Comparison of SDI, LEPA, and spray irrigation performance for cotton in the North Texas High Plains[1]

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Abstract

Producers in the North Texas High Plains (Amarillo and north) are considering cotton as an alternative crop to corn because cotton has a similar profit potential for about one-half the irrigation requirement. However, limited heat units pose some risk for cotton production. We hypothesized that cotton under subsurface drip irrigation (SDI) would undergo less evaporative cooling following an irrigation event compared with low energy precision applicators (LEPA) or spray irrigation and, therefore, would increase heat unit accumulation and lead to earlier maturation. We did not observe any differences in cotton maturity between irrigation methods in 2003; however, preliminary data in 2004 showed that soil temperatures were greater for SDI than LEPA or spay following an irrigation event. In the 2003 season, lint yield and water use efficiency were greater with SDI under low irrigation capacities (25% and 50% of full irrigation), but were greater with LEPA and spray under full irrigation. Fiber quality, as indicated by total discount, was greater with SDI for all capacities except full irrigation. We are continuing this experiment for two more seasons.

Introduction

Producers in the Northern Texas High Plains (Amarillo and north) have recently shown renewed interest in cotton. This region is adjacent to one of the largest cotton producing areas in the United States, centered approximately at Lubbock (190 km south), where approximately 4 million bales are produced annually (USDA-NASS, 2004; TDA-TASS, 2004). This renewed interest stems from, among other factors, lower water requirements relative to corn, which is presently more widely produced in the northern area and has a similar revenue potential (Howell et al., 1997; 2004). The primary limitation to cotton production in the Northern High Plains is the lack of heat units (Peng et al., 1989; Morrow and Krieg, 1990) and the lack of an industry infrastructure (gins, custom harvesters, etc.). The other main limitation is of course water, specifically the declining availability of irrigation water from the Ogallala aquifer, insufficient and sporadic in-season rainfall, and high evaporative demand. Despite these limitations, Howell et al. (2004) showed that cotton production in this area is feasible, with lint yields and water use efficiencies comparable to those in more ideal climates (Zwart and Bastiaanssen, 2004).

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Pressurized irrigation systems such as mechanically moved and microirrigation can enhance cotton lint yield and water use efficiency compared to furrow (gravity) irrigation or dryland regimes, provided the pressurized system is properly designed and managed. Mechanically moved systems have numerous variants of applicator packages, with the more common configurations being mid- and low-elevation spray application (MESA and LESA, respectively) and LEPA (Low Energy Precision Applicator; Lyle and Bordovsky, 1983; Bordovsky et al., 1992). Microirrigation, usually in the form of subsurface drip irrigation (SDI), has been widely adopted by commercial cotton producers throughout the South Plains and Trans Pecos regions of Texas beginning in the early 1980s (Henggeler, 1995; 1997; Enciso et al., 2003). Although SDI has significantly greater initial costs than spray or LEPA systems (O'Brien et al., 1998; Segarra et al., 1999), it has been documented to slightly outperform LEPA and spray in terms of lint yield, lint quality (as reflected by loan prices), and water use efficiency (Segarra et al., 1999; Bordovsky and Porter, 2003). Similar trends have been reported for surface drip where laterals were placed in alternate furrows (Yazar et al., 2002) and each planted row (Cetin and Bilgel, 2002). Nonetheless, Segarra et al. (1999) analyzed four years of cotton data at Halfway, Texas and concluded that SDI may not always provide as high economic returns as LEPA, but this largely depended on system life, installation costs, pumping lift requirements, and hail damage that commonly occurs in West Texas. Also, Howell et al. (1987) found no differences in lint yield of narrow row (0.5 m) cotton between surface drip and furrow irrigation systems that were designed and managed to minimize soil water deficits, although soil water evaporative losses were less for surface drip.

There is a general perception by some cotton producers that SDI also enhances seedling emergence and plant maturity due to reduced evaporative cooling compared to LEPA or spray, which is a critical consideration in a thermally limited environment and is seldom considered in economic analyses. There is, however, limited data in direct support of this view, as soil water depletion in the root zone is most responsible for inducing earliness (Guinn et al., 1981; Mateos et al., 1991; Orgaz et al., 1992). Nonetheless, a few studies may indirectly support the premise that SDI can enhance cotton maturity and are briefly described here. Wang et al. (2000) reported that mean soil temperatures were 4.4 °C greater for plots irrigated with surface drip laterals than stationary rotating sprinklers, and they observed greater emergence rates and seedling development of soybeans. They noted, however, that their results may have been influenced by the solar heating of water as it passed through the black plastic drip laterals rather than the greater evaporating surface area of the sprinkler plots. Tolk et al. (1995) showed that corn transpiration rates, canopy temperature, and vapor pressure deficits were significantly reduced for several hours following irrigation by overhead impact sprinklers, but not greatly changed following irrigation by LEPA in alternate furrows. The reduced evaporative cooling thought to be associated with SDI, on the other hand, may be countered by the greater cooling effect of increased irrigation frequency (Wanjura et al., 1996). Constable and Hodgson (1990) reported that cotton under SDI matured several days later than cotton under furrow irrigation.

The objectives of this study are to compare cotton yield and quality for spray, LEPA, and SDI under full and deficit irrigation in the Northern Texas High Plains, which is a marginal climate for cotton production. This paper presents the results of the first (2003) season of data, and some preliminary soil temperature data from the second (2004) season.

Procedures

An experiment was conducted during the 2003 and 2004 growing seasons using MESA, LESA, LEPA, and SDI to irrigate cotton at the USDA Conservation and Production Research Laboratory in Bushland, Texas (35° 11′ N lat., 102° 06′ W long., 1070 m elevation MSL). As of this writing, only the 2003 season is complete, so most data presented here reflects a single season. The climate is semi-arid with a high evaporative demand of about 2,600 mm per year (Class A pan evaporation) and low precipitation averaging 470 mm per year. Most of the evaporative demand and precipitation occur during the growing season (May to October) and average 1,550 mm and 320 mm, respectively. Cumulative heat units for cotton average 1,050°C during the growing season (mean daily air temperature minus base temperature of 15.6 °C); however, Peng et al. (1989) state that about 1,450°C is required for full maturity cotton in the region to our south centered around Lubbock, TX. The climate is also characterized by strong regional advection from the South and Southwest, where average daily wind runs at 2 m height can exceed 460 km especially during the early part of the growing season. The soil is a Pullman clay loam (fine, mixed, thermic torrertic Paleustoll; Unger and Pringle, 1981; Taylor et al., 1963), with slow permeability due to a dense B21t layer that is 0.15 to 0.40 m below the surface and a calcic horizon that begins about 1.2 to 1.5 m below the surface.

Agronomic practices were similar to those practiced for high lint yield in the High Plains region of Texas. Cotton (*Gossypium hirsutum* L., Paymaster[3] 2280 BG RR) was planted on 21 May 2003, and disked and replanted on 10 June 2003 (following severe hail damage to seedlings) at 17.3 plants m^{-2}, on east-west oriented raised beds spaced 0.76 m. The same variety was planted on 20 May 2004 at 19.0 plants m^{-2}. Furrow dikes were installed after crop establishment to control runoff (Schneider and Howell, 2000). In 2003, preplant fertilizer containing nitrogen (N) and phosphorous (P) (10-34-0) was incorporated into the raised beds, at rates resulting in 31 and 107 kg ha^{-1} of N and P, respectively, which were based on a soil fertility analysis. In 2004, similar rates of preplant fertilizer were applied (34 and 114 kg ha^{-1} of N and P, respectively). Additional N (32-0-0) was injected into the irrigation water from first square to early bloom, resulting in a total N application of 48 kg ha^{-1} in both seasons for the full irrigation treatment while deficit irrigation treatments received proportionately less. Treflan was applied at one time before planting at 2.3 L ha^{-1} to control broadleaf weeds in both seasons. No other in-season chemical inputs were required in either year, and no post harvest chemical inputs were required in 2003.

The experimental design consisted of four irrigation methods (MESA, LESA, LEPA, SDI, described in more detail shortly), and five irrigation levels (I_0, I_{25}, I_{50}, I_{75}, and I_{100}). The I_{100} level was sufficient to prevent yield-limiting soil water deficits from developing, based on crop evapotranspiration (ET_c) estimates from the North Plains ET Network (NPET, Howell et al., 1998), and the subscripts are the percentage of irrigation applied relative to the full irrigation amount. The different irrigation levels were used to estimate production functions, and to simulate the range of irrigation capacities one might encounter in the region. The I_0 level received sufficient irrigation for emergence only and to settle and firm the furrow dikes and

[3] The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service.

represents dryland production. The experiment was a variant of the split-block design (Little and Hills, 1978), where irrigation methods were in the direction of travel of a three-span lateral move system, and irrigation levels were perpendicular to the direction of travel. This sacrificed the precision of comparing different irrigation levels, but was necessary to facilitate operation of the lateral-move system using applicators common in the Southern High Plains. Each span of the linear move system constituted a complete block (i.e., replicated three times), and irrigation methods were randomized within each block. Plots were 25 m long by 9 m wide with 12 rows each, and 5 m planted borders separated irrigation level strips.

Spray and LEPA irrigations were applied with a hose-fed Valmont (Valmont Irrigation, Valley, NE) Model 6000 lateral move irrigation system. Drop hoses were located over every other furrow at 1.52 m spacing. Applicators were manufactured by Senninger (Senninger Irrigation Inc., Orlando, FL) and were equipped with 69 kPa pressure regulators and #17 plastic nozzles, giving a flow rate of 0.41 L s^{-1}. The MESA and LESA spray heads were positioned 1.5 and 0.3 m above the furrow, respectively. A double-ended drag sock (A. E. Quest and Sons, Lubbock, TX) was used with LEPA. The SDI consisted of Netafim (Netafim USA, Fresno, CA) Typhoon dripline that was shank injected in 1999 under alternate furrows at 0.3 m depth below the surface (before bedding). Irrigation treatment levels were controlled by varying the speed of the lateral-move system for the spray and LEPA methods, and by different emitter flow and spacing for the SDI method. All treatments were irrigated uniformly with MESA at the I_{100} level until furrow dikes were installed to ensure crop establishment.

Soil water was measured gravimetrically near the center of each plot prior to planting and just after harvest in the 1.8 m profile in 0.3 m increments, oven dried, and converted to volumetric contents using known soil bulk densities by profile layer. During the season, soil water was measured volumetrically near the center of each plot on a weekly basis by neutron attenuation in the 2.4 m profile in 0.2 m increments according to procedures described in Evett and Steiner (1995) and Evett et al. (2003). The gravimetric samples were used to compute seasonal water use (irrigation + rainfall + change in soil water), and the neutron measurements were to verify that irrigation was sufficient so that no water deficits developed in the I_{100} treatment.

Soil temperature was measured in 2004 at the I_{50} and I_{100} irrigation levels in the LESA, LEPA, and SDI plots using thermocouples made from 20 AWG Type-T thermocouple wire (Omega Engineering, Stamford, CN). The plots had a set of three (LESA and SDI) or four (LEPA) thermocouples at one bed location per plot, where thermocouples were buried in the sides of the bed (approximately 6 cm from the center) at 5 and 10 cm depths. In the LESA and SDI plots, two thermocouples were buried at the 5 cm depth on each side of the bed, and one thermocouple was buried at the 10 cm depth on the north side of the bed (adjacent to the irrigated furrow). In the LEPA plots, thermocouples were buried in each side of the bed both at the 5 and 10 cm depths. The fourth channel in the LESA and SDI plots was used for an infrared thermometer to measure canopy temperature. The thermocouples and infrared thermometers were not operational until 27 July 2004, when the crop height was approximately 0.75 m or greater, and the canopy width was 0.30 to 0.40 m.

Plants were mapped both seasons in all plots on a weekly basis beginning with 1st square, which included data on height, width, nodes, and number and position of fruit forms. In 2003, hand samples of bolls were collected from each plot on 19 Nov from a 10 m^2 area that was sequestered from other activity during the season. Samples were weighed, ginned, and analyzed for micronaire, strength, color grade, and uniformity at the International Textile Center, Lubbock, Texas. Seed cotton was harvested on 21 November with a commercial cotton stripper. Cotton stalks were shredded on 8 December and rotary-tilled into the beds on 10 December. The same sampling, harvest, and fiber analysis procedure is anticipated for the 2004 season.

Lint yield, seasonal water use (estimated from total irrigation + in season rainfall + change in soil water content in the 1.8 m profile), micronaire, strength, uniformity, water use efficiency (WUE), and irrigation water use efficiency (IWUE), total discount, and total return were tested for differences for each irrigation method using the SAS mixed model (PROC MIXED, Littell et al., 1996). In PROC MIXED, fixed and random effects are specified separately. Random effects were block replicates, block by irrigation level, and block by irrigation method, and the fixed effect was irrigation method. Differences of fixed effects were tested using least square means ($\alpha \leq 0.05$) within each irrigation level. WUE is defined as the ratio of economic yield (i.e., lint yield, LY) to seasonal water use (WU) or $WUE = LY\ WU^{-1}$. Seasonal water use includes evapotranspiration, deep percolation (if any), and runoff minus run on (if any). 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). Further details of experimental design, procedures, and equipment can be found in Colaizzi et al. (2004).

Results and Discussion

The 2003 growing season had much less rainfall and greater temperatures than average, and some record highs were set during the fall (16 September to 23 October). Total rainfall from planting to harvest (10 June to 21 November) was 167 mm, whereas the 65-year average for this period is 280 mm (fig. 1). There was 64 mm of rainfall between 10 and 30 June, which allowed in-season irrigations to be delayed until 8 July as there was sufficient water stored in the soil profile. No significant rainfall occurred again until 29 August, and the last irrigation was on 20 August. Preseason irrigations (100 to 200 mm) are not shown. Crop water use (ET_c) shown here was computed by the North Plains ET Network based on short-season cotton (Howell et al., 1998). The irrigation + rainfall totals for the I_{100} treatment tracked ET_c fairly well until irrigations were terminated (just after maximum bloom), indicating irrigation timing and amounts were appropriate. Additional water for consumptive use after 20 August was provided by water stored in the soil profile.

The record heat from 16 September to 23 October was probably fortuitous in that it compensated for a late start (recall hail damage required replanting on 10 June). The first open boll was not observed until 22 September, but nearly all bolls were open by 20 October, and the first frost occurred on 26 October. Additional frost events defoliated all remaining vegetative matter so that chemical defoliant was not required by harvest (21 November). The crop reached full maturity with only 1076 °C-days (growing degree days based on a 15.6°C base temperature). This was considerably less than the 1450 °C-days thought to be required for full maturity cotton in the Southern High Plains (Peng et al., 1989), but only slightly less than that reported by

Howell et al. (2004) for the 2000 and 2001 cotton seasons at our location, and was at the minimal range of growing degree days reported by Wanjura et al. (2002) for 12 years of data at Lubbock, TX.

No differences in maturity rates (open harvestable bolls) were noted for any irrigation method. Differences in maturity rates appeared to vary primarily with irrigation level, beginning with dryland (I_0), which had the greatest soil water depletion, and proceeding through each subsequent level, in agreement with Guinn et al. (1981), Mateos et al. (1991), and Orgaz et al. (1992).

Overall, SDI tended to perform best at the I_{25} and I_{50} irrigation levels, followed by LEPA. At the I_{75} level, LEPA outperformed the other methods, and at the I_{100} level, MESA performed best (table 1). Most parameter differences within a given irrigation level were not significant. Fully irrigated MESA (I_{100}) had the highest lint yield (1,229 kg ha^{-1}), premium (\$0.0950 kg^{-1}), and gross return (\$1,515.96 ha^{-1}) of all treatments in this study, but these were not significantly greater than other irrigation methods at I_{100} (except for LESA, which had significantly less premium at \$0.0466 kg^{-1}). SDI had the highest premiums at all levels except I_{100}, which suggests SDI generally results in higher fiber quality. Similar trends were observed with grain sorghum yield in a previous study using the same experimental design (Colaizzi et al., 2004).

The greatest values of lint yield, seasonal water use, WUE, premium, and gross return occurred at the I_{100} level among irrigation methods (table 1, irrigation level averages). However, the greatest IWUE and most optimal fiber quality parameters (except fiber length) occurred at the I_{75} level. Note that WUE at I_{50} and I_{100} were more than doubled and almost quadrupled, respectively, compared to dryland (I_0). The lint yield, seasonal water use, and WUE were generally within the range of values reported by Howell et al. (2004) for the 2000 and 2001 cotton seasons under MESA irrigation at our location; however, total irrigation applied (including pre-season irrigation) in the present study was somewhat less due to both a shorter growing season and slightly greater pre- and early season precipitation. Lint yields were almost as high as those reported by Wanjura et al. (2002) for their 1992 season, which only had 1092 °C-days, and they found that lint yield was more correlated to growing degree days than irrigation applied over their 12 years of data. For irrigation methods among levels (table 1, irrigation method averages), SDI had the greatest lint yield, seasonal water use, WUE, IWUE, premium, and gross return, followed by LEPA. Irrigation levels tended to result in parameter differences that were statistically significant, whereas for irrigation methods, parameter differences tended to be merely numerical.

The relationship between lint yield and seasonal water use was highly significant ($P < 0.001$) following linear regression (fig. 2). This relationship was not significantly different from those for individual irrigation methods, not surprising since lint yield showed greater variability with irrigation levels than for irrigation methods (table 1). Note that this relationship represents a single season, and different responses should be expected for different years (Wanjura et al., 2002; Howell et al., 2004). The X-axis intercept was significantly different from zero ($P < 0.001$), where 400 mm of water was required for minimum lint yield. This was double that reported by Howell et al. (2004) for the 2000 and 2001 seasons at our location. WUE was highly responsive to irrigation level through lint yield, with maximum WUE achieved at maximum lint yield (fig. 3). Both linear and quadratic regressions were significant ($P < 0.001$) with zero intercepts (intercepts were not significantly different from zero, and should not be by definition of WUE).

Finally, although the irrigation method did not appear to influence cotton earliness for this experiment in 2003, there is some evidence that the irrigation method can nonetheless influence small differences in soil temperatures. We measured soil temperature for several weeks beginning in 27 July 2004. Measurements included the final irrigation event of the season on 5 August, when 37 mm of irrigation water was applied to the I_{100} plots (fig. 4). Almost immediately, there was a sudden decrease in soil temperature at the 5 cm depth for each irrigation method (fig. 4a). During the next 24 hours, the soil temperature in the SDI plots was greater than LEPA and LESA at both the 5 and 10 cm depths, until 7 mm of rain fell just before 18:00 the following day. After the rain event, there were little differences, and it is uncertain whether this was from the rain event or a redistribution of soil water following the irrigation event. Soil temperatures at a given depth were nearly identical for each irrigation method before the irrigation event (data not shown).

During the three-day period following the irrigation event, we computed heat units based on both air and soil temperature on an hourly basis (i.e., hourly temperature above the 15.6 °C base temperature, divided by 24) (table 2). The hourly basis is thought to be more physiologically accurate than using daily mean temperature for computing heat units, especially for short time periods (Fry, 1983). The accumulated heat units using air temperature was 20.4 °C, but heat units using soil temperature was a few degrees greater and varied both by irrigation level (I_{50} and I_{100}) and irrigation method (LESA, LEPA, and SDI). The greatest difference was observed in the I_{100} plots at the 5 cm depth, where SDI accumulated 1.8 °C more than LESA.

The lack of differences in cotton earliness by irrigation method may be related to our current procedure of not initiating the different irrigation methods until the crop is established, (i.e., we used MESA for all the plots to ensure uniform germination). Soil evaporation may be sufficient to cool the seed bed and the small seedlings so that any heat unit advantage to SDI may be eliminated early in the season. This hypothesis, along with the soil temperature data, prompted us to redesign this experiment to make better use of SDI for crop germination. Thus, the same irrigation method will be used throughout the year for a given treatment, and SDI plots will no longer be subject to possible evaporative cooling by MESA early in the season. We will also concentrate the soil thermocouples in several beds within a single plot to help facilitate soil temperature measurement during the entire season.

Conclusion

Relative response of cotton to spray, LEPA, and SDI varied with irrigation capacity. At lower irrigation system capacity (I_{25} and I_{50}), SDI outperformed (either numerically or significantly) both spray and LEPA; whereas at full irrigation system capacity (I_{100}), spray outperformed both LEPA and SDI but only on a numerical basis. At the I_{75} level, LEPA numerically outperformed SDI, and SDI numerically outperformed spray. Cotton response had greater variation between irrigation capacities than irrigation methods, and highly significant relationships were observed between lint yield and seasonal water use, and water use efficiency and lint yield. Nonetheless, SDI had slightly greater premiums than other methods, suggesting SDI may enhance fiber quality. No differences in cotton maturity were observed among irrigation methods; however, preliminary data in 2004 clearly showed that soil temperature for SDI was greater during and after an irrigation event than that for LEPA or LESA. We believe the lack of differences in cotton maturity may have been related to using MESA for all plots until the crop is established to ensure uniform germination. Therefore, this experiment has been redesigned to make better use of SDI to germinate the crop, to avoid the possible early-season evaporative cooling associated with using MESA in the SDI plots.

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Table 1. Yield, water use, fiber quality, and return parameters as affected by irrigation levels and methods. Numbers followed by the same letter are not significantly different (α ≤ 0.05).

Irrigation Level [a]	Irrigation Method	Lint Yield (kg ha^{-1})	Seasonal Water Use (mm)	WUE (kg m^{-3})	IWUE (kg m^{-3})	Micronaire value	Fiber strength (g tex^{-1})	Fiber length (mm)	Fiber Uniformity (%)	Total Discount or Premium ($ kg^{-1})	Gross Return ($ ha^{-1}) [b]
I_0 (25 mm)	---	196	437	0.046	---	5.17	28.8	0.76	79.1	-$0.1575	$192.71
I_{25} (71 mm)	MESA	213b	477b	0.045b	0.024c	5.20a	28.4b	0.75b	78.9b	$-0.1646b	$208.19b
	LESA	288ab	495ab	0.058b	0.130bc	5.13a	29.4ab	0.79a	80.2ab	$-0.1386b	$288.55ab
	LEPA	362ab	494ab	0.072ab	0.234ab	4.50b	30.1a	0.79a	80.4a	$-0.0810a	$379.56ab
	SDI	491a	530a	0.092a	0.416a	4.70b	29.9a	0.80a	80.9a	$-0.0396a	$540.88a
I_{50} (117 mm)	MESA	536b	604ab	0.089b	0.288b	5.07a	30.2ab	0.83ab	81.3a	$-0.0810b	$567.16b
	LESA	575b	582b	0.098b	0.321b	5.07a	29.2b	0.81b	81.2a	$-0.1111b	$591.89b
	LEPA	685ab	629a	0.109ab	0.415ab	4.77ab	31.3a	0.84ab	81.8a	$0.0150a	$797.32ab
	SDI	844a	627a	0.135a	0.549a	4.40b	30.3ab	0.85a	82.2a	$0.0587a	$1010.08a
I_{75} (165 mm)	MESA	1001a	705a	0.142a	0.491a	4.53a	31.3a	0.86a	82.3a	$0.0623a	$1201.93a
	LESA	984a	685a	0.143a	0.480a	4.40ab	30.8a	0.86a	82.3a	$0.0605a	$1179.55a
	LEPA	1149a	701a	0.164a	0.581a	4.07bc	31.1a	0.87a	81.7a	$0.0500a	$1368.85a
	SDI	1082a	714a	0.152a	0.540a	3.80c	31.6a	0.87a	82.4a	$0.0829a	$1322.12a
I_{100} (211 mm)	MESA	1229a	752a	0.164a	0.492a	4.07a	31.4a	0.88a	82.5a	$0.0950a	$1515.96a
	LESA	1208a	754a	0.160a	0.482a	3.57b	30.9a	0.87a	81.7a	$0.0466b	$1429.41a
	LEPA	1153a	727a	0.158a	0.456a	3.53b	30.9a	0.88a	82.2a	$0.0557ab	$1375.79a
	SDI	1150a	725a	0.159a	0.454a	3.67b	30.4a	0.88a	81.9a	$0.0818ab	$1402.89a
Irrigation Level Averages											
I_0 (25 mm)	---	196d	437e	0.046c	---	5.17a	28.8c	0.76c	79.1b	$-0.1575c	$192.71d
I_{25} (71 mm)	---	339d	499d	0.067c	0.201c	4.88a	29.4c	0.79c	80.1b	$-0.1060c	$354.3d
I_{50} (117 mm)	---	660c	610c	0.108b	0.393b	4.83a	30.2b	0.83b	81.6a	$-0.0300b	$741.62c
I_{75} (165 mm)	---	1054b	701b	0.150a	0.523a	4.20b	31.2a	0.87a	82.2a	$0.0638a	$1268.12b
I_{100} (211 mm)	---	1185a	739a	0.160a	0.471ab	3.71c	30.9a	0.88a	82.0a	$0.0697a	$1431.02a
Irrigation Method Averages											
---	MESA	745a	635a	0.110a	0.324a	4.72a	30.3ab	0.83a	81.3a	$-0.0220bc	$873.29a
---	LESA	764a	629a	0.115a	0.353a	4.54a	30.0b	0.83a	81.4a	$-0.0356c	$872.35a
---	LEPA	837a	638a	0.126a	0.421a	4.22b	30.8a	0.85a	81.5a	$0.0100ab	$980.39a
---	SDI	892a	649a	0.134a	0.490a	4.14b	30.6ab	0.85a	81.8a	$0.0460a	$1068.99a

[a] Numbers in parentheses are in-season (planting to harvest) irrigation totals and do not include 100 to 200 mm of preplant irrigation.
[b] Based on a base loan value of $1.1352 kg^{-1}.

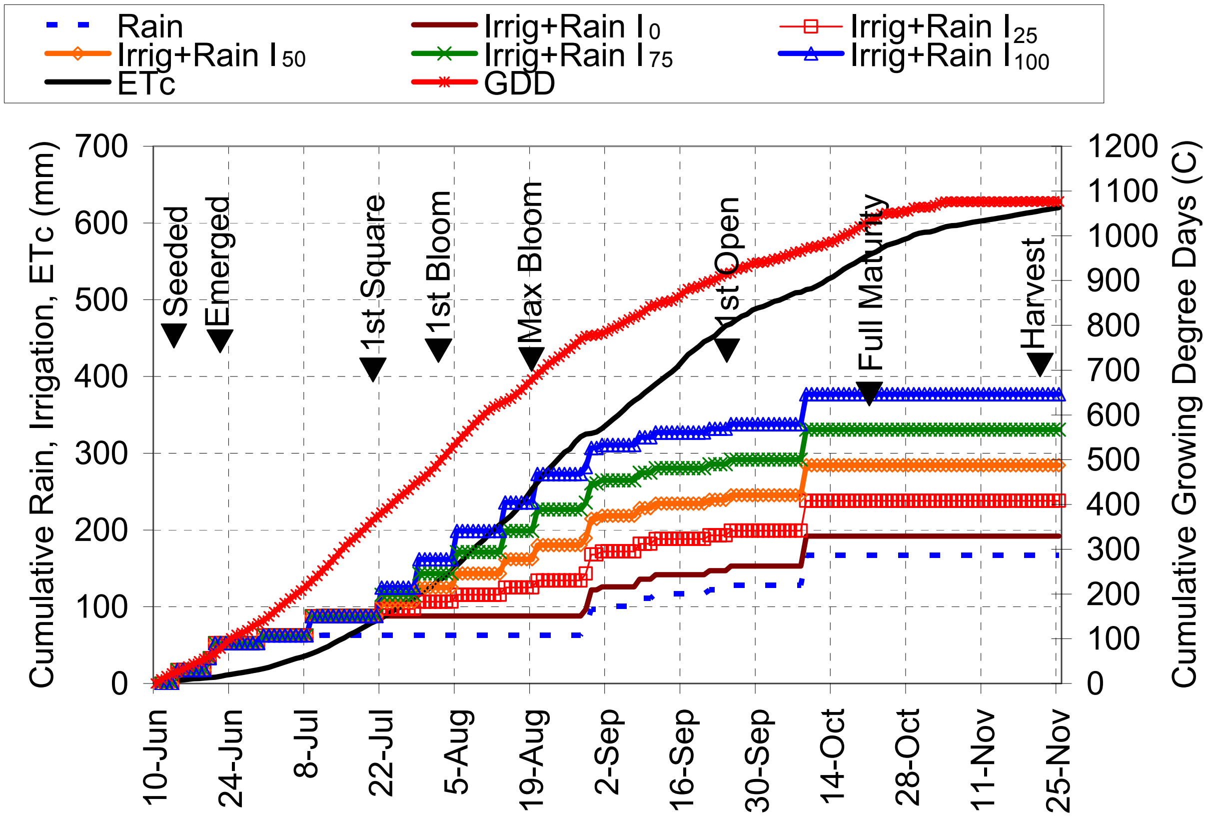

Figure 1. Seasonal rainfall, irrigation + rainfall for each LEVEL treatment, NPET-computed crop water use (ET_c), and growing degree days (°C, based on 15.9 °C base temperature), and growth stages for 2003 cotton season.

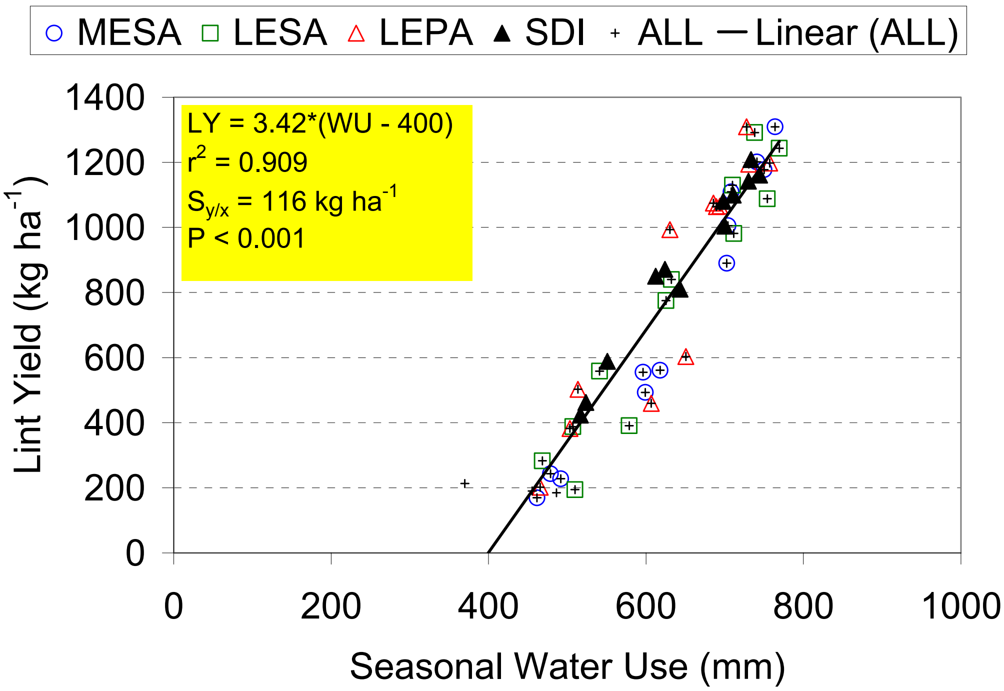

Figure 2. Cotton lint yield response (LY) to seasonal water use (WU) for the 2003 season, and coefficient of determination (r^2), standard error of the estimate ($S_{y/x}$), and significance (P).

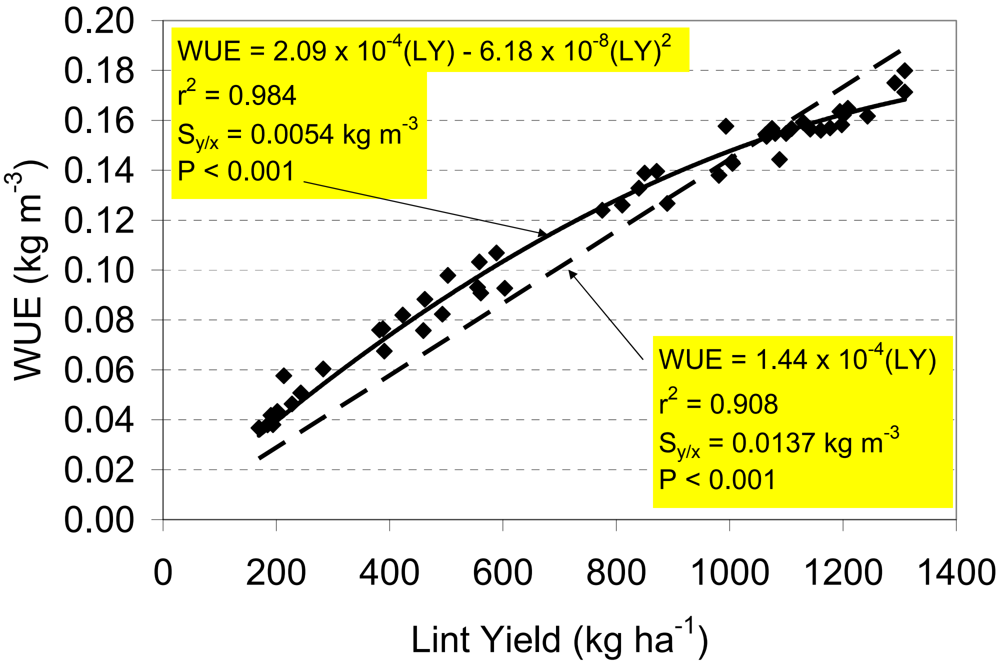

Figure 3. Water use efficiency (WUE) response to lint yield (LY) for the 2003 season, and coefficient of determination (r^2), standard error of the estimate ($S_{y/x}$), and significance (P).

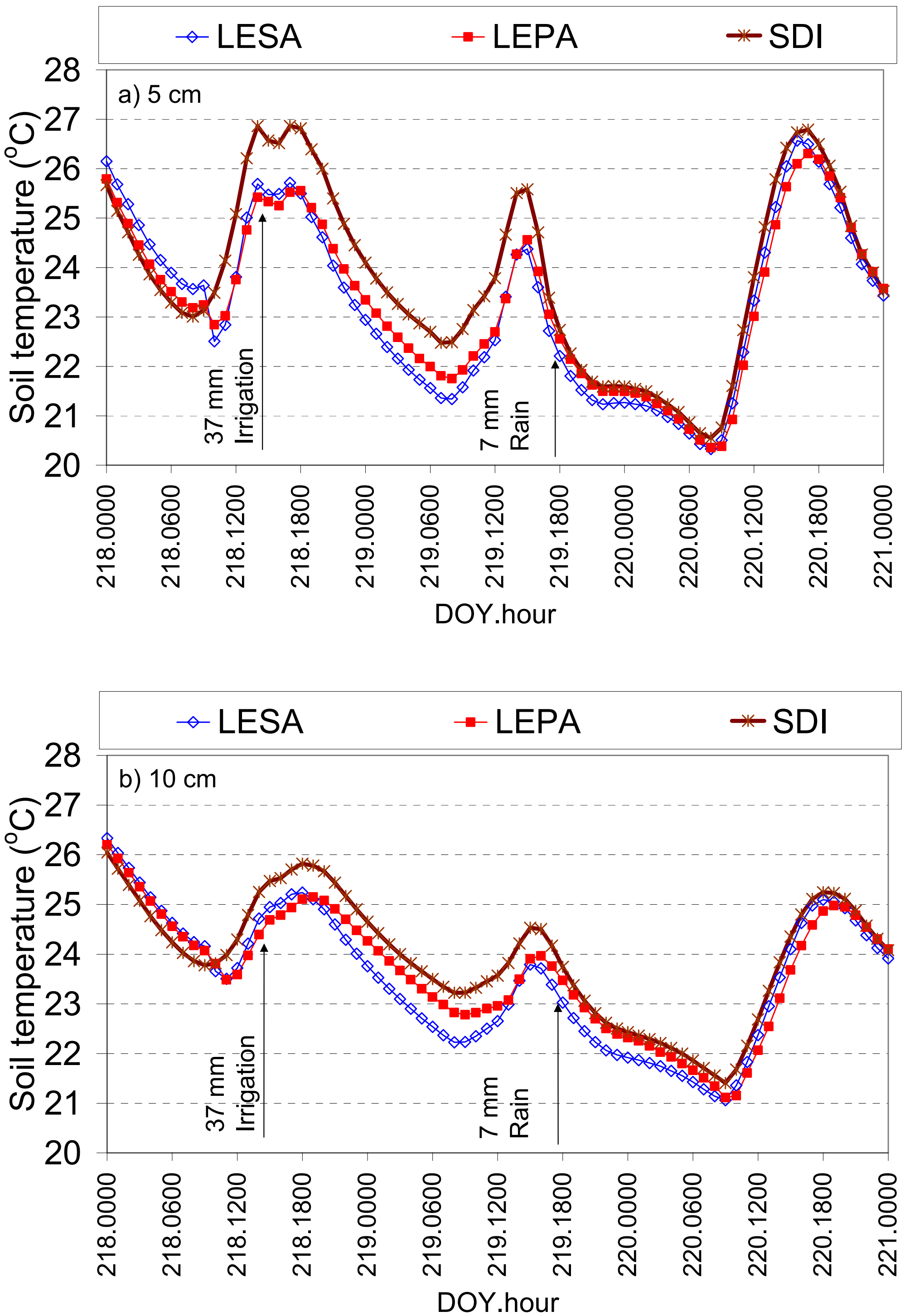

Figure 4. Soil temperature during August 5, 6, and 7, 2004 (DOY 218, 219, and 220) for I_{100} plots at (a) 5 cm, and (b) 10 cm below the surface.

Table 2. Accumulated heat units during August 5, 6, and 7, 2004 (DOY 218, 219, and 220) based on soil temperatures using a base temperature of 15.6 °C. The accumulated heat units based on air temperature was 20.4 °C for this period.

Irrigation Level	Irrigation Method	Soil temp 5 cm °C	Soil temp 10 cm °C
I_{50}	LESA	24.2	25.1
I_{50}	LEPA	24.8	25.3
I_{50}	SDI	25.2	25.9
I_{100}	LESA	23.0	23.7
I_{100}	LEPA	23.2	24.1
I_{100}	SDI	24.8	25.1