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ABSTRACT. *Subsurface drip irrigation (SDI), low−energy precision application (LEPA), and spray irrigation can be very efficient by minimizing water losses, but relative performance may vary for different irrigation system capacities, soils, crops, and climates. A three−year study was conducted at Bushland, Texas, in the Southern High Plains to compare SDI, LEPA, and spray irrigation for grain sorghum on a slowly permeable Pullman clay loam soil. Performance measures were grain yield, seed mass, soil water depletion, seasonal water use, water use efficiency (WUE), and irrigation water use efficiency (IWUE). Each irrigation method was compared at five irrigation levels: 0%, 25%, 50%, 75%, and 100% of crop evapotranspiration. The irrigation levels simulated varying well capacities typically found in the region and dryland conditions. In all three years, SDI had greater yield, WUE, and IWUE than other irrigation methods at the 50% irrigation level and especially at the 25% level, whereas spray outperformed SDI and LEPA at the 75% and 100% 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 100% levels. Performance was most sensitive to irrigation level, then year, and then irrigation method, although relative rankings of performance for each irrigation method within an irrigation level were consistent across years. For this climate and soil, SDI offers the greatest potential yield, WUE, and IWUE for grain sorghum when irrigation capacities are very low.*

Keywords. *Grain, LEPA, Microirrigation, Sorghum, Sprinkler irrigation, Subsurface drip irrigation.*

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, for which 150% yield increase over dryland is typical (TASS, 2002). Irrigated agriculture in the region, however, is dependent on groundwater withdrawals from the Ogallala aquifer, a finite water resource that 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 late 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% replenish-

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ment), 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 soil surface and increasing the potential for runoff. Howell et al. (2002) reported that furrow dikes improved corn yield for both full and limited spray irrigation compared to flat and bed tillage (no dikes), but did not observe runoff due to dike erosion. Schneider (2000) discussed other potentially large water loss pathways, including deep percolation, wind drift, and surface evaporation (Tolk et al., 1995) and emphasized that both LEPA and spray can be highly efficient, provided that these pathways are carefully evaluated in order to select the most appropriate sprinkler package.

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, the water loss pathways described for spray and LEPA are eliminated using SDI. Camp (1998) reviewed published research on SDI and noted that crop yields were equal to or exceeded those of other irrigation systems, and water use was significantly less. Ayars et al. (1999) reviewed 15 years of SDI research at the USDA−ARS Water Management Research Laboratory in Fresno, California, 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) reported that 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 five levels of irrigation capacities.

PROCEDURE

SITE DESCRIPTION

The research was conducted at the USDA Conservation and Production Research Laboratory in Bushland, Texas (35° 11′ N lat., 102° 06′ W long., 1170 m elevation MSL), 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). Evaporative demand and precipitation during the growing season (May to September) 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 h 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 propeller diker (Sunco Marketing, North Platte, Neb.) 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.

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} Atrazine
Insecticide applied	0.58 L ha^{-1} Lorsban	None	None
Gravimetric soil water samples	19 May 11 October	21 May 30 October	3 June 18 November
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 June[b]	31 May
Harvest date	21 September	29 October	14 November
Emergence irrigations	27 May − 25 mm 31 May − 12 mm	30 May − 12 mm 11 June − 12 mm 22 June − 12 mm 25 June − 12 mm 27 June − 12 mm 9 July − 25 mm	7 June − 13 mm 13 June − 12 mm 21 June − 12 mm
Irrigations to set furrow dikes	20 June − 25 mm	19 July − 25 mm	7 July − 25 mm
First treatment irrigation	12 July	24 July	8 July
Last irrigation	28 August	11 September	8 September
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 June failed to emerge.

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 combine (Hege Equipment, Inc., Colwick, Kansas) with a 1.52 m wide (two−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 three−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 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, which was irrigated with spray applicators and therefore included the surface evaporation component (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 three−span lateral−move system, where each span covered a single block, and methods were randomized

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 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.

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, three−span lateral−move irrigation system (model 6000, Valmont Irrigation, Valley, Neb.). 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 (36 rows 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 listed 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 Typhoon dripline (Netafim USA, Fresno, Cal.). The dripline was shank injected under alternate furrows (1.52 m spacing and six 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.

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

Irrigation Level	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	0.30	1.93

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

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 and 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 incremental 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 neutron soil moisture meter (model 503DR, Campbell Pacific Nuclear, Martinez, Cal.). Measurements (30 s sampling time) were taken from 0.1 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 measurements 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 et al., 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 earlier) 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 into 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, Texas, with 2000 and 2001 being notable drought years. Rainfall during the 2000 and 2001 growing seasons began near average but fell considerably below average 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. Rainfall during the 2002 season began below average but become more frequent as the season progressed. A fortuitous event of 27 mm occurred five days after planting on June 5 (DOY 156). 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

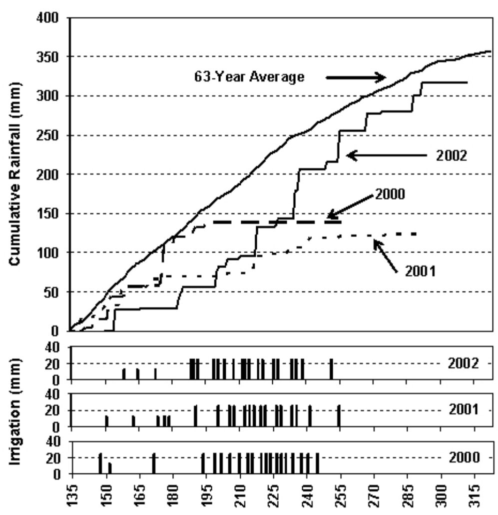

Figure 1. Rainfall at Bushland, Texas, for 2000, 2001, and 2002, and 63−year average (spray and LEPA irrigations at I_{100} level). SDI irrigations were made daily, and totaled spray / LEPA applications were made on a weekly basis.

reproductive growth stages (boot, heading, and flowering) when grain sorghum is 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 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 8 to 13 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 maximum and minimum values of treatment mean profile water content observed during this study were 601 and 354 mm, respectively. This range of field−observed values was similar to the upper (623 mm) and lower (350 mm) limits of plant−available water reported by Taylor et al. (1963), which were based on laboratory values, and to those reported by Musick and Sletten (1966, 575, and 362 mm, respectively), 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 maximum profile water content.

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 preseason 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 (fig. 2e) began with only about a half−full profile despite preplant irrigations; water contents at the I_{100} level (fig. 2f) were slightly larger.

Irrigation scheduling appeared adequate for all three seasons. The soil water profiles of the I_{100} treatments were maintained at sufficient levels to avoid yield−reducing water stress during the irrigation season, and so did not depart from the definition of "full" irrigation (fig. 2). Recall that "full" irrigation is defined as the amount required to meet 100% of the crop evapotranspiration (ET_c), and $ET_c = K_c \times ET_o$ where K_c is the crop coefficient, and ET_o is grass reference evapotranspiration. In 2001, less irrigation water was required than in 2000 or 2002 (table 1), although the 2001 season had the least rainfall. This was due to both the shorter variety of grain sorghum planted and peak water use occurring when atmospheric demand was less compared with 2000. Irrigations were terminated when the crop could use the remaining soil water reserves to reach physiological maturity (black layer to harvest), hence the sharp decline in soil water late in the seasons, except for 2002 when precipitation occurred.

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

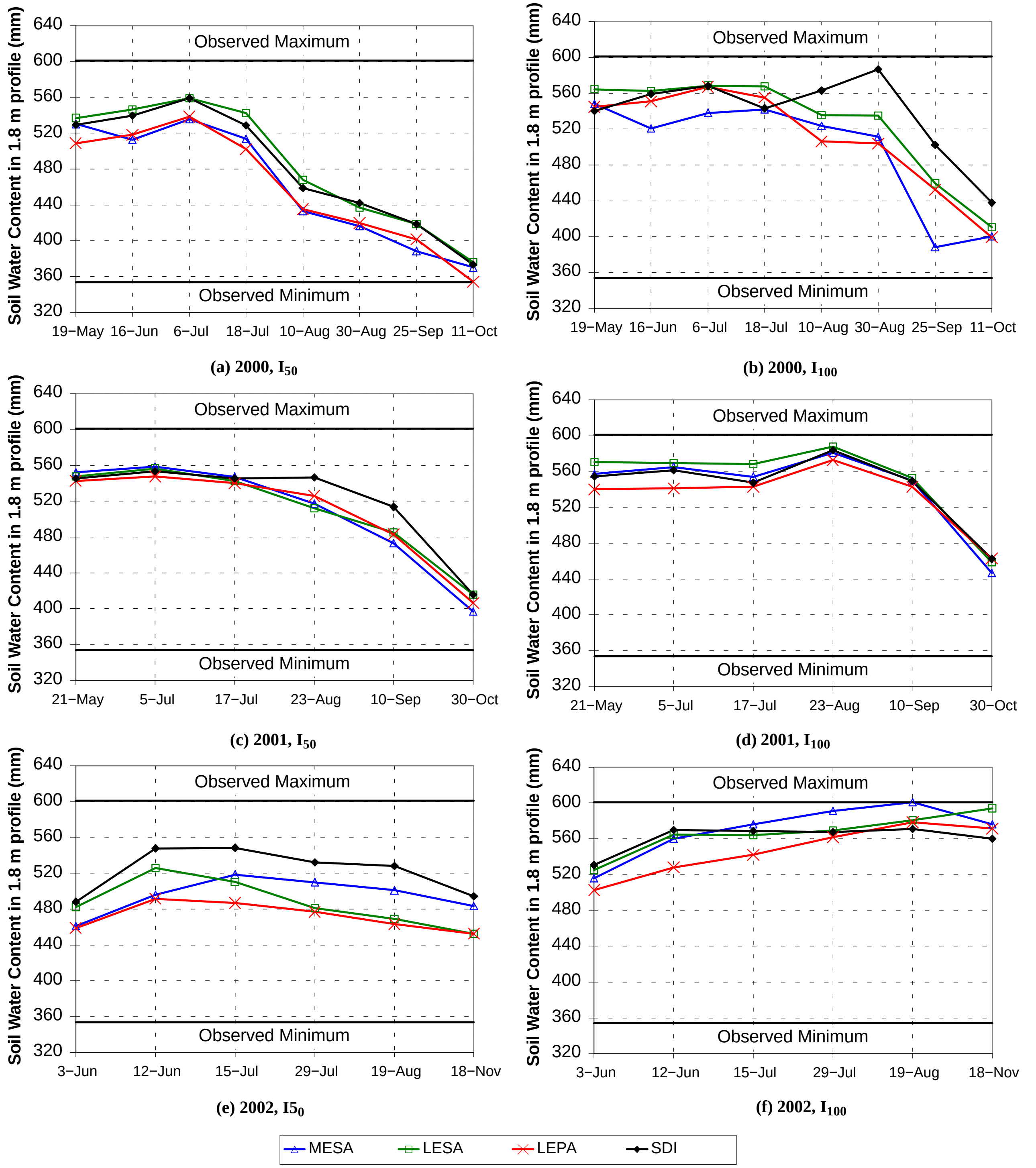

Figure 2. Soil water content in the 1.8 m profile for I_{50} and I_{100} treatments.

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 to 5). Soil water increased at depth for these treatments, and because the depth to the groundwater table is about 75 m, these increases probably reflect a loss of water to deep percolation rather than upward flux. Because of these increases, it is difficult to assess the depth of soil water extraction for the affected treatments. In the treatments unaffected by apparent 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

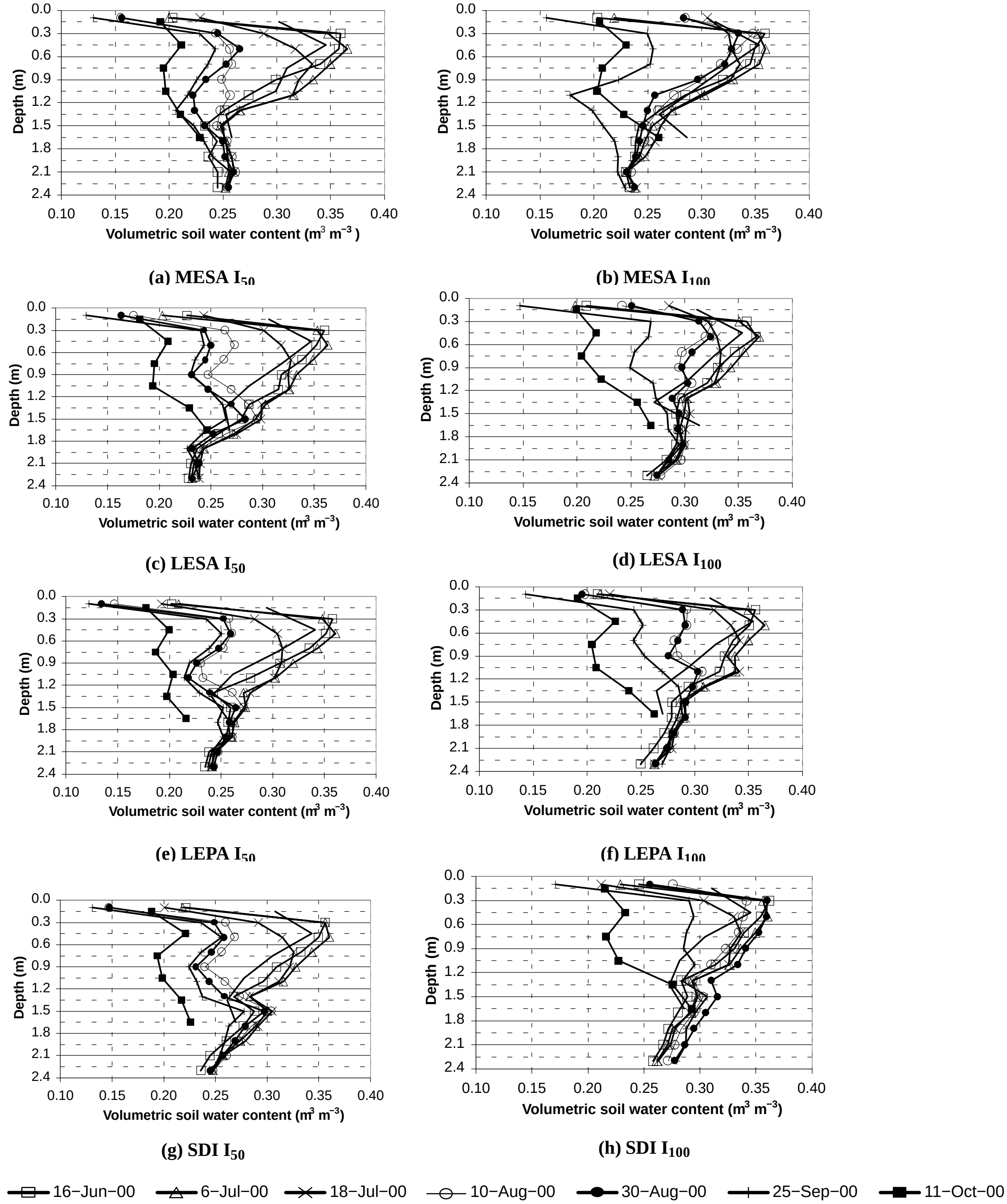

Figure 3. Volumetric soil water contents in the 2.4 m profile in 2000.

extraction depth, such as depth and amount of antecedent soil water, 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 shows the need to measure soil water 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. The K_c value used to compute ET_c for full irrigation includes a portion of soil evaporation (both beneath the plant and in the interrows exposed to sunlight) since the entire soil surface was wetted during irrigation when these values were developed. The fraction of soil surface wetted would be less for LEPA (especially because only interrows were irrigated) and probably negligible for SDI because no surface wetting was observed; 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.

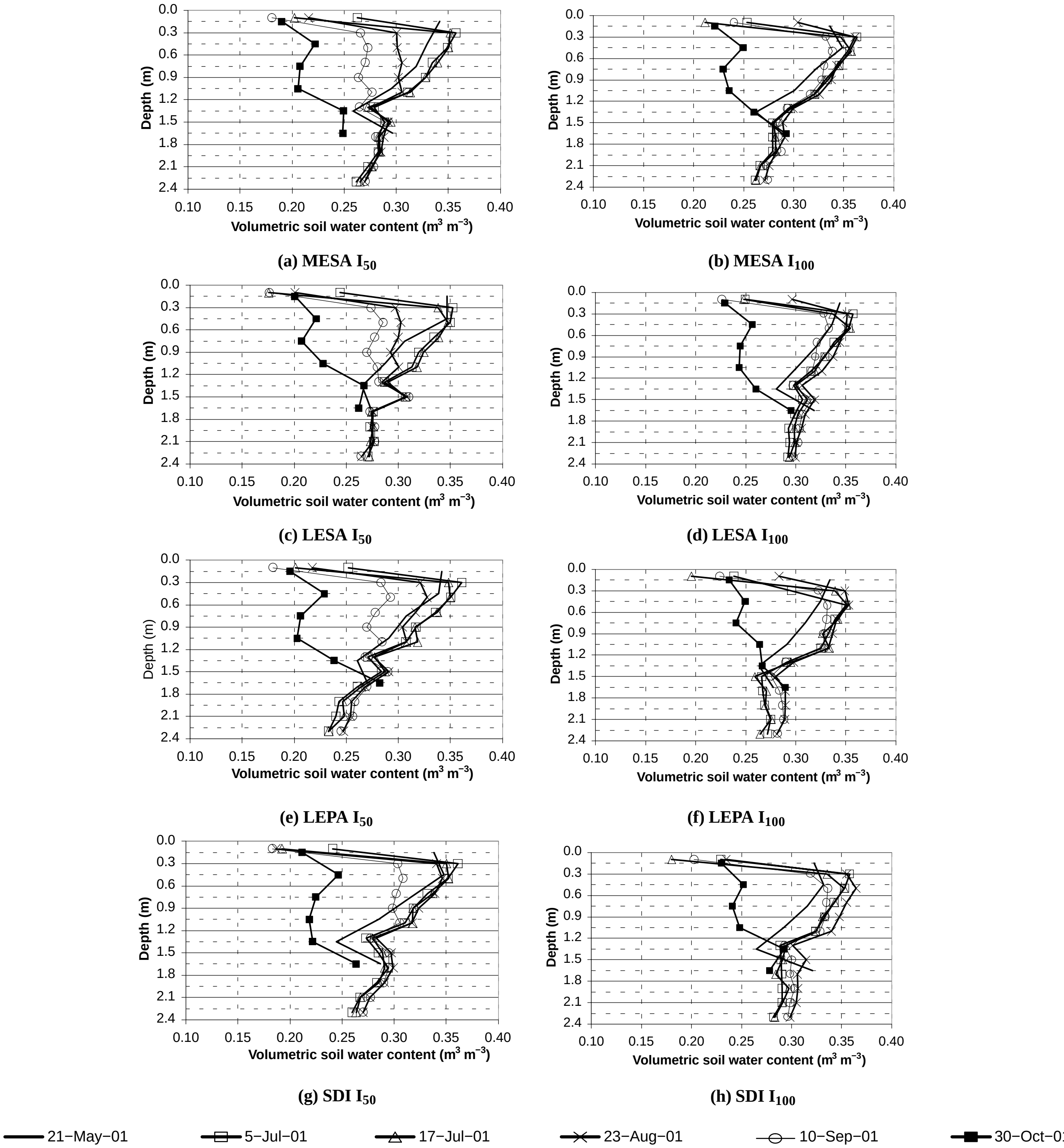

Figure 4. Volumetric soil water contents in the 2.4 m profile in 2001.

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 United Nations FAO 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. We modeled evaporation, deep percolation, and seasonal water use for each treatment in the present study using the FAO 56 dual crop coefficient procedure for grain sorghum. The modeled estimates are reported as three−year averages in table 4. For each irrigation level, SDI had much less modeled evaporation (E) than LEPA or spray, but modeled deep percolation (DP) was much greater. Modeled seasonal water use (ET_c + DP) showed reasonable agreement with measured values; however, future research should attempt to measure evaporation separately in order to verify these results. In addition, some water losses might 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. We are continuing this study for cotton and have adopted this irrigation scheduling protocol.

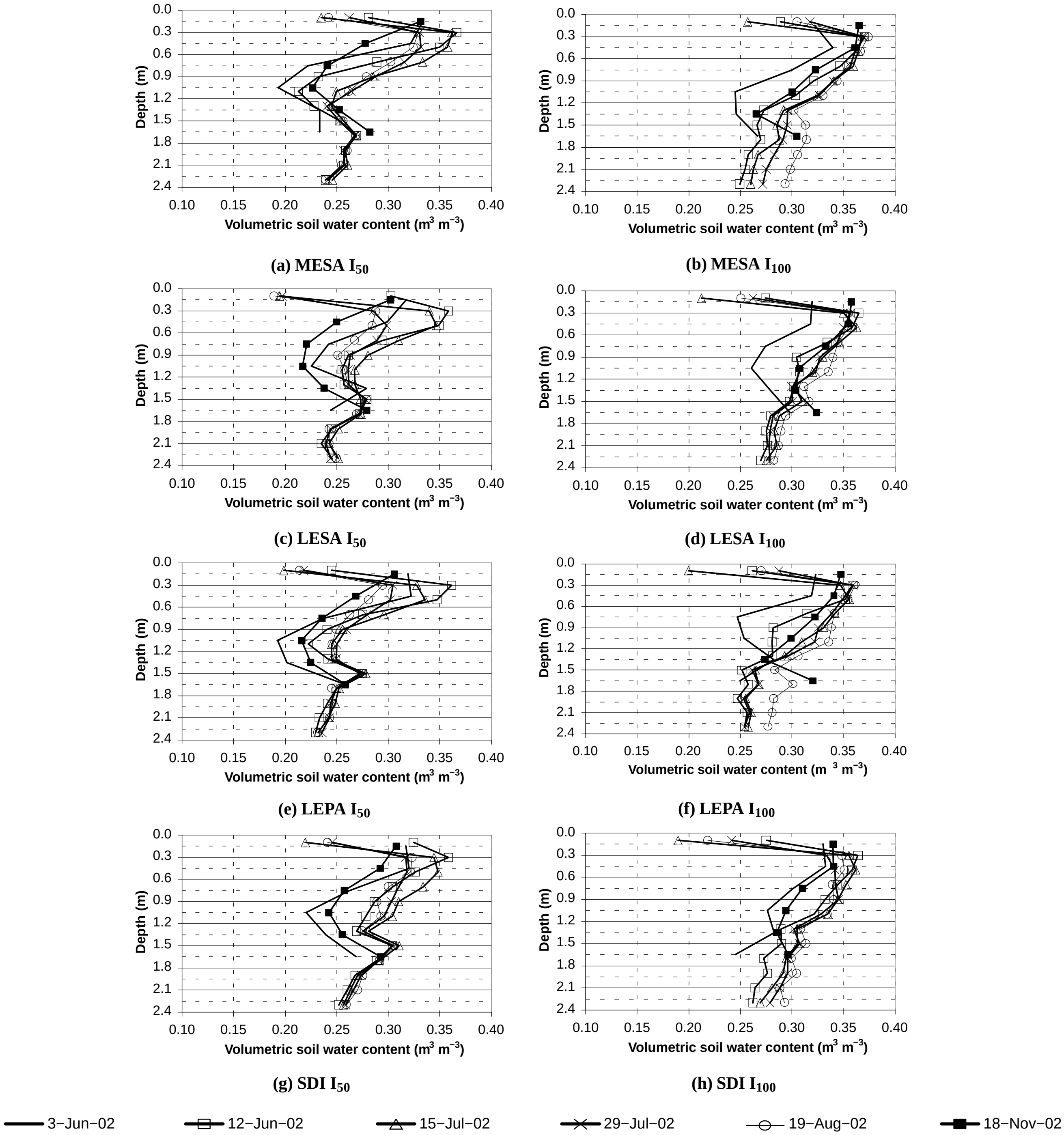

Figure 5. Volumetric soil water contents in the 2.4 m profile in 2002.

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 5, 6, and 7, respectively. Results will be 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 5 and 6), but was nearly 12 Mg ha^{-1} during 2002 for the SDI I_{50} treatment (table 7). 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.

Table 4. Modeled components of the soil water balance using the FAO 56 dual crop coefficient procedure for grain sorghum, and measured seasonal water use (three-year averages). For modeled vs. measured seasonal water use, slope = 0.99, intercept = 15 mm, r^2 = 0.96, and root mean squared error (RMSE) = 23 mm.

		FAO 56 Model							
Irrigation Level	Irrigation Method	E (mm)	T (mm)	ET_c (mm)	E/ET_c (%)	DP (mm)	Seasonal Water Use (mm)	Measured Seasonal Water Use (mm)	Difference in Seasonal Water Use (mm)
I_0	−−	112	250	362	31	2	363	379	16
I_{25}	MESA	119	349	468	26	2	469	459	−11
	LESA	119	349	468	26	2	469	469	0
	LEPA	118	379	497	24	2	498	471	−28
	SDI	63	404	468	14	12	480	479	−1
I_{50}	MESA	125	447	572	22	2	573	562	−12
	LESA	125	454	578	22	2	580	572	−9
	LEPA	120	458	578	21	2	580	563	−17
	SDI	62	506	569	11	12	581	568	−13
I_{75}	MESA	141	492	633	22	10	643	634	−9
	LESA	141	492	633	22	10	643	652	9
	LEPA	132	517	649	20	10	659	643	−16
	SDI	73	540	613	11	33	646	629	−17
I_{100}	MESA	144	545	689	21	43	732	725	−7
	LESA	144	545	689	21	43	732	725	−8
	LEPA	133	557	689	19	45	734	710	−24
	SDI	73	568	642	11	84	725	727	2

Table 5. 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	2.69 c[c]	19 a	159 a	467 a	0.63 c	1.57 c
	LESA	3.11 bc	19 a	174 a	482 a	0.70 bc	1.89 bc
	LEPA	3.58 b	20 a	173 a	481 a	0.81 b	2.25 b
	SDI	4.51 a	20 a	153 a	461 a	1.07 a	2.94 a
I_{50} (275 mm)	MESA	6.22 b	20 a	163 a	576 a	1.15 b	2.35 b
	LESA	6.25 b	21 a	163 a	577 a	1.16 b	2.37 b
	LEPA	6.80 ab	21 a	157 a	571 a	1.27 ab	2.60 ab
	SDI	7.36 a	22 a	159 a	574 a	1.37 a	2.82 a
I_{75} (381 mm)	MESA	9.14 a	25 a	173 a	693 a	1.39 a	2.48 a
	LESA	8.93 a	24 ab	167 a	687 a	1.39 a	2.41 a
	LEPA	8.00 b	22 b	155 ab	675 ab	1.25 b	2.14 a
	SDI	8.57 ab	23 ab	134 b	656 b	1.37 ab	2.30 a
I_{100} (488 mm)	MESA	10.51 a	27 a	150 a	777 a	1.42 a	2.20 a
	LESA	10.08 a	27 a	157 a	783 a	1.35 a	2.10 a
	LEPA	8.86 b	24 b	148 a	774 a	1.20 b	1.83 a
	SDI	9.09 b	24 b	104 b	733 b	1.31 ab	1.87 a
Irrigation Level Averages							
I_0 (62 mm)	−−	0.63 e[d]	20 c	196 a	397 e	0.19 d	−−
I_{25} (169 mm)	−−	3.47 d	20 c	165 b	472 d	0.80 c	2.16 bc
I_{50} (275 mm)	−−	6.65 c	21 c	161 bc	575 c	1.24 b	2.53 a
I_{75} (381 mm)	−−	8.66 b	24 b	158 bc	678 b	1.35 a	2.33 ab
I_{100} (488 mm)	−−	9.63 a	25 a	140 c	767 a	1.32 ab	2.00 c
Irrigation Method Averages							
−−	MESA	7.14 a[e]	23 a	161 a	628 a	1.15 b	2.15 b
−−	LESA	7.09 a	23 ab	165 a	632 a	1.15 b	2.19 ab
−−	LEPA	6.81 a	21 b	158 a	625 a	1.13 b	2.20 ab
−−	SDI	7.38 a	22 ab	137 b	606 b	1.28 a	2.48 a

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

[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.

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 7 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 7). 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 (MESA) preplant irrigations. The SDI I_{25} treatment, for example, had 470 mm of water in the 1.8 m profile at planting, but the other methods had less than 440 mm; soil water contents at harvest ranged from 428 mm to 439 mm (data not shown for I_{25}, also see figures 2e and 2f for the I_{50} and I_{100} levels, respectively). 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 7). 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 the 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 in all three seasons. This trend was not

Table 7. 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	5.43 b[c]	29 a	−15 a	471 b	1.26 b	3.48 b
	LESA	3.21 c	28 a	6 a	492 ab	0.70 c	1.79 c
	LEPA	5.26 bc	28 a	−6 a	480 b	1.19 b	3.35 b
	SDI	9.22 a	29 a	32 a	543 a	1.90 a	6.34 a
I_{50} (275 mm)	MESA	11.39 a	31 a	−22 a	569 a	2.15 a	4.43 a
	LESA	8.19 b	31 a	30 a	622 a	1.39 b	3.09 b
	LEPA	11.07 a	31 a	6 a	598 a	1.97 a	4.30 ab
	SDI	11.89 a	32 a	−6 a	612 a	2.16 a	4.61 a
I_{75} (381 mm)	MESA	12.20 a	32 a	−98 b	600 b	2.18 a	3.30 a
	LESA	10.77 a	31 a	−34 a	664 a	1.73 b	2.88 a
	LEPA	11.77 a	31 a	−53 ab	645 ab	1.94 ab	3.17 a
	SDI	11.54 a	31 a	−59 ab	666 a	1.91 ab	3.09 a
I_{100} (488 mm)	MESA	11.70 a	32 a	−61 a	743 ab	1.66 a	2.41 a
	LESA	11.43 a	31 a	−70 a	734 b	1.65 a	2.35 a
	LEPA	11.42 a	30 a	−70 a	734 b	1.64 a	2.35 a
	SDI	11.29 a	30 a	−30 a	802 a	1.53 a	2.30 a
Irrigation Level Averages							
I_0 (62 mm)	--	0.86 c[d]	25 b	−22 ab	358 e	0.28 d	--
I_{25} (169 mm)	--	5.78 b	29 ab	4 a	496 d	1.26 c	3.74 ab
I_{50} (275 mm)	--	10.63 a	31 a	2 a	600 c	1.92 a	4.11 a
I_{75} (381 mm)	--	11.57 a	31 a	−61 b	644 b	1.94 a	3.11 bc
I_{100} (488 mm)	--	11.46 a	31 a	−58 b	754 a	1.62 b	2.35 c
Irrigation Method Averages							
--	MESA	10.18 a[e]	30 a	−49 b	596 c	1.81 a	3.41 a
--	LESA	8.40 b	31 a	−17 a	628 ab	1.37 b	2.53 b
--	LEPA	9.88 ab	30 a	−30 ab	614 bc	1.69 a	3.29 ab
--	SDI	10.99 a	31 a	−16 a	656 a	1.88 a	4.09 a

[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.

always significant, especially in 2002 (table 7) when rainfall masked differences between the I_{50}, I_{75} and I_{100} levels, and yield for all three levels 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 5). In 2001, this pattern was observed only for soil water depletion and seasonal water use at the I_{100} level (table 6). In 2002, SDI used more water for the season (802 mm) than all other treatments and years (table 7).

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 7). In a study with corn under SDI in Colby, Kansas, during 1989 to 1991, Lamm et al. (1995) reported yield depressions in two out of three years (1989 and 1990) for 125% of full irrigation and attributed this to poor aeration or leaching of nutrients. Darusman et al. (1997) deduced deep percolation from tensiometer measurements for the 1990 and 1991 seasons of that study and reported greater soil water flux below the root zone for the 100% and 125% treatments. 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 7), 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 5, 6, and 7 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 the smallest at the I_{100} level.

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 5), the seasonal water use was significantly less than all other methods, resulting in WUE being significantly greater. In 2002 (table 7), 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 and Seasonal Water Use Relationships

Grain yield as a function of seasonal water use is illustrated in figure 6. A single linear function adequately describes all treatments in 2000, 2001, and only the I_0 and I_{25} levels in 2002. The I_{50}, I_{75}, and I_{100} levels in 2002 are 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 6 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 8 shows production functions for grain sorghum from previous studies at Bushland, Texas, and Tryon, Nebraska, 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 8; 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) proposed that slopes of production functions may better represent physiological water use efficiency of grain than do WUE or IWUE ratios.

Figure 7 presents the same data as figure 6, except that the production function is further separated by irrigation method, and dryland (I_0) was excluded from the regressions. A single linear function, which is not much different from that of figure 6, can describe the spray (MESA and LESA) methods. 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 is less responsive to variation in water use. 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 8; they also reported higher IWUE for mid−level deficit irrigation using LEPA.

Figure 8 shows WUE as related to grain sorghum yield, where the 2002 I_{50}, I_{75}, and I_{100} treatments are separated from the rest of the data, as in figures 6 and 7. 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 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.

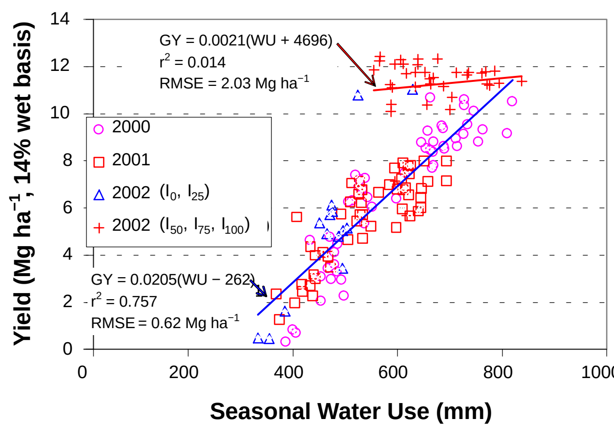

Figure 6. Grain yield as a function of seasonal water use for the three crop seasons (2000−2002): GY = grain yield, WU = water use, and RMSE = root mean squared error.

Table 8. Grain sorghum production functions from selected studies.

Location and Reference	Years of Study	Variety	Irrigation Method	Production Function[a]
Bushland, Texas[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) and 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, Nebraska[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}), WU is seasonal water use (mm), and ET is measured ET (mm).
[b] Pullman clay loam soil.
[c] Valentine very fine sand soil.

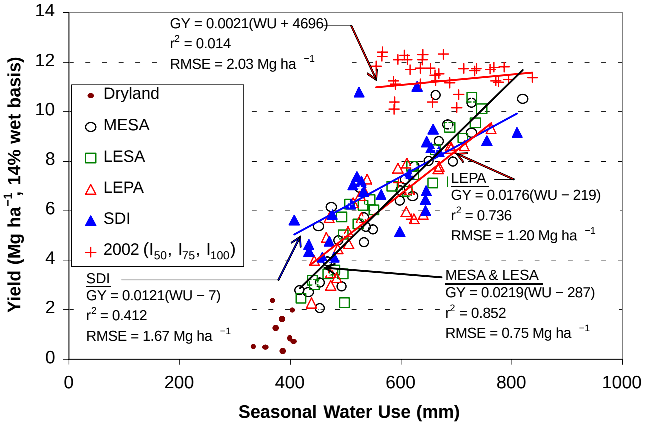

Figure 7. Grain yield as a function of seasonal water use for the three crop seasons (2000−2002) separated by irrigation method: GY = grain yield, WU = water use, and RMSE = root mean squared error.

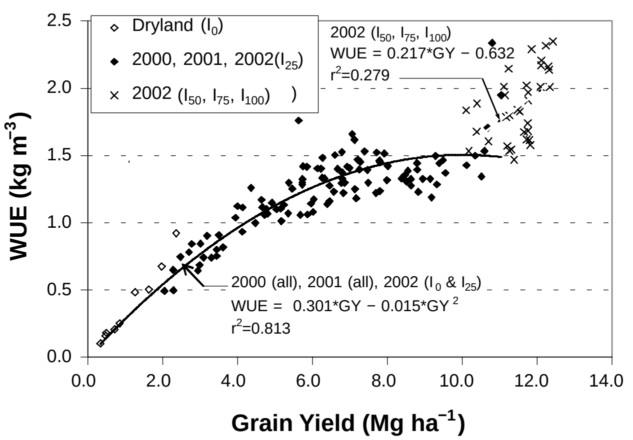

Figure 8. Water use efficiency as a function of yield for the three crop seasons (2000−2002) in Bushland, Texas: GY = grain yield and WUE = water use efficiency.

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 observed. It appears that at low irrigation capacities, the SDI and to a lesser extent LEPA methods reduced soil evaporation and permitted 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 did not reduce grain yield; they could even have enhanced 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, may have induced 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. Additional analyses, however, should include various crop rotations, the trade−off between irrigated area and available (present and future) water resources, pumping costs, and different tillage options. These confounding factors underscore the need for agricultural engineers and scientists to strengthen collaborative efforts with extension agricultural economists.

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 was not different between methods within an irrigation level in most cases, but SDI and LEPA appeared to partition more water to transpiration and less to soil evaporation, which would enhance 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. Deep percolation may have occurred 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. Future research efforts should be directed toward separation of the evaporation and transpiration components of evapotranspiration, quantification of deep percolation, and a systems approach to economic analyses that expands beyond the simple relationships of water use and yield.

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