Cotton production with SDI, LEPA, and spray irrigation in a thermally-limited climate[1]

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Abstract

Producers in the Northern Texas Panhandle and Southwestern Kansas 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 growing degree days 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 growing degree day accumulation and lead to earlier maturation. Cotton maturity was more related to irrigation rate than irrigation method, with dryland and minimal irrigation rates reaching maturity earliest. However, fiber quality, as indicated by total discount, was usually better with SDI. Lint yield and water use efficiency were greatest with SDI at low irrigation rates in 2003, and lint yield and gross returns were greatest with SDI regardless of irrigation rate in 2004.

Introduction

The Southern High Plains of Texas, centered at approximately Lubbock, is one of the major cotton-producing areas in the United States, contributing approximately 10-20 percent of the average 20 million bales of upland cotton produced in the nation (USDA-NASS, 2005; TDA-TASS, 2005). In recent years, cotton production has expanded northward toward the Northern Texas Panhandle and Southwestern Kansas as an alternative to corn because cotton has only one-half the irrigation requirement but has a similar revenue potential as corn (Howell et al., 1997; 2004). The primary limitation to cotton production where corn has traditionally been produced is the lack of growing degree days (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; 2005). 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), analyzing four years of continuous monoculture cotton data at Halfway, Texas, concluded that SDI may not always provide economic returns as large as LEPA does; 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 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. Next to air temperature, soil water depletion in the root zone appears most responsible for inducing earliness for cotton (Guinn et al., 1981; Mateos et al., 1991; Orgaz et al., 1992) as well as for other crops (Wang, 1960; Idso et al., 1978). Nonetheless, a few studies may indirectly support the premise that SDI can enhance cotton maturity. 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 evaluate cotton yield, fiber quality, and maturity rates for spray, LEPA, and SDI under full and deficit irrigation in the Northern Texas Panhandle, which is a marginal climate for cotton production. This paper presents the results of the 2003 and 2004 growing seasons.

Procedure

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). 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 growing degree days (heat units) for cotton average 1,050 °C-days 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, with average daily wind runs at 2 m height exceeding 460 km, especially during the early part of the growing season. The soil is a Pullman clay loam (fine, superactive, mixed, thermic torrertic Paleustoll; USDA-NRCS, 2005), with slow permeability due to a dense B21t layer that is 0.15- to 0.40-m below the surface. A calcic horizon begins about 1.2 m below the surface.

Agronomic practices were similar to those practiced for high lint yield in the High Plains region of Texas (Table 1). 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}. In 2004 only, this variety was also planted in an adjacent, non-irrigated field at 12.5 plants m^{-2}, where every third row was not planted (known regionally as "skip row" planting). Furrow dikes were installed in the irrigated field after crop establishment both years 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 and 50 kg ha^{-1} in 2003 and 2004, respectively, for the full irrigation treatment. Deficit irrigation treatments received proportionately less N in irrigation water. 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 or post-harvest chemical inputs were required in either year.

The experimental design consisted of four irrigation methods (MESA, LESA, LEPA, SDI, described in more detail shortly), and five irrigation rates (I_0, I_{25}, I_{50}, I_{75}, and I_{100}). The I_{100} rate was sufficient to prevent yield-limiting soil water deficits from developing, and the subscripts are the percentage of irrigation applied relative to the full (I_{100}) irrigation rate. The I_{100} rate was based on soil water measurements with neutron scattering to 2.4-m depth. Early in the season, irrigation water was applied when soil water measurements indicated a deficit of 25 mm

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[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.

below field capacity in the I_{100} treatment. From first square to termination of irrigations, the appropriate irrigation amount was applied on a weekly basis. The different irrigation rates were used to estimate production functions, and to simulate the range of irrigation capacities one might encounter in the region. The I_0 rate received sufficient irrigation for emergence only and to settle and firm the furrow dikes and represents dryland production. In 2004, the adjacent non-irrigated field ("skip row," designated I_{sr}) was actually a true dryland treatment; however, available resources limited soil water and plant measurements to the irrigated field (I_0 through I_{100} treatments) so that only final lint yield and fiber quality were obtained for the I_{sr} treatment. The statistical design 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 rates were perpendicular to the direction of travel. This sacrificed the power of comparing different irrigation rates, 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 rate 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 to 1.8-m depth 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 to 2.4-m depth 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 used to verify that irrigation was sufficient so that no water deficits developed in the I_{100} treatment.

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. Hand samples of bolls were collected from each plot on 19 Nov 2003 and 14 Dec 2004 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 following hand sampling with a commercial cotton stripper, and stalks were shredded and rotary-tilled into the beds.

Lint yield, seasonal water use (estimated from total irrigation + in season rainfall + change in soil water content to the 1.8-m depth), 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 rate, 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 rate. Here, WUE was 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 was 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

Rainfall, Irrigation, and Growing Degree Days

The 2003 and 2004 growing seasons contrasted in that 2003 had below average rainfall and above-average air temperatures (Figure 1) and *vice-versa* for 2004 (Figure 2). In 2003, in-season rainfall was near the 66-year average until around 30 June, which allowed in-season irrigations to be delayed until 8 July as there was sufficient water stored in the soil profile (Figure 1a). No significant rainfall occurred again until 29 August, and the last irrigation was on 20 August. Irrigations plus rainfall (since planting only; does not include preplant irrigation) for the I_{100} treatment tracked crop water use (measured by gravimetric samples and neutron scattering in the 1.8-m profile, I_{100} treatment average) 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.

Cumulative growing degree days (15.6 ˚C base temperature; Fry, 1983; Peng et al., 1989) from replanting (10 June) to harvest (21 November) in 2003 totaled 1076 °C-days (Figure 1b). This was above the 17-year average of 893 °C-days for this period, and record high air temperatures from 16 September to 23 October were no doubt fortuitous in compensating for a late start following replanting due to hail damage. The first open boll in the I_{100} treatment was not observed until 22 September (900 °C-days), 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).

In 2004, in-season rainfall was unusually frequent but remained slightly below the 66-year average until late September, after which precipitation was above average for the remainder of the year (Figure 2a). Precipitation frequency continued to be unusually high for the remainder of the season, and the crop could not be harvested until 14 December. Numerous freeze events beginning 14 Oct (including 36 cm of snow on 2 Nov) defoliated all vegetative material and hastened boll opening by harvest so that no chemical defoliant was required. The period up to the first neutron scattering measurement (23 June) indicated only 5 mm of water use on average for the I_{100} irrigation rate (Figure 2a). This was unlikely because there were two 25-mm irrigation events and numerous rainfall events (totaling 38 mm). Furthermore, evaporation from bare soil plus a very small amount of transpiration from young plants was estimated at 53 mm using the Food and Agriculture Organization Paper No. 56 (FAO 56) dual crop coefficient approach (Allen et al., 1998). It is possible that unaccounted water entered the soil profile control volume from field run-on following a series of rainfall events 3-6 June that totaled 21 mm before the furrow dikes were installed (16 June).

Cumulative growing degree days for 2004 were near the 17-year average from planting (20 May) until around 9 August, and below average thereafter, only reaching 865 °C-days by harvest (Figure 2b). This is considerably below the 17-year average of 1000 °C-days for the same period. Cumulative growing degree days for both the 2003 and 2004 seasons were considerably less than the 1450 °C-days thought to be required for full maturity cotton in the Southern High Plains (Peng et al., 1989). The 2003 season (1076 °C-days) was 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. The 2004 season (865 °C-days) represents the least amount of growing degrees documented for full maturity cotton that we are aware of.

Crop Response to Irrigation Methods and Rates

No differences in maturity rates (open harvestable bolls) were noted for any irrigation method (MESA, LESA, LEPA, or SDI) in both the 2003 and 2004 seasons. Differences in maturity rates appeared to vary primarily with irrigation rates, beginning with I_0 and I_{sr}, 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).

Crop response in terms of lint yield, seasonal water use, water use efficiency (WUE), irrigation water use efficiency (IWUE), fiber quality parameters, discount or premium, and gross return were evaluated for irrigation rates and methods for 2003 (Table 2) and 2004 (Table 3). In 2003, crop response with SDI was most favorable at the I_{25} and I_{50} irrigation rates, followed by LEPA. At I_{75}, LEPA outperformed the other methods, and at I_{100}, MESA performed best. For a given irrigation rate, seasonal water use was greatest for SDI at I_{25} and I_{75}, nearly the same as LEPA at I_{50}, but smallest at I_{100}. Total discount or premium reflects fiber quality from a base loan value of \$1.1352 kg^{-1}, and SDI had the highest premiums at all irrigation rates except for I_{100}, which suggests SDI generally results in higher fiber quality. This is an important consideration given the greater emphasis placed on fiber quality by the textile industry in recent years. 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 always significantly greater than other irrigation methods at I_{100}. Most parameter differences within a given irrigation rate were not significant, including seasonal water use, and crop response varied more by irrigation rate than method. Among irrigation methods, I_{100} resulted in the greatest values of lint yield, seasonal water use, WUE, premium, and gross return. However, I_{75} resulted in the greatest IWUE and most optimal fiber quality parameters (except fiber length). Note that WUE at I_{50} and I_{100} were more than doubled and almost quadrupled, respectively, over I_0.

Similar trends were observed with grain sorghum yield in a previous study using the same experimental design (Colaizzi et al., 2004).

The cooler and wetter conditions of 2004 (Table 3) resulted in less seasonal water use, IWUE, micronaire, fiber strength, and greater discounts compared to 2003 (Table 2). Micronaire values were especially poor (the greatest was only 3.37 for I_0), and all treatments resulted in discounts below the base loan value. The greater precipitation also reduced the response to irrigation rates for lint yield, seasonal water use, WUE, IWUE, and gross return. Nonetheless, crop response parameters, including fiber quality, were significantly greater with SDI at all irrigation rates except for I_{25}, as well as among irrigation rates. Fiber quality, however, was best for the skip row treatment (I_{sr}), which reflects true dryland cotton production in the region, and I_{sr} had the smallest loan value discount (-\$0.0422 kg^{-1}) of all treatments in 2004, and the second highest gross return (\$649.25 kg^{-1}). From a commercial production standpoint, net returns would have been greatest for I_{sr} in 2004 because there were no costs associated with irrigation, but probably negative in 2003 because drought conditions would have resulted in near nonexistent lint yield.

The 2003 and 2004 lint yield, seasonal water use, and WUE were within the range of values reported by Howell et al. (2004) for the 2000 and 2001 cotton seasons under MESA irrigation at our location, and 2003 lint yields were almost as high as those reported by Wanjura et al. (2002) for their 1992 season, which only had 1092 °C-days. They found that lint yield was more correlated to growing degree days than irrigation applied over their 12 years of data.

Production Functions and Water Use Efficiency

The relationships between lint yield and seasonal water use were significant ($P < 0.001$) following linear regression for each year (Figure 3). These relationships were not significantly different from those for individual irrigation methods, not surprising since lint yield showed greater variability with irrigation levels than for irrigation methods (Tables 2 and 3). The different responses should be expected for different years due to interactions between seasonal water use, growing degree days, and other environmental factors (Wanjura et al., 2002; Howell et al., 2004). The X-axis intercept was significantly different from zero in 2003 ($P < 0.001$) but not in 2004 ($P = 0.234$). In 2003, 400 mm of water was required for minimum lint yield, which was double reported by Howell et al. (2004) for the 2000 and 2001 seasons at our location.

Conclusion

Cotton maturity was influenced by soil water depletion (reflected by irrigation rate) rather than irrigation method. Fiber quality was usually better with SDI in both years, which is becoming increasingly important in the global market. For a given irrigation rate, seasonal water use differences were not always significant or consistent between irrigation methods, with seasonal water use sometimes being greater with SDI, possibly due to enhanced plant vigor. In 2003, SDI outperformed (either numerically or significantly) other irrigation methods at low irrigation rates (I_{25} and I_{50}). However, MESA and LESA outperformed both LEPA and SDI at the I_{100} rate, but only on a numerical basis. At the I_{75} rate, LEPA numerically outperformed SDI, and SDI numerically outperformed MESA and LESA. In 2004, SDI outperformed (often significantly) all other methods at the I_{50}, I_{75}, and I_{100} rates, as well as among irrigation rates. In both years, significant (but different) relationships were observed between lint yield and seasonal water use.

In order to further investigate crop response to irrigation methods, this study has been expanded to include detailed studies of near-surface soil temperature and volumetric moisture content, where arrays of permanent thermocouple and time-domain reflectometry (TDR) probes were installed in the raised beds beginning with the 2005 season. Large hail on 10-11 June 2005 destroyed the third cotton crop, and the field was replanted in soybeans, but it appears we have obtained quality soil temperature and moisture data for several irrigation events. Plans are to plant cotton again in 2006.

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Table 1. Agronomic and irrigation data for 2003 and 2004.

Variable	2003	2004
Fertilizer applied	31 kg ha^{-1} preplant N 107 kg ha^{-1} preplant P 48 kg ha^{-1} irr N (I_{100}) [a]	34 kg ha^{-1} preplant N 114 kg ha^{-1} preplant P 50 kg ha^{-1} irr N (I_{100}) [a]
Herbicide applied	2.3 L ha^{-1} Treflan	2.3 L ha^{-1} Treflan
Insecticide applied	NONE	NONE
Gravimetric soil water samples	20-May 24-Nov	17-May 20-Dec
Cotton variety	Paymaster 2280 BG, RR	Paymaster 2280 BG, RR
Plant density	17 plants m^{-2}	19 plants m^{-2}
Planting date	10-Jun [b]	20-May
Harvest date	21-Nov	14-Dec
I_0 preplant irrigation	200 mm	25 mm
I_{25} preplant irrigation	200 mm	25 mm
I_{50} preplant irrigation	175 mm	25 mm
I_{75} preplant irrigation	125 mm	25 mm
I_{100} preplant irrigation	100 mm	25 mm
Irrigations to set furrow dikes	9-Jul	18-Jun
First treatment irrigation	21-Jul	14-Jul
Last irrigation	20-Aug	8-Aug
I_0 in-season irrigation	25 mm	50 mm
I_{25} in-season irrigation	71 mm	72 mm
I_{50} in-season irrigation	117 mm	94 mm
I_{75} in-season irrigation	165 mm	115 mm
I_{100} in-season irrigation	211 mm	137 mm
Precipitation	230 mm [c]	495 mm

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

[b] The first planting on 21 May sustained severe hail damage on 3 June.

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

Table 2. 2003 season 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 ($\alpha \leq 0.05$).

Irrigation Rate [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 [b] ($ kg^{-1})	Gross Return ($ ha^{-1})
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	$1402.89a
Irrigation Rate Averages											
I$_{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.

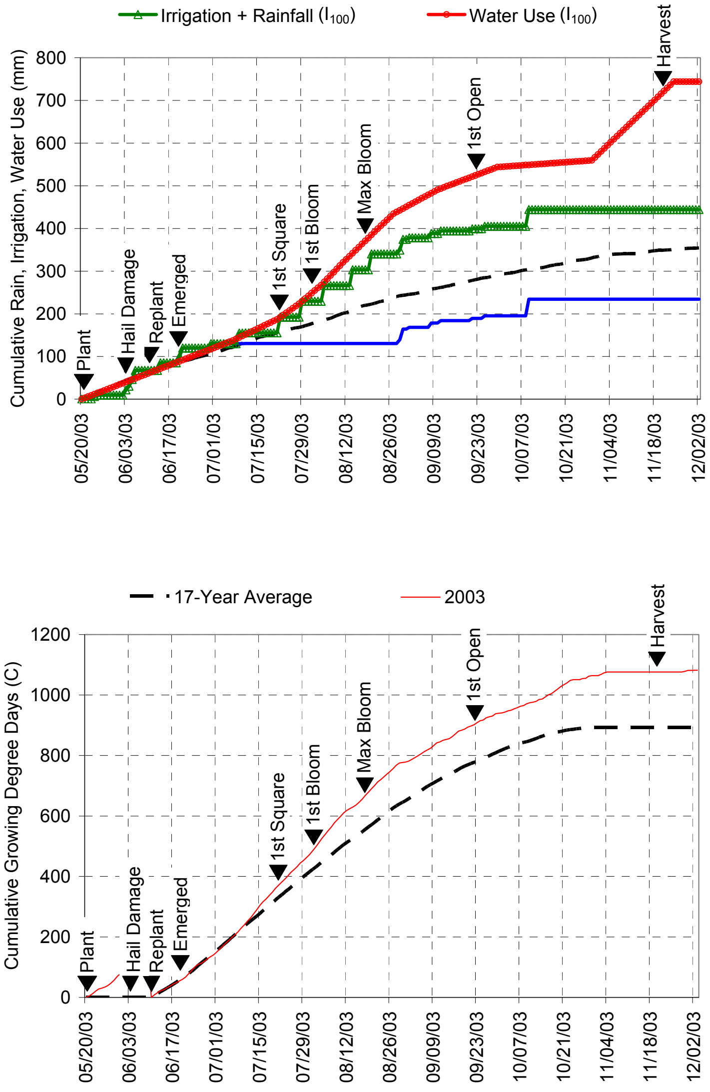
[b] Based on a base loan value of $1.1352 kg^{-1}(average of all treatments for both years), from International Textile Center, Lubbock, Texas.

Table 3. 2004 season 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 ($\alpha \leq 0.05$).

Irrigation Rate [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 [b] ($ kg^{-1})	Gross Return ($ ha^{-1})
I_{25} (72 mm)	MESA	622a	355c	0.176a	0.124ab	2.83a	26.9b	0.82b	79.9a	$-0.1910a	$587.68a
	LESA	579a	390bc	0.148bc	0.064b	2.70a	28.3a	0.85a	79.8a	$-0.1797a	$553.01a
	LEPA	586a	428a	0.137c	0.074b	2.70a	27.8ab	0.84a	80.3a	$-0.1921a	$555.60a
	SDI	648a	404ab	0.161ab	0.160a	2.77a	27.8ab	0.83ab	79.6a	$-0.1723a	$623.62a
I_{50} (94 mm)	MESA	594b	402b	0.148a	0.065b	2.73a	26.8ab	0.84a	79.8a	$-0.1731a	$571.63ab
	LESA	563b	411b	0.137a	0.032b	2.70a	26.9ab	0.83a	80.6a	$-0.227ab	$510.32b
	LEPA	592b	406b	0.146a	0.063b	2.63a	26.1b	0.82a	80.5a	$-0.2431b	$528.20b
	SDI	681a	452a	0.151a	0.158a	2.77a	27.2a	0.84a	80.3a	$-0.1683a	$658.41a
I_{75} (115 mm)	MESA	644b	434ab	0.148b	0.096b	2.63a	26.9a	0.84a	80.5a	$-0.1954a	$604.78b
	LESA	637b	448a	0.142b	0.091b	2.73a	26.7a	0.83a	80.5a	$-0.1881a	$603.54b
	LEPA	673b	437ab	0.154b	0.122b	2.70a	27.3a	0.83a	80.4a	$-0.2057a	$625.20b
	SDI	779a	410b	0.191a	0.214a	2.80a	27.2a	0.84a	80.9a	$-0.1665a	$755.62a
I_{100} (137 mm)	MESA	684b	461a	0.148b	0.110b	2.70b	27.0b	0.83b	80.7b	$-0.2009b	$640.29b
	LESA	675b	489a	0.139b	0.104b	2.77b	27.2ab	0.82b	80.3b	$-0.1885b	$639.49b
	LEPA	733b	462a	0.159b	0.147b	2.80b	26.8b	0.83b	80.7b	$-0.187b	$695.54b
	SDI	879a	455a	0.194a	0.253a	3.03a	28.3a	0.85a	81.9a	$-0.0854a	$923.80a
Irrigation Rate Averages											
I_{sr} (0 mm)	---	594bc	---	---	---	3.30a	30.0a	0.87a	82.1a	$-0.0422a	$649.25ab
I_0 (50 mm)	---	533c	367c	0.145a	---	3.37a	27.9bc	0.81c	80.1bcd	$-0.0956a	$553.46b
I_{25} (72 mm)	---	609c	394c	0.155a	0.106a	2.75bc	27.7b	0.84b	79.9d	$-0.1838bc	$579.97b
I_{50} (94 mm)	---	607c	418b	0.146a	0.080a	2.71c	26.8d	0.83b	80.3cd	$-0.2029c	$567.14b
I_{75} (115 mm)	---	683ab	432b	0.159a	0.131a	2.72c	27.0cd	0.84b	80.6bc	$-0.1889bc	$647.29ab
I_{100} (137 mm)	---	743a	467a	0.160a	0.154a	2.83b	27.3bc	0.83b	80.9b	$-0.1655b	$724.78a
Irrigation Method Averages											
---	MESA	636b	413a	0.155b	0.099b	2.73ab	26.9b	0.83b	80.2a	$-0.1901b	$601.09b
---	LESA	614b	434a	0.142b	0.073b	2.73ab	27.3ab	0.83ab	80.3a	$-0.1958b	$576.59b
---	LEPA	646b	433a	0.149b	0.101b	2.71b	27.0b	0.83b	80.5a	$-0.2070b	$601.13b
---	SDI	747a	430a	0.174a	0.196a	2.84a	27.6a	0.84a	80.7a	$-0.1481a	$740.36a

[a] Numbers in parentheses are in-season (planting to harvest) irrigation totals and do not include 25 mm of preplant irrigation.

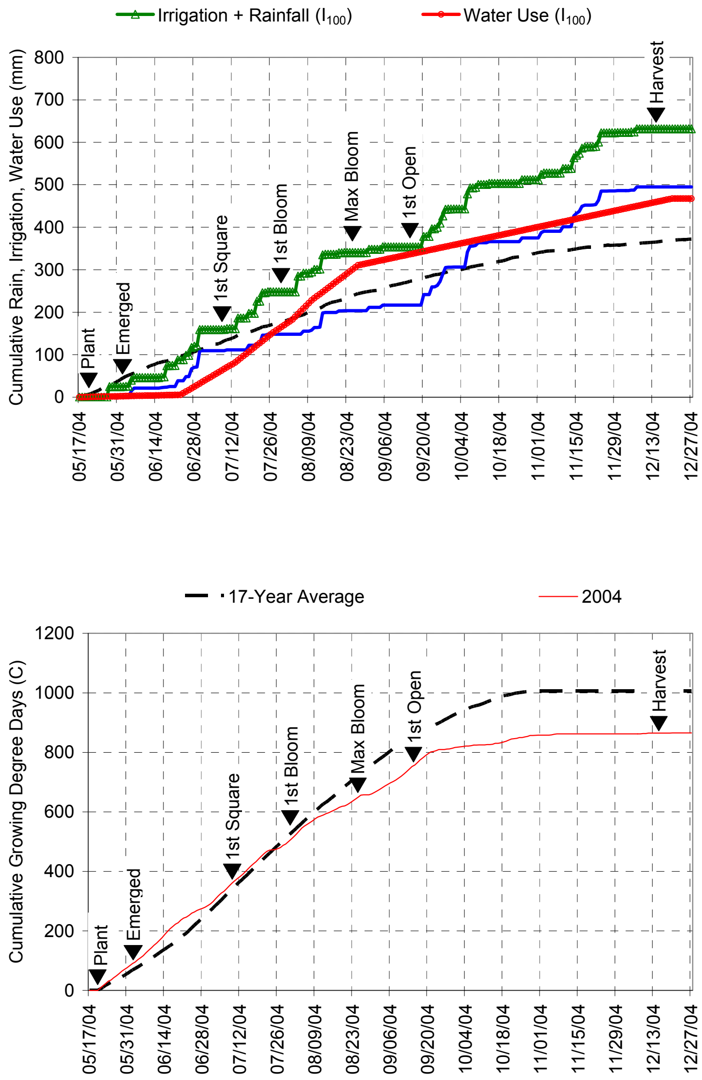
[b] Based on a base loan value of $1.1352 kg^{-1} (average of all treatments for both years), from International Textile Center, Lubbock, Texas.



a.

b.

Figure 1. 2003 cotton season for full irrigation (I_{100}) rate.



a.

b.

Figure 2. 2004 cotton season for full irrigation (I_{100}) rate.

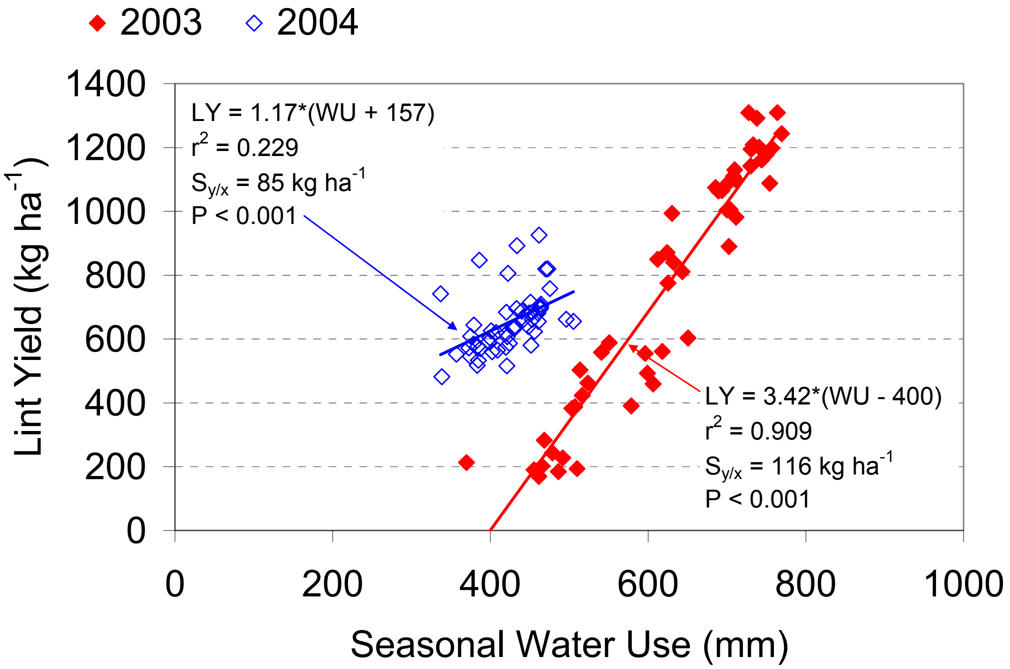


Figure 3. Production functions for the 2003 and 2004 cotton seasons.