus applications were low and needed only in 2000 and 2002 because the Pullman clay loam soil contains a high inherent phosphorus level, which is not readily leached. Lorsban was applied on 23 August 2000 to control greenbugs (*Schizaphis graminum*), which reached a threshold population by mid-season (soft to hard dough stage). Greenbug populations remained below yield-reducing thresholds in 2001 and 2002.

Grain yields were measured by harvesting the full length of each plot (25 m) using a Hege (Hege Equipment, Inc., Colwick, KS) combine with a 1.52-m wide (2-row) header. Each plot sample was weighed and three subsamples were dried to determine moisture content. Grain yields reported here were converted to 14% moisture content by mass. Three 500-seed subsamples were also weighed to determine seed mass.

Experimental Design

The experimental treatments consisted of four irrigation *methods* and five irrigation *levels* replicated three times. The irrigation *methods* were low-energy precision applicator (LEPA), low-elevation spray applicator (LESA), mid-elevation spray applicator (MESA), and subsurface drip irrigation (SDI). The LEPA, LESA, and MESA devices were aboard a self-propelled 3-span lateral-move system. The irrigation equipment is described in more detail in the next section. The irrigation *levels* included a full amount and four deficit levels (designated I_{100}, I_{75}, I_{50}, I_{25}, and I_0 respectively). The I_{100} level was sufficient to prevent soil water deficits that would limit yield from developing, based on crop evapotranspiration (ET_c) estimates from the North Plains ET Network (Howell et al., 1998). The ET_c was computed as the product of a grass reference evapotranspiration (ET_o) and a single crop coefficient (K_c). The ET_o was computed using the American Society of Civil Engineers (ASCE) Standardized ET equation (Walter et al., 2002) using weather data measured at Bushland. The K_c value was locally derived using lysimeter studies of grain sorghum (Steiner et al., 1991; Howell et al., 1997b). The subscripts of the deficit irrigation levels are the percentage of the full level of crop ET. The I_0 level received sufficient irrigation only for emergence and to set furrow dikes, and represents dryland production. The deficit levels simulate low-yielding wells common in the region where a given area is not fully irrigated (Musick et al., 1988) and establishes WUE and IWUE relationships (Howell, 2001).

The experimental design was a variant of the split-block design (Little and Hills, 1978). Irrigation methods were in strips along the direction of travel (E-W, same as row direction) of the 3-span lateral move system, where each span covered a single block and methods were randomized for each block replicate (applicator devices over the SDI strips were removed and drop hoses plugged after crop emergence). Irrigation levels were in strips perpendicular to the methods and were implemented by changing the speed of the lateral move. This sacrificed the precision in comparing different irrigation levels, but was necessary to facilitate operation of the lateral move system using commercially available applicator devices commonly used in the Southern High Plains. Plots were 25-m long by 9-m wide with 12 rows each; irrigation level strips were separated by a 5-m border.

Irrigation Equipment

Spray and LEPA irrigations were applied with a hose-fed, 3-span Valmont (Valmont Irrigation, Valley, NE) Model 6000 lateral move irrigation system. The system had a diesel-electric power plant with a CAMS control panel for speed control. Each span was 39-m long and irrigated forty-eight 0.76-m spaced rows (thirty-six after SDI treatments initiated). The applicator devices were located above alternate furrows (1.52-m spacing), so there were 24 applicators per span or 72 applicators total (18 per span and 54 total after SDI treatments initiated). Applicator device details are in table 2. The applicator nozzles were sized to apply 6.25 mm when the lateral move system was operated at full speed and 25 mm at 25% of full speed, so that precipitation rates were similar to those at the outer span of a typical 400-m long center pivot with a flow rate of about 42 L s^{-1} (7 mm d^{-1} or 0.84 L ha^{-1} s^{-1}).

The SDI equipment consisted of Netafim (Netafim USA, Fresno, CA) Typhoon dripline. The dripline was chiseled under alternate furrows (1.52-m spacing and 6 drip lines per 12-row replicate) to a depth of 0.30 m. The dripline was connected to PVC pipe laterals (50-mm ID) at the delivery and collector ends, with one lateral per replicate. Each delivery lateral had its own valve, flow meter, and flow volume totalizer, and each collector lateral had its own flush out valve. Different irrigation levels were established using different emitter flow rates and spacing in the dripline (table 3). This design allowed all 12 SDI plots to be irrigated simultaneously using only three delivery and collector laterals.

Irrigation Procedure

Irrigation dates and amounts are summarized in table 1. All plots received pre-treatment uniform irrigations with MESA spray heads to ensure germination, emergence, and to set and firm the furrow dikes. These totaled 62 mm, 112 mm, and 62 mm in 2000, 2001, and 2002, respectively. The greater amount of irrigation in 2001 was due to emergence problems described earlier. After furrow dikes were set, the treatment application method was used, and treatment irrigation levels were applied. Sprinkler treatment irrigations were scheduled when cumulative ET for fully irrigated grain sorghum (I_{100}) reached 25 mm (minus any rainfall) as computed by the North Plains ET Network. All sprinkler plots were irrigated on the same day, with the deficit 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 on a daily basis in smaller amounts.

Soil Water Measurements

Gravimetric soil water samples were taken in each plot to determine seasonal soil water depletion to a depth of 1.8 m in 0.3 m increments just prior to planting and shortly following harvest (table 1) (bottom sample was centered at 1.65-m depth and extended from 1.5 to 1.8 m.). Soil water was also measured volumetrically several times during each growing season using a CPN Model 503DR (Campbell Pacific Nuclear, Martinez, CA) neutron soil moisture meter. Measurements (30-s sampling time) were taken from 0.1-m to 2.3-m depths in 0.2-m increments in the I_{50} and I_{100} plots only. This allowed verification that irrigation scheduling was adequate and that gravimetric samples were reasonable. The meter was calibrated according to procedures of Evett and Steiner (1995) with three separate calibrations for each distinct layer (0.1 m, 0.3 to 1.1 m [Bt], and 1.3 to 2.3 m [Btca] depths). Respective coefficients of determination (r^2) were 0.993, 0.986, and 0.984, standard errors of estimates were 0.0073, 0.0070, and 0.0073 $m^3 m^{-3}$, and sample sizes were 5, 30, and 35. Calibrations included “wet” and “dry” moisture contents representative of the upper and lower limits of plant extractable water. A depth control stand (Evett, 2003) was used during the calibrations, field measurements, and standard counts.

Statistical Model

Grain yields, seed mass, seasonal water use (total irrigation + rain + change in soil water content), WUE, and IWUE (defined in the Introduction) were tested for differences for each irrigation method using the SAS mixed model (PROC MIXED, Littell et al., 1996). Random effects included block replicates, block by irrigation level, and block by irrigation method, and the fixed effect was the irrigation method. Differences of fixed effects were tested using least square means ($p \leq 0.05$), and means were separated by letter groupings using a macro by Saxton (1998). Denominator degrees of freedom were approximated by the procedure of Kenward and Roger (1997), which reduces Type I errors that may occur with complex linear hypotheses of fixed effects. As error control factors (e.g.: blocks, splits, etc.) are introduced in the experimental design, the number of variance components increases. The SAS mixed model estimates variance components using restricted maximum likelihood (REML); and since each component is an estimate, the sample size decreases (reducing degrees of freedom) as the number of components increases. The Kenward-Roger procedure provides a more conservative approximation of decimal degrees of freedom by inflating the variance-covariance matrix of fixed and random effects and then computing Satterthwaite-type degrees of freedom.

Results

Rainfall and Climate

Figure 1 shows irrigation and cumulative rainfall for the 2000, 2001, and 2002 growing seasons. Cumulative rainfall throughout all three seasons remained below a 63-year (1939-

2002) average at Bushland, TX, with 2000 and 2001 being notable drought years. The 2000 and 2001 growing seasons began with rainfall near average but declined considerably as the seasons progressed. Rainfall during the 2000 season ceased after July 18 (DOY 200), bringing the cumulative total to only 139 mm (table 1). Rainfall distribution was more uniform in 2001, but the total was even less than 2000 at just 124 mm.

Rainfall patterns during the 2002 season were reversed. The 2002 season began with below-average rainfall but become more frequent as the season progressed. A well-timed event of 27 mm occurred five days after planting on June 5 (DOY 156), and 2 mm fell on June 17 (DOY 168). July rainfall was near the monthly average at 63 mm, but August rainfall totaled 114 mm, nearly twice the monthly average of 68 mm. This coincided with the reproductive growth stages (boot, heading, and flowering) of grain sorghum, which are most sensitive to water stress (Lewis et al., 1974). Above average rainfall continued during September and October, delaying harvest until November 14 (DOY 318). By then the seasonal total was 317 mm, but this was still below the 63-year average of 350 mm.

Air temperatures, growing degree days, and basal crop evapotranspiration (basal crop coefficient times reference evapotranspiration) were near a 14-year (1988-2002) average in 2000 and 2001, but were slightly above this average in 2002 (data not shown), especially early in the season. The 2002 crop reached physiological growth stages eight to thirteen days sooner (days since planting) than the 2000 crop. The 2001 crop was replanted with a shorter season variety and developed at nearly the same rate as the longer season 2002 crop.

Soil Water

Figure 2 shows soil water contents in the 1.8-m profile (majority of grain sorghum rooting depth) for the I_{50} and I_{100} irrigation levels of each season. The upper and lower limits of treatment mean profile water content for this study were 655 and 319 mm, respectively. This range of field observed values was about 30 mm outside the upper and lower limits of plant available water reported by Taylor et al. (1963), which were based on laboratory values, and Musick and Sletten (1966), which were based on field observations. In the study of Musick and Sletten (1966), the profile was not as fully wetted as the present study, hence their smaller reported range of profile water contents in their study.

Precipitation before the 2000 and 2001 seasons was sufficient so that preplant irrigations were unnecessary; however, 112 mm of irrigation water was applied before planting in 2002 as very little pre-season precipitation occurred. Gravimetric soil water samples around planting in 2000 and 2001 indicated that water in the 1.8-m soil profile was both plentiful and fairly equal for all treatments, averaging 547 mm total (SD = 25 mm). In 2002, all methods at the I_{50} level (figure 2e) began with only about a half full profile despite preplant irrigations; water contents at the I_{100} level (figure 2f) were larger but less uniform between irrigation methods.

Water availability for irrigation was limited in 2000, sufficient in 2001, and plentiful in 2002. In July and August 2000, there were larger than normal irrigation demands in the area as crop water use had reached a seasonal maximum and rainfall was absent. More water would have been applied had it been available, and seasonal irrigation totals in 2000 would have been greater than 2002 instead of being equal (table 1). In 2001, less irrigation water was required, although the 2001 season had the least rainfall. This was likely due to both the shorter variety of grain sorghum planted and peak water use occurring when atmospheric demand was less compared with 2000.

Figures 3, 4, and 5 show the volumetric soil water profiles for 2000, 2001, and 2002, respectively. Each profile shows a single irrigation method for a given level (I_{50} or I_{100}). The first and last measurements are from gravimetric samples, and the remaining measurements are from neutron scattering, similar to figure 2. The gravimetric samples extend to 1.8 m (increments in 0.3 m with the deepest sample centered at 1.65 m), and the neutron moisture meter measurements extend to 2.4 m (increments of 0.2 m with the deepest measurement centered at 2.3 m).

There was evidence of percolation to at least 2.4-m depth in the SDI I_{100} treatment in 2000, in the LEPA and SDI I_{50} and I_{100} treatments in 2001, and for the I_{100} irrigation level for all irrigation methods in 2002 (Figs. 3-5). Because soil water increased at depth for these treatments, there was probably loss of water to deep percolation; and, because of these increases, it is difficult to assess the depth of soil water extraction for the affected treatments. In the treatments unaffected by deep percolation, extraction depth varied from 1.6 to 2.1 m in 2000 (Figs. 3a and 3b), from 1.35 to 1.65 in 2001 (Figs. 4b and 4d), and from 1.5 to 1.65 m in 2002 (Figs. 5a and 5c). The variable depths of extraction point out that multiple variables can affect extraction depth, such as depth and amount of antecedent soil moisture, rainfall and irrigation patterns, soil variability, and sorghum response to these in terms of rooting pattern. Our data show that sorghum does extract water more deeply than 1.4 m in some years, reversing the conjecture of Musick et al. (1966) that the boundary between the Bt and Btca horizons is the lower limit of sorghum soil water extraction. This result also points up the need to measure soil water deeply in these studies, to greater than 2.1 m.

Figures 3, 4, and 5 suggest that LEPA and SDI are more prone to deep percolation than spray under full irrigation, where “full irrigation” is defined as the amount required to meet 100% of crop evapotranspiration (ET_c). The ET_c was computed as the product of a grass reference evapotranspiration (ET_o) and a single crop coefficient (K_c). The K_c value includes a portion of soil evaporation (both beneath the plant and in the interrows exposed to sunlight) as all of the soil surface was wetted during irrigation when these values were developed. The fraction of soil surface wetted would be less for LEPA (especially for alternately-irrigated interrows) and possibly negligible for SDI; hence, evaporation and ET_c would be less, and the LEPA and SDI plots were probably over-irrigated using the present definition of full irrigation. Indeed, the SDI method tended to develop and maintain more water in the profile than the other methods under deficit irrigation (I_{100} in 2000 and I_{50} in 2001 and 2002), likely because less soil water was lost to evaporation. Differences in irrigation methods could be accounted for by defining new K_c functions specific to LEPA or SDI to reflect the reduction in evaporation, or by accounting for interrow soil evaporation separately using the dual crop coefficient procedure of Food and Agriculture Organization of the United Nations Paper No. 56 (FAO 56, Allen et al., 1998). Tolk and Howell (2001) reported better agreement between crop water use measured with small weighing lysimeters and the dual crop coefficient procedure than with a single crop coefficient. Some water losses might also be avoided by supplementing computed ET_c with soil water measurements in real time when scheduling irrigations, which probably would have reduced the over-application of irrigation water, especially in 2002.

Grain Yield and Water Use

Grain yields, seed mass, soil water depletion, seasonal water use, WUE, and IWUE for 2000, 2001, and 2002 are shown in tables 4, 5, and 6, respectively. Results are described by low irrigation capacity (I_{25} and I_{50} levels) and high irrigation capacity (I_{75} and I_{100} levels).

I_{25} and I_{50} Irrigation Levels

For low irrigation capacity, the SDI method had the highest grain yield, WUE, and IWUE compared with the other three methods for all three seasons; however, large and timely rainfall events in 2002 greatly enhanced yield and masked differences among methods within all levels, and between levels at I_{50} and greater. Grain yield ranged from 2.69 to 7.36 Mg ha^{-1} during 2000 and 2001 (tables 4 and 5), but was nearly 12 Mg ha^{-1} during 2002 for the SDI I_{50} treatment (table 6). The relative rankings of WUE and IWUE followed similar patterns as grain yield, with SDI ranking the highest. The IWUE for SDI at the I_{25} level in 2002 was the largest of the entire study at 6.34 kg m^{-3}. Seed mass was not significantly different between methods except during 2001, when mass for the spray methods was less than for LEPA or SDI in the I_{25} irrigation level only. Seed mass ranged from 17 to 22 mg during 2000 and 2001 but was much greater for 2002, ranging from 28 to 32 mg.

Soil water depletion was not significantly different between methods within the I_{25} or I_{50} level for any season. (Negative soil water depletion in table 6 indicates increases in soil water from rainfall late in the 2002 season). Seasonal water use also was not significantly different between methods within a level, except in 2002 for the I_{25} level where SDI used considerably more water but yield was also much greater than the spray or LEPA methods (table 6). All SDI treatments in 2002 began with more soil water in their profiles than the other methods, likely because less water was lost to bare soil evaporation following preplant irrigations. This is illustrated in figure 6 for the I_{25} level (also see figures 2e and 2f for the I_{50} and I_{100} levels, respectively; and recall that water contents were not measured during the season for the I25 and I75 levels). The SDI treatment at planting had 470 mm of water in the 1.8-m profile, but the other methods had less than 440 mm; soil water contents at harvest ranged from 428 mm to 439 mm. With the exception of the I_{25} level in 2002, the differences in WUE and IWUE were more due to yield differences rather than differences in water use, although SDI appears to have benefited the most from rainfall in 2002.

In 2002, grain yield for the LESA method was less than all other methods at the I_{25}, I_{50}, and I_{75} irrigation levels (table 6). This yield reduction was significant compared with MESA and SDI at the I_{25} level and significant compared with all methods at the I_{50} level. The LESA method at the I_{50} level also had the most soil water depletion (30 mm) and seasonal water use (622 mm) in the 1.8 m profile, although these were not significantly greater than the other methods. As noted previously in figure 2e (I_{50} level in 2002), soil water in the LESA treatment decreased more than other methods between 12 June and 29 July, but never fell below that for the LEPA treatment. The lower grain yield for LESA might be explained by less available soil water during reproductive stages (Late July to early August); however, the cause of rapidly declining soil water is not clear. Perhaps runoff or excessive erosion of furrow dikes occurred, but this would not be expected for spray with deficit irrigation (Schneider and Howell, 2000). From figure 2e, however, the LEPA soil water profile at the I_{50} level was less than or equal to LESA throughout the season, but LEPA had yields similar to MESA and SDI. Perhaps plants irrigated with LESA initially developed more rapidly than plants irrigated with LEPA, but could not adapt to reduced soil water as well as the plants under LEPA that developed with less available water throughout the season.

I_{75} and I_{100} Irrigation Levels

For larger simulated irrigation capacities, the spray irrigation methods had greater grain yield, WUE, and IWUE than LEPA or SDI for all three seasons. This trend was not always significant, especially in 2002 (table 6) when rainfall masked differences between the I_{50}, I_{75} and I_{100} levels. For these three levels, yields exceeded 11 Mg ha^{-1}. The largest yield during the entire study was 12.20 Mg ha^{-1} for MESA at the I_{75} level. This treatment also had the largest WUE of the entire study at 2.18 kg m^{-3}. Seed mass, soil water depletion, and seasonal water use was greater for spray than for LEPA or SDI in 2000 (table 4). In 2001, this pattern was observed only for soil water depletion and seasonal water use at the I_{100} level (table 5). In 2002, SDI used more water for the season (802 mm) than not only the other methods at the I_{100} level, but also for the entire three seasons (table 6).

As discussed previously, both SDI and LEPA appear more prone to deep percolation under the present definition of full irrigation (100% replacement of computed evapotranspiration). This might cause greater leaching of nutrients below the root zone, which in turn could reduce grain yield. For example, the I_{75} level had slightly larger grain yields than the I_{100} level in 2002 (Table 6). We also speculate that enhanced yields with spray at the I_{75} and I_{100} levels could be linked to greater partitioning of water to evaporation from droplets intercepted by the crop canopy. Larger humidity values within the 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.

An exception to the grain yield, WUE, and IWUE patterns occurred in 2002 for LESA at the I_{75} level (table 6), where grain yield was numerically less (10.77 Mg ha^{-1}) than the other methods and soil water depletion and seasonal water use were significantly greater than MESA but not LEPA or SDI. This resulted in WUE of LESA being significantly less than MESA but not LEPA or SDI; IWUE of LESA was also the least but only numerically. As noted previously, the grain yield reduction of LESA was more pronounced at the I_{25} and I_{50} levels.

Averages by Irrigation Level and Method

The lower portions of tables 4, 5, and 6 show the respective 2000, 2001, and 2002 average of each parameter by irrigation level and method. For all three seasons, differences in grain yield, seed mass, seasonal water use, WUE, and IWUE were greater across irrigation levels than irrigation methods. The largest WUE occurred at the I_{75} and I_{100} levels in 2000 and at the I_{50} and I_{75} levels in 2001 and 2002. These ranged from 1.31 to 1.35 kg m^{-3} in 2000 and 2001 and were 1.92 to 1.94 kg m^{-3} in 2002. The smallest WUE occurred for dryland (I_0) for all three seasons, ranging from 0.19 to 0.69 kg m^{-3}. For all three seasons, the greatest IWUE occurred at the I_{50} level and smallest at the I_{100} level. These ranged from 2.00 to 2.53 kg m^{-3}, 1.50 to 2.13 kg m^{-3}, and 2.35 to 4.11 kg m^{-3} in 2000, 2001, and 2002, respectively.

Despite irrigation level generally showing a greater influence than irrigation method for most parameters, the SDI method used less water in 2000 and 2001 and had the largest yield, WUE, and IWUE all three seasons. In 2000 (table 4), the seasonal water use was significantly less than all other methods, resulting in WUE being significantly greater. In 2002 (table 6), the seasonal water use of SDI was greater than the other methods, but so were WUE and IWUE. Thus the more desirable performance of SDI relative to spray at lower irrigation levels compensated for the less desirable performance at higher irrigation levels.

Grain Yield – Seasonal Water Use Relationships

Grain yield as a function of seasonal water use is illustrated in figure 7. A single linear function adequately describes all treatments in 2000, 2001, and the I_0 and I_{25} levels only in 2002. The I_{50}, I_{75}, and I_{100} levels in 2002 were separated because rainfall removed any significant grain yield response to irrigation level and water use. This leads us to believe that water use in 2002 included some loss to deep percolation, as discussed previously, and some luxury consumption by the crop. The significant production function in figure 7 shows a 262 mm water use threshold to initiate grain production and an increase of 2.05 kg of grain per m^3 of water for water use exceeding 262 mm. Table 7 shows production functions for grain sorghum from previous studies at Bushland, TX and Tryon, NE using surface, spray, LEPA, and line sprinkler irrigation. The slope and water use threshold for grain production of the present study are greater than those in table 7; hence, there was a greater increase in grain production per unit water used once the threshold water use was exceeded. Howell et al. (1995) and Schneider and Howell (1998) propose that slopes of production functions may better represent physiological water use efficiency of grain than do WUE or IWUE ratios.

Figure 8 is the same data as figure 7, except the production function is further separated by irrigation method, and dryland (I_0) was excluded from the regressions. A single linear function could describe the spray (MESA and LESA) methods, which was not much different from that of figure 7. LEPA had a slightly different function, but the SDI function was significantly different. The water use slopes decreased for LEPA and SDI, respectively, indicating that grain production becomes less responsive to increasing water use when converting from spray to LEPA to SDI. Thus the slopes of the production functions also reflect the efficiency of the irrigation method (in addition to plant physiological water use efficiency). This illustrates potential advantages of LEPA and SDI over spray in controlling evaporative losses as irrigation water capacity decreases. The slope of the LEPA function (0.0176 Mg ha^{-1} mm^{-1}) was similar to that of Schneider and Howell (1995) for spray and LEPA (0.0184 Mg ha^{-1} mm^{-1}) in table 7; they also reported higher IWUE for mid-level deficit irrigation using LEPA.

Figure 9 shows WUE as related to grain sorghum yield, where the 2002 I_{50}, I_{75}, and I_{100} treatments were separated from the rest of the data as was done in figures 7 and 8. The curvilinear function is similar to a function for winter wheat given by Musick et al. (1994). The non-linearity is the result of the water use threshold to initiate grain production and demonstrates that large yields are required to achieve large WUE, but this carries a strong diminishing production return up to a maximum yield. The yield corresponding to maximum WUE is 10.0 Mg ha^{-1} with WUE = 1.51 kg m^{-3}. Tremendous increases in grain yield result in moving from dryland to very low capacity irrigation, which illustrates the critical role irrigation plays in efficient crop production.

Discussion

The results of the present three-year study represent the typically wide range of climatic conditions that can be expected in the Southern High Plains. Drought persisted in two out of three years (2000 and 2001), allowing each irrigation method to be evaluated under relatively demanding conditions. The 2001 season was shorter due to a late start, which further allowed study of conditions likely to be encountered in production agriculture. The 2002 season began relatively hotter and dryer than the previous two seasons, but received significant rainfall during critical reproductive stages. This allowed evaluation of rainfall utilization for each irrigation method.

In all three seasons, SDI had larger yields, WUE, and IWUE than the LEPA or spray (MESA or LESA) methods at smaller irrigation capacities (I_{25} and I_{50}), with the spray methods essentially equal and LEPA generally performing as well as or better than spray. At very low capacities (I_{25}), SDI significantly out-yielded all other methods, and clearly better utilized rainfall in 2002, when grain yield (9.22 Mg ha^{-1}) approached that of high capacity irrigation in other years. This trend was reversed for larger irrigation capacities (I_{75} and I_{100}), for which spray outperformed SDI and LEPA.

At small irrigation capacities, differences in WUE or IWUE between methods were mainly due to grain yield differences and not differences in water use, whereas at larger irrigation capacities, both grain yield and water use differences were sometimes observed. It appears that at low irrigation capacities, the SDI and to a lesser extent LEPA methods reduce soil evaporation and permit more partitioning of water to plant transpiration compared with spray, which would enhance grain yield. At larger irrigation capacities, application rates of spray were sufficient so that any wind or evaporative loss would not reduce grain yield, and perhaps even could enhance yield by enhancing respiration due to the humidification of the canopy, which would reduce stomatal closure. The higher application rates using LEPA and SDI, however, did induce deep percolation, which could reduce yield by leaching nutrients below the root zone. The larger irrigation capacities could also induce runoff for LEPA and reduce soil water content relative to other methods (Schneider and Howell, 2000), but soil water profile measurements suggested this occurred only in 2000 for full irrigation.

Either from a proactive or reactive basis, management of low capacity irrigation systems will become more crucial to maintain efficient crop production in regions dependent on irrigation water from the Ogallala aquifer. The data presented here illustrate the potential for SDI under such conditions, in that reductions in yield due to declining irrigation well capacity can be abated by converting from spray to SDI. Adoption of SDI remains limited primarily because of higher capital costs, but also because data required for robust economic comparisons are lacking. Lamm et al. (2002) presented an economic comparison between center pivots and SDI for corn in Western Kansas and found, among other things, that results were “very sensitive to higher potential yields with SDI,” implying that the success of such an analysis is contingent on possessing data such as that presented here.

Conclusions

At 25% and 50% of full irrigation, grain sorghum yields, water use efficiency (WUE), and irrigation water use efficiency (IWUE) for subsurface drip irrigation (SDI) were larger than low energy precision applicator (LEPA) and spray irrigation methods. Performance of LEPA was generally equal to or better than spray. At 25% of full irrigation, performance of SDI was significantly better than all other irrigation methods. Water use mostly was not different between methods within an irrigation level, but SDI and LEPA appear to partition more water to transpiration and less to soil evaporation, which enhances grain yield.

At 75% and full irrigation, grain yield, WUE, and IWUE for spray irrigation methods were larger than for LEPA or SDI. Water use was sometimes significantly different between methods within an irrigation level, with water use often greater for spray. Spray application rates appear to be sufficient such that grain yield is not reduced if wind drift or evaporative losses occur. Yield for spray may have been enhanced by enhanced respiration due to humidification of the canopy and consequent reduction in stomatal closure. Considerable deep percolation was observed for SDI and to a lesser extent LEPA, which could reduce yields by leaching nutrients below the root zone. Deep percolation and perhaps yield losses might be reduced by establishing separate definitions of full irrigation for LEPA and SDI that account for more partitioning of ET into transpiration and less to evaporation.

The largest WUE occurred at 50 to 75% of full irrigation, and the smallest WUE occurred for dryland. The largest IWUE occurred at 50% of full irrigation. It appears the most efficient use of water and other resources for grain sorghum production is to irrigate the crop at 50% of full irrigation.

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Table 1. Agronomic and irrigation data for 2000, 2001, and 2002.

Variable	**2000**	**2001**	**2002**
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
Herbicide applied	4.7 L ha^{-1} Bicep	4.7 L ha^{-1} Bicep	1.6 kg ha^{-1} Atrizine
Insecticide applied	0.58 L ha^{-1} Lorsban	none	none
Gravimetric soil water samples	19 May 11 Oct	21 May 30 Oct	3 Jun 18 Nov
Grain sorghum variety	Pioneer 84G62	Pioneer 8966	Pioneer 84G62
Plant density	30 plants m^{-2}	23 plants m^{-2}	22 plants m^{-2}
Planting date	26 May	22 Jun[b]	31 May
Harvest date	7 Oct	29 Oct	14 Nov
Emergence irrigations	27 May – 25 mm 31 May – 12 mm	30 May – 12 mm 11 Jun – 12 mm 22 Jun – 12 mm 25 Jun – 12 mm 27 Jun – 12 mm 9 Jul – 25 mm	7 Jun – 13 mm 13 Jun – 12 mm 21 Jun – 12 mm
Irrigations to set furrow dikes	20 Jun – 25 mm	19 Jul – 25 mm	7 Jul – 25 mm
First treatment irrigation	12 Jul	24 Jul	8 Jul
Last irrigation	28 Aug	11 Sep	8 Sep
I_0 total irrigation	62 mm	112 mm	62 mm
I_{25} total irrigation	169 mm	194 mm	169 mm
I_{50} total irrigation	275 mm	275 mm	275 mm
I_{75} total irrigation	381 mm	356 mm	381 mm
I_{100} total irrigation	488 mm	438 mm	488 mm
Precipitation	139 mm	124 mm	317 mm

[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 Jun failed to emerge.

Table 2. 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 (Senninger Irrigation, Inc., Orlando, Florida) except where noted.

[b] All devices equipped with 69 kPa pressure regulators and #17 (6.75 mm) plastic spray nozzles, giving a flow rate of 0.412 L s^{-1}.

[c] A.E. Quest and Sons, Lubbock, TX.

Table 3. Subsurface drip irrigation (SDI) dripline information.[a]

Irrigation Level	**Emitter Flow Rate (L hr^{-1})**	**Emitter spacing (m)**	**Emitter application rate (mm hr^{-1}) at 69 kPa**
I_0	Smooth tubing – no emitters		
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	0.30	1.93

[a] All SDI dripline manufactured by Netafim (Netafim USA, Fresno, CA).

Table 4. Measured and computed parameters as affected by irrigation levels and methods in 2000.

Irrigation Level [a]	**Irrigation Method**	**Yield[b] (Mg ha^{-1})**	**Seed mass (mg)**	**Soil water depletion (mm)**	**Seasonal water use (mm)**	**WUE (kg m^{-3})**	**IWUE (kg m^{-3})**
I_0 (62 mm)	-----	0.63	20	196	397	0.19	-----
I_{25} (169 mm)	MESA	2.69c[c]	19a	159a	467a	0.63c	1.57c
I_{25}	LESA	3.11bc	19a	174a	482a	0.70bc	1.89bc
I_{25}	LEPA	3.58b	20a	173a	481a	0.81b	2.25b
I_{25}	SDI	4.51a	20a	153a	461a	1.07a	2.94a
I_{50} (275 mm)	MESA	6.22b	20a	163a	576a	1.15b	2.35b
I_{50}	LESA	6.25b	21a	163a	577a	1.16b	2.37b
I_{50}	LEPA	6.80ab	21a	157a	571a	1.27ab	2.60ab
I_{50}	SDI	7.36a	22a	159a	574a	1.37a	2.82a
I_{75} (381 mm)	MESA	9.14a	25a	173a	693a	1.39a	2.48a
I_{75}	LESA	8.93a	24ab	167a	687a	1.39a	2.41a
I_{75}	LEPA	8.00b	22b	155ab	675ab	1.25b	2.14a
I_{75}	SDI	8.57ab	23ab	134b	656b	1.37ab	2.30a
I_{100} (488 mm)	MESA	10.51a	27a	150a	777a	1.42a	2.20a
I_{100}	LESA	10.08a	27a	157a	783a	1.35a	2.10a
I_{100}	LEPA	8.86b	24b	148a	774a	1.20b	1.83a
I_{100}	SDI	9.09b	24b	104b	733b	1.31ab	1.87a
Irrigation level averages.							
I_0 (62 mm)	-----	0.63e[d]	20c	196a	397e	0.19d	-----
I_{25} (169 mm)	-----	3.47d	20c	165b	472d	0.80c	2.16bc
I_{50} (275 mm)	-----	6.65c	21c	161bc	575c	1.24b	2.53a
I_{75} (381 mm)	-----	8.66b	24b	158bc	678b	1.35a	2.33ab
I_{100} (488 mm)	-----	9.63a	25a	140c	767a	1.32ab	2.00c
Irrigation method averages.							
-----	MESA	7.14a[e]	23a	161a	628a	1.15b	2.15b
-----	LESA	7.09a	23ab	165a	632a	1.15b	2.19ab
-----	LEPA	6.81a	21b	158a	625a	1.13b	2.20ab
-----	SDI	7.38a	22ab	137b	606b	1.28a	2.48a

[a] Numbers in parentheses are seasonal irrigation totals for each irrigation level (mm).

[b] Yields converted from dry mass to 14% moisture content by mass.

[c] Numbers followed by the same letter are not significantly different ($p \leq 0.05$) within an irrigation level.

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

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

Table 5. Measured and computed parameters as affected by irrigation levels and methods in 2001.

Irrigation Level [a]	Irrigation Method	Yield[b] (Mg ha^{-1})	Seed mass (mg)	Soil water depletion (mm)	Seasonal water use (mm)	WUE (kg m^{-3})	IWUE (kg m^{-3})
I_0 (112 mm)	-----	1.86	15	163	382	0.69	-----
I_{25} (194 mm)	MESA	3.14b[c]	17b	139a	439a	0.89b	1.20b
I_{25}	LESA	2.89b	17b	134a	434a	0.83b	0.96b
I_{25}	LEPA	3.25b	19a	151a	451a	0.89b	1.31b
I_{25}	SDI	4.70a	20a	131a	433a	1.38a	2.63a
I_{50} (275 mm)	MESA	5.22b	20a	158a	539a	1.16b	1.79b
I_{50}	LESA	5.81ab	20a	134a	515a	1.36ab	2.10ab
I_{50}	LEPA	5.66ab	20a	139a	520a	1.31ab	2.02ab
I_{50}	SDI	6.81a	21a	132a	517a	1.59a	2.59a
I_{75} (356 mm)	MESA	6.87a	21a	147a	609a	1.32a	1.86a
I_{75}	LESA	7.07a	21a	143a	606a	1.36a	1.94a
I_{75}	LEPA	6.45a	21a	146a	609a	1.31a	1.71a
I_{75}	SDI	6.20a	21a	96b	564b	1.24a	1.58a
I_{100} (438 mm)	MESA	7.93a	21a	113a	657a	1.40a	1.73a
I_{100}	LESA	7.36ab	21a	113a	657a	1.30a	1.57a
I_{100}	LEPA	6.88ab	21a	78b	622b	1.29a	1.43a
I_{100}	SDI	6.43b	21a	93ab	645ab	1.15a	1.28a
Irrigation level averages.							
I_0 (62 mm)	-----	1.86d[d]	15c	163a	382e	0.69c	-----
I_{25} (169 mm)	-----	3.49c	18b	139a	439d	1.00b	1.53b
I_{50} (275 mm)	-----	5.87b	20a	141a	523c	1.35a	2.13a
I_{75} (381 mm)	-----	6.65a	21a	133a	597b	1.31a	1.77ab
I_{100} (488 mm)	-----	7.15a	21a	99b	645a	1.28a	1.50b
Irrigation method averages.							
-----	MESA	5.79a[e]	20b	139a	561a	1.19a	1.65a
-----	LESA	5.78a	20ab	131a	553a	1.21a	1.64a
-----	LEPA	5.56a	20b	129a	550a	1.18a	1.62a
-----	SDI	6.04a	21a	113a	540a	1.36a	2.02a

[a] Numbers in parentheses are seasonal irrigation totals for each irrigation level (mm).

[b] Yields converted from dry mass to 14% moisture content by mass.

[c] Numbers followed by the same letter are not significantly different ($p \leq 0.05$) within an irrigation level.

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

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

Table 6. Measured and computed parameters as affected by irrigation levels and methods in 2002.

Irrigation Level [a]	**Irrigation Method**	**Yield**[b] **(Mg ha^{-1})**	**Seed mass (mg)**	**Soil water depletion (mm)**	**Seasonal water use (mm)**	**WUE (kg m^{-3})**	**IWUE (kg m^{-3})**
I_0 (62 mm)	-----	0.86	25	-22	358	0.28	-----
I_{25} (169 mm)	MESA	5.43b[c]	29a	-15a	471b	1.26b	3.48b
I_{25}	LESA	3.21c	28a	6a	492ab	0.70c	1.79c
I_{25}	LEPA	5.26bc	28a	-6a	480b	1.19b	3.35b
I_{25}	SDI	9.22a	29a	32a	543a	1.90a	6.34a
I_{50} (275 mm)	MESA	11.39a	31a	-22a	569a	2.15a	4.43a
I_{50}	LESA	8.19b	31a	30a	622a	1.39b	3.09b
I_{50}	LEPA	11.07a	31a	6a	598a	1.97a	4.30ab
I_{50}	SDI	11.89a	32a	-6a	612a	2.16a	4.61a
I_{75} (381 mm)	MESA	12.20a	32a	-98b	600b	2.18a	3.30a
I_{75}	LESA	10.77a	31a	-34a	664a	1.73b	2.88a
I_{75}	LEPA	11.77a	31a	-53ab	645ab	1.94ab	3.17a
I_{75}	SDI	11.54a	31a	-59ab	666a	1.91ab	3.09a
I_{100} (488 mm)	MESA	11.70a	32a	-61a	743ab	1.66a	2.41a
I_{100}	LESA	11.43a	31a	-70a	734b	1.65a	2.35a
I_{100}	LEPA	11.42a	30a	-70a	734b	1.64a	2.35a
I_{100}	SDI	11.29a	30a	-30a	802a	1.53a	2.30a
Irrigation level averages.							
I_0 (62 mm)	-----	0.86c[d]	25b	-22ab	358e	0.28d	-----
I_{25} (169 mm)	-----	5.78b	29ab	4a	496d	1.26c	3.74ab
I_{50} (275 mm)	-----	10.63a	31a	2a	600c	1.92a	4.11a
I_{75} (381 mm)	-----	11.57a	31a	-61b	644b	1.94a	3.11bc
I_{100} (488 mm)	-----	11.46a	31a	-58b	754a	1.62b	2.35c
Irrigation method averages.							
-----	MESA	10.18a[e]	30a	-49b	596c	1.81a	3.41a
-----	LESA	8.40b	31a	-17a	628ab	1.37b	2.53b
-----	LEPA	9.88ab	30a	-30ab	614bc	1.69a	3.29ab
-----	SDI	10.99a	31a	-16a	656a	1.88a	4.09a

[a] Numbers in parentheses are seasonal irrigation totals for each irrigation level (mm).

[b] Yields converted from dry mass to 14% moisture content by mass.

[c] Numbers followed by the same letter are not significantly different ($p \le 0.05$) within an irrigation level.

[d] Numbers followed by the same letter are not significantly different ($p \le 0.05$) between irrigation level averages.

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

Table 7. Grain sorghum production functions from selected studies.

Location and Reference	Years of Study	Variety	Irrigation Method	Production function[a]
Bushland, TX [b]				
Musick and Dusek (1971)	1963-1965	RS-610 (1963-64); RS-626 (1965)	Level border	GY = 0.0139(ET - 44)
Stewart et al. (1983)	1979-1981	Northrup King 2778 (1979); DeKalb DK57 (1980-81)	Graded furrow	GY = 0.0154(ET - 143)
Schneider and Howell (1995)	1992-1993	DeKalb DK46	LEPA and spray	GY = 0.0184(WU - 89)
Tryon, NE [c]				
Garrity et al. (1982)	1977-1978	RS-636	Line sprinkler	GY = 0.0184(ET - 66)[b]
Garrity et al. (1982)	1977-1978	NC+55X	Line sprinkler	GY = 0.0192(ET - 109)
Garrity et al. (1982)	1977-1978	NB-505	Line sprinkler	GY = 0.0118(ET - 12)

[a] GY is grain yield (Mg ha^{-1}) and WU or ET is seasonal water use or measured ET (mm).

[b] Pullman clay loam soil.

[c] Valentine very fine sand soil.

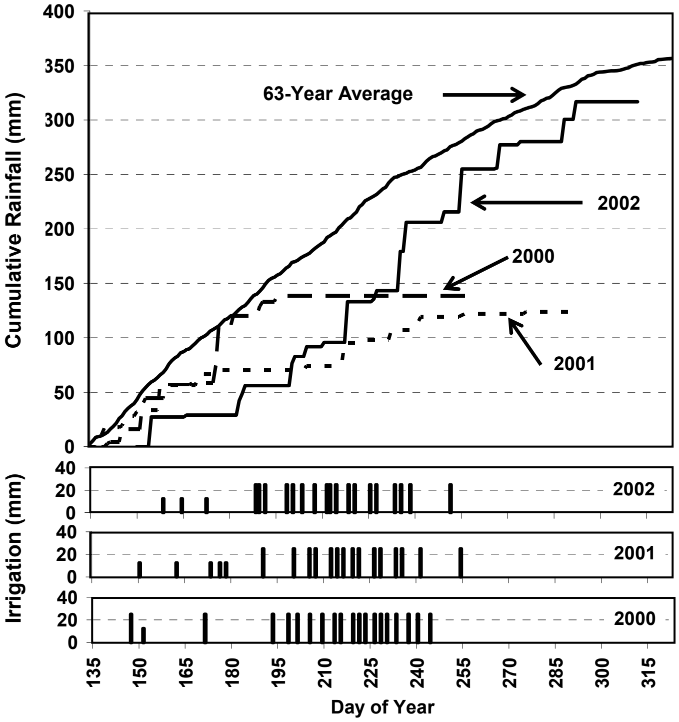
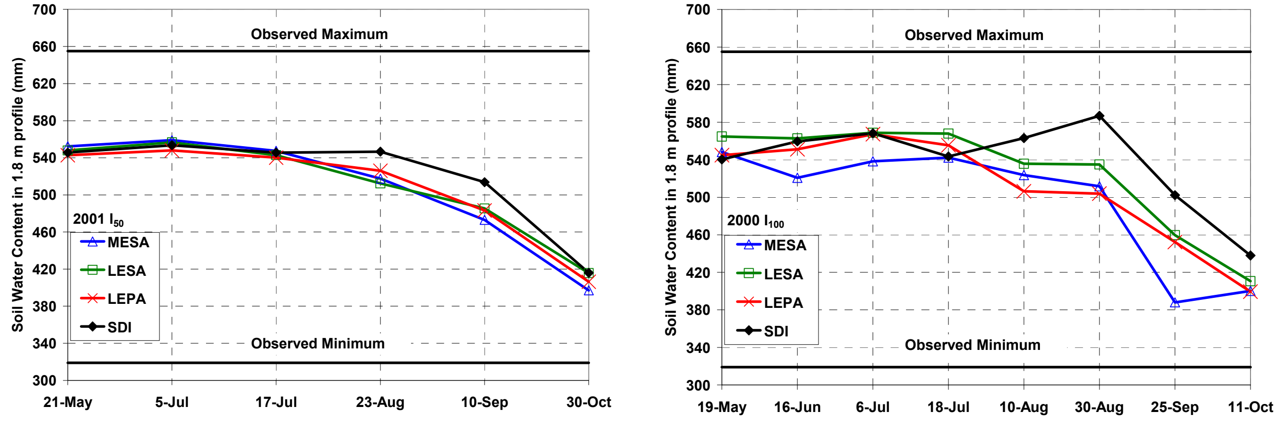
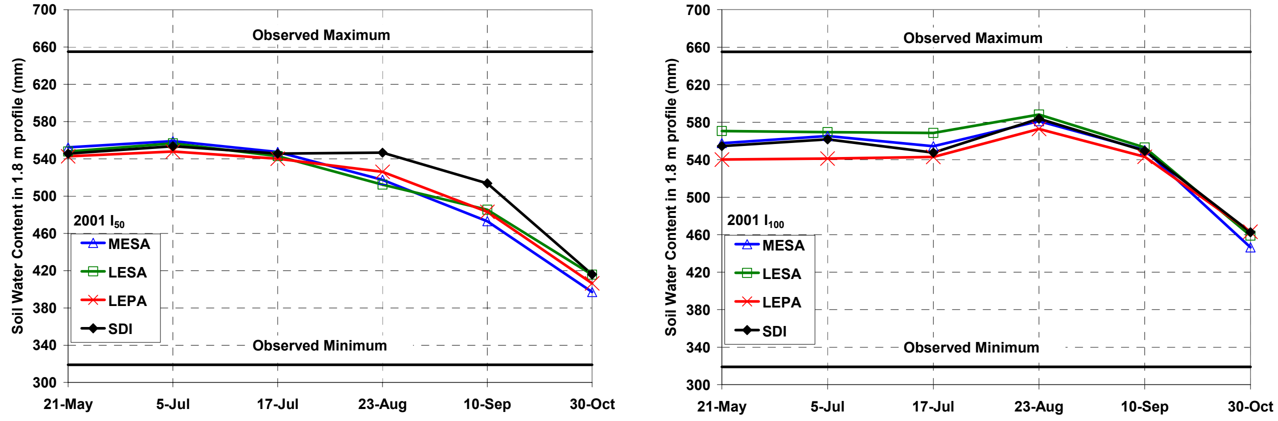


Figure 1-Rainfall at Bushland, TX for 2000, 2001, and 2002, and 63-year average; spray and LEPA irrigations at I_{100} level. SDI irrigations were made daily and totaled spray / LEPA applications on a weekly basis.



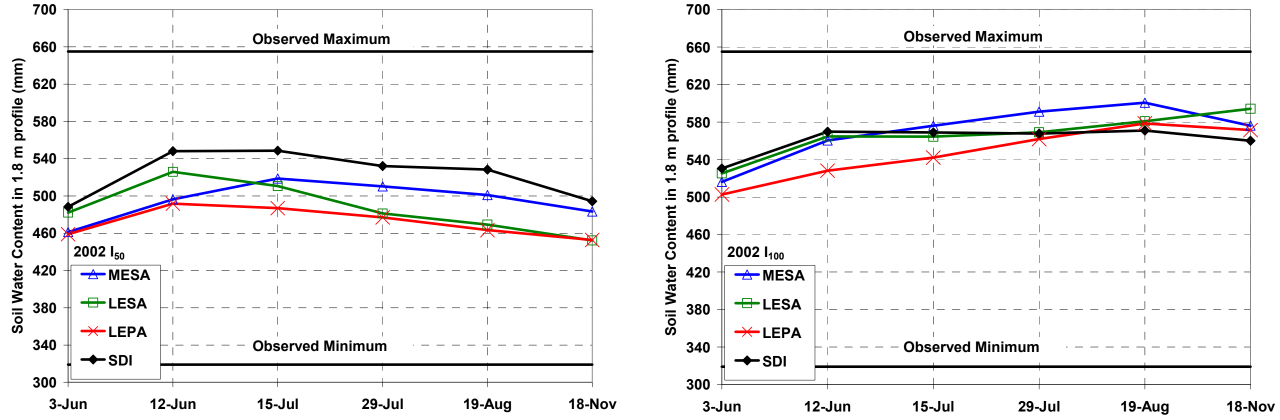
a) 2000, I_{50}

b) 2000, I_{100}



c) 2001, I_{50}

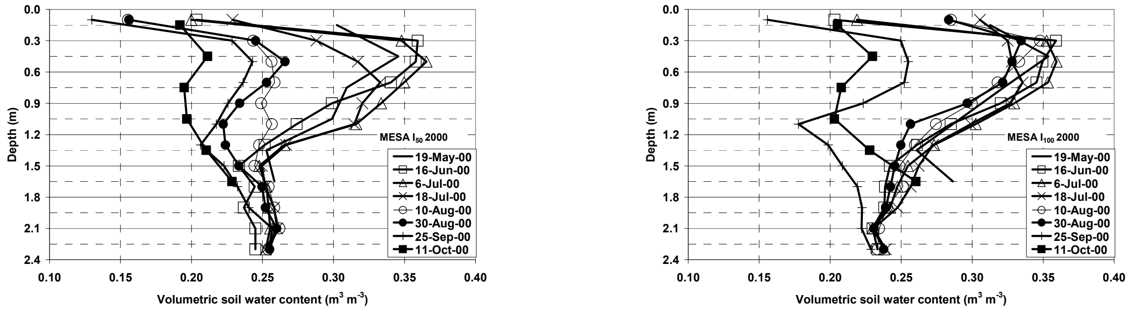
d) 2001, I_{100}



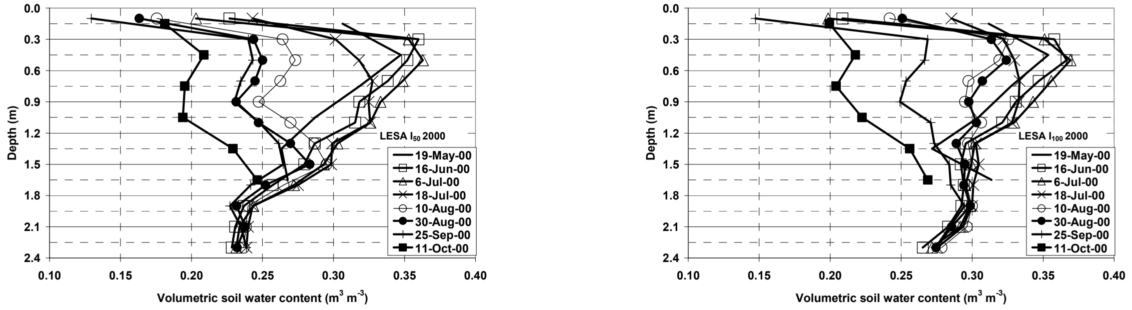
e) 2002, I_{50}

f) 2002, I_{100}

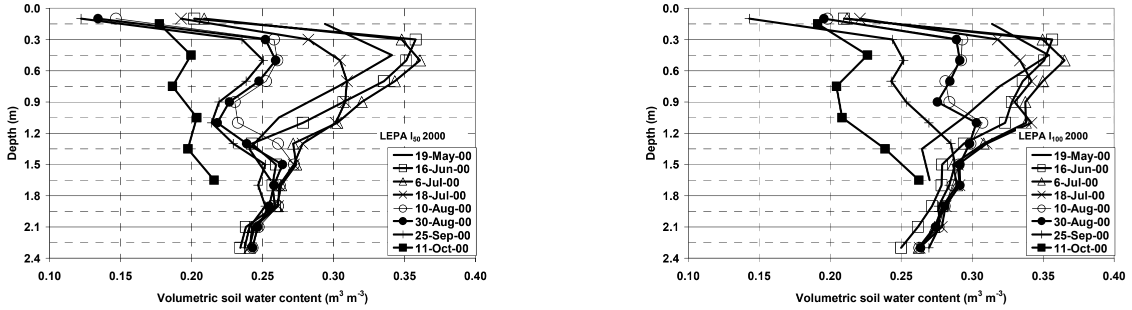
Figure 2- Soil water content in the 1.8 m profile for I_{50} and I_{100} treatments.



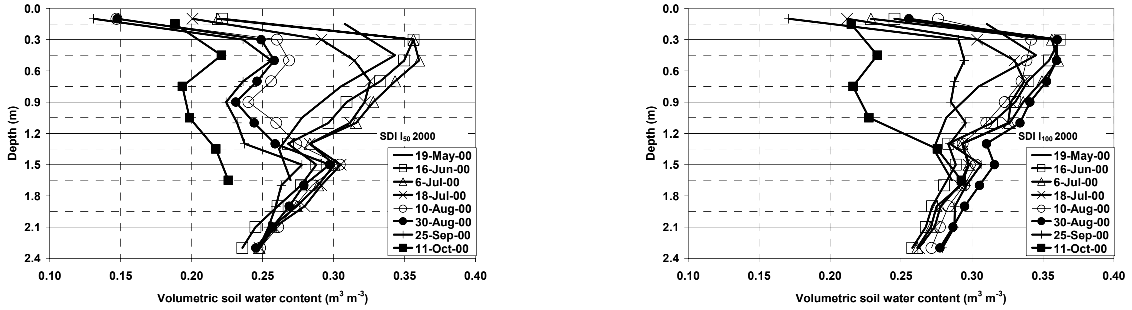
a) MESA I_{50} b) MESA I_{100}



c) LESA I_{50} d) LESA I_{100}

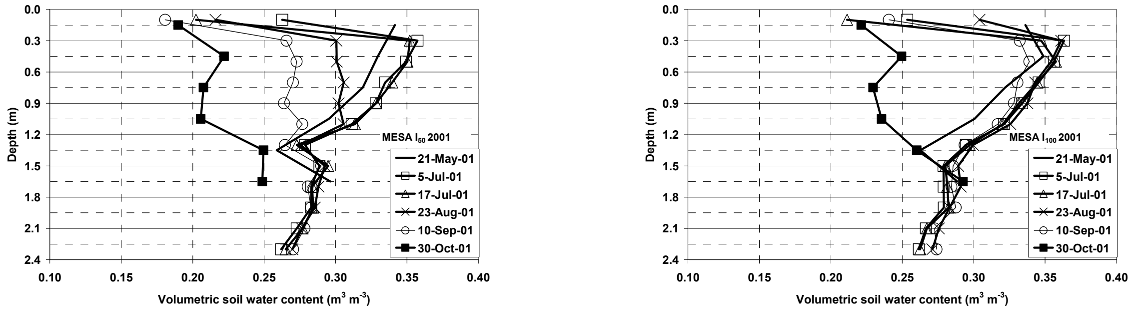


e) LEPA I_{50} f) LEPA I_{100}

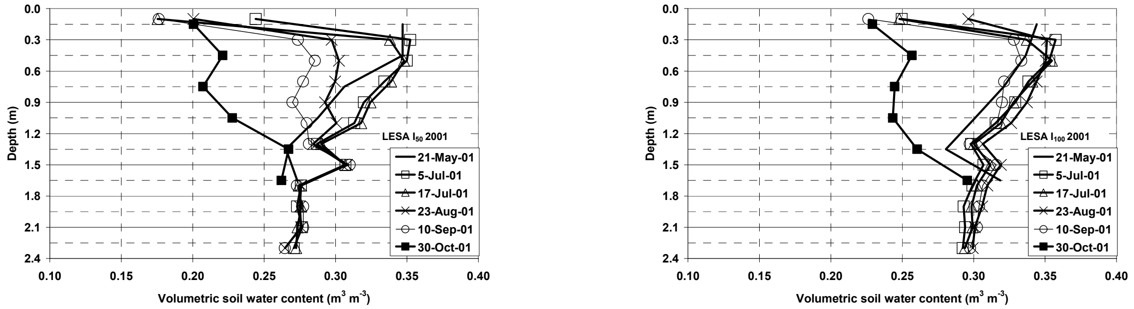


g) SDI I_{50} h) SDI I_{100}

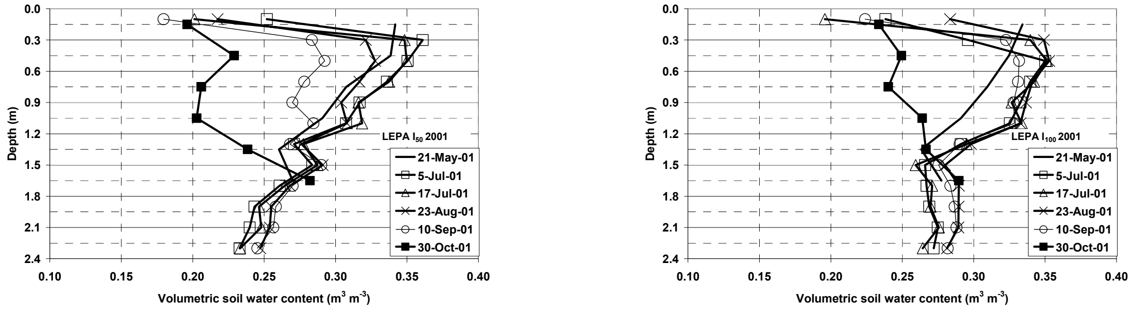
Figure 3- Volumetric soil water contents in the 2.4 m profile in 2000.



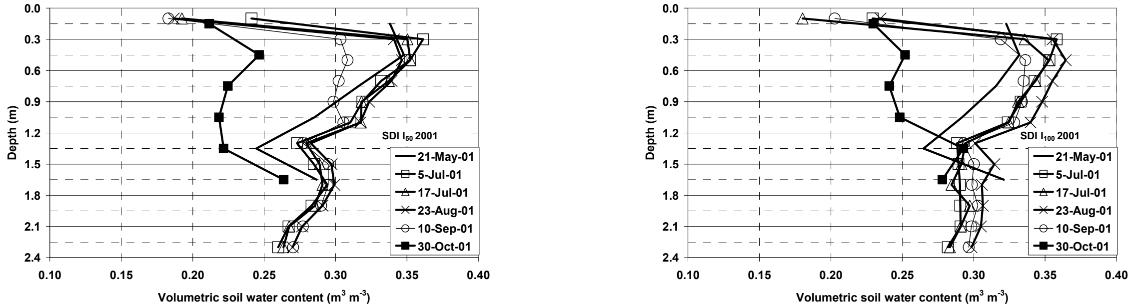
a) MESA I_{50} b) MESA I_{100}



c) LESA I_{50} d) LESA I_{100}

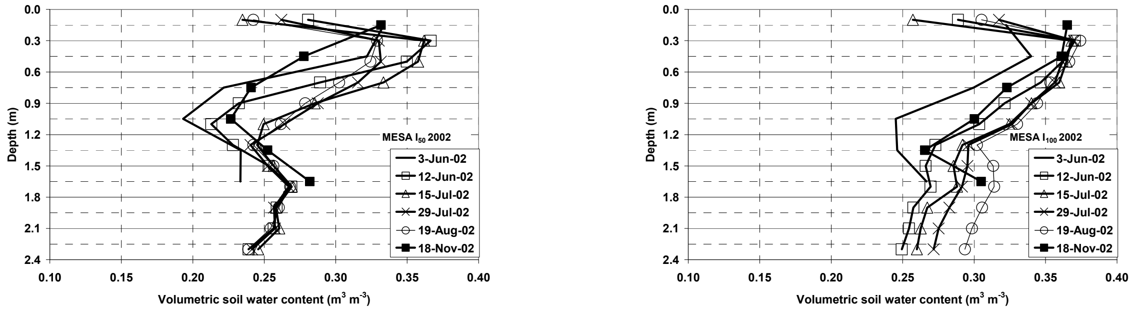


e) LEPA I_{50} f) LEPA I_{100}

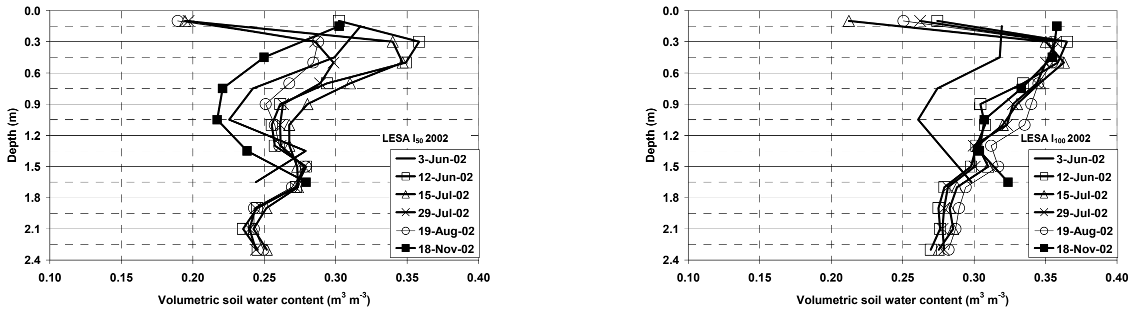


g) SDI I_{50} h) SDI I_{100}

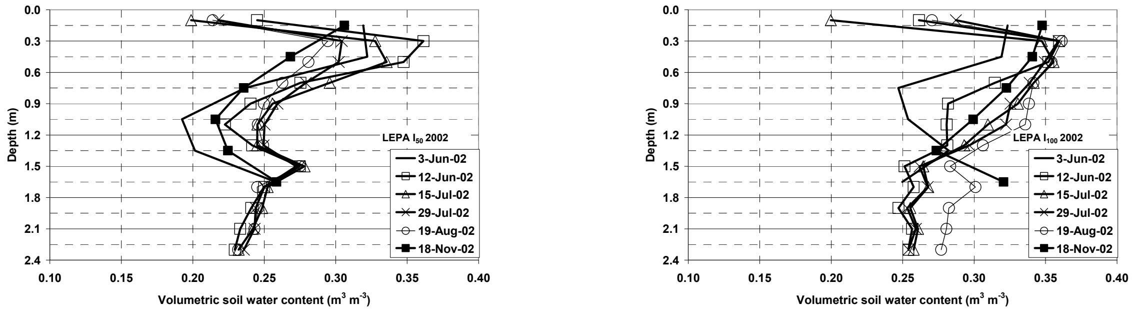
Figure 4- Volumetric soil water contents in the 2.4 m profile in 2001.



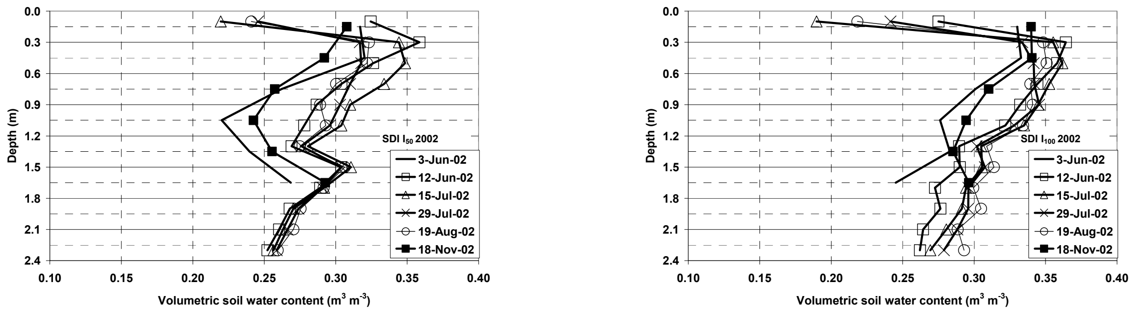
a) MESA I_{50} b) MESA I_{100}



c) LESA I_{50} d) LESA I_{100}



e) LEPA I_{50} f) LEPA I_{100}



g) SDI I_{50} h) SDI I_{100}

Figure 5- Volumetric soil water contents in the 2.4 m profile in 2002.

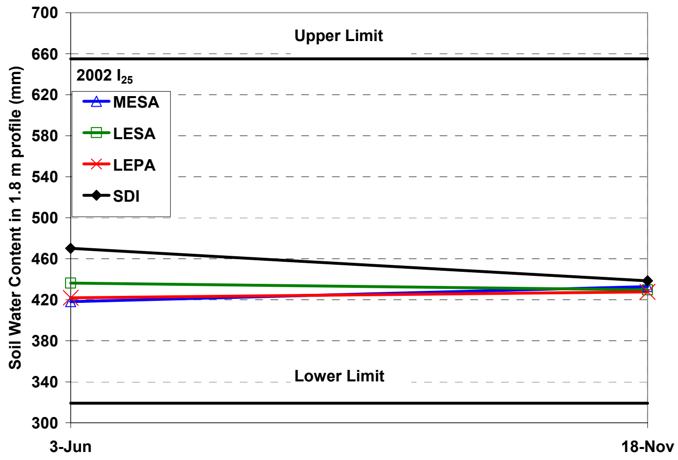


Figure 6- Soil water content in the 1.8 m profile for I_{25} treatments in 2002.

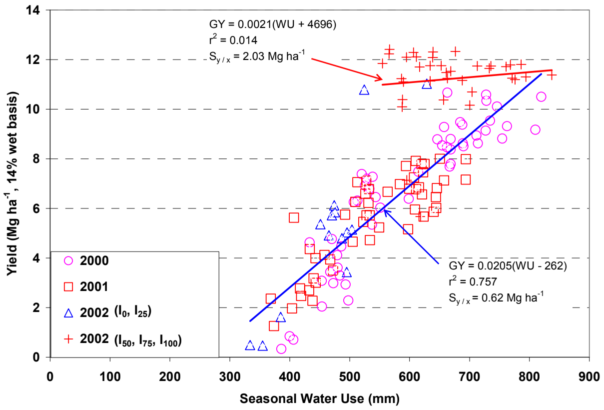


Figure 7-Grain yield as a function of seasonal water use for the three crop seasons (2000-2002).

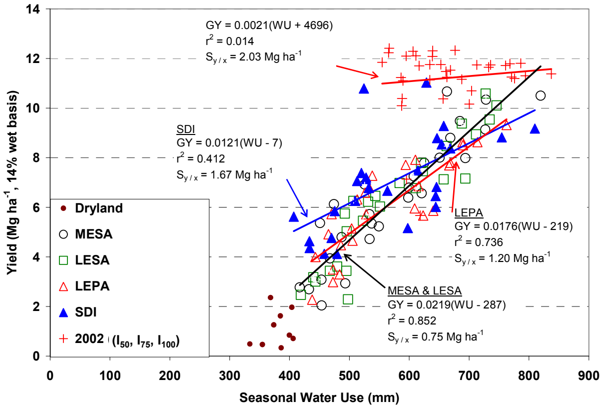


Figure 8-Grain yield as a function of seasonal water use for the three crop seasons (2000-2002) separated by irrigation method.

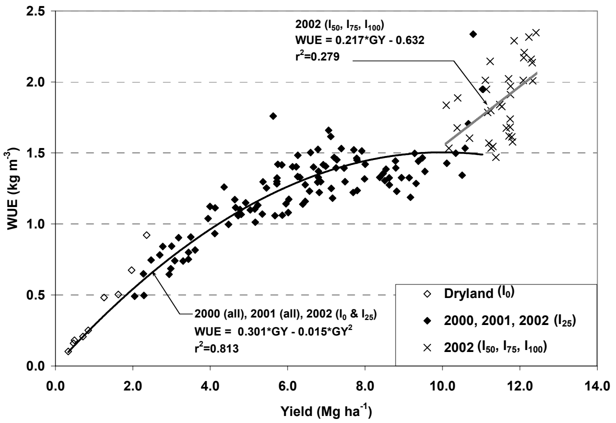


Figure 9-Water use efficiency as a function of yield for the three crop seasons (2000-2002) in Bushland, Texas.