Economic Analysis of Subsurface Drip Irrigation Lateral Spacing and Installation Depth for Cotton

J. M. Enciso, P. D. Colaizzi, W. L. Multer

Abstract. *Cotton lint yield, seed mass, fiber quality parameters, gross return, and net return were compared for subsurface drip irrigation (SDI) lateral spacing and installation depth in a clay loam soil in western Texas for three seasons. Drip laterals were spaced either in alternate furrows (2 m) or beneath every planted bed (1 m), and installation depths were either 0.2 or 0.3 m beneath the soil surface. Net return was gross return minus fixed and variable costs. Fixed costs included the annual payment for financing the initial investment of SDI materials and installation (5.00% interest over 10 years), the annual land lease, and the annual depreciation of the SDI system. Variable costs were those associated with cotton production and were similar for the two drip lateral spacings. Lint yield, seed mass, and gross and net returns were significantly greater for the 1 m lateral spacing in the first two seasons, but these parameters were significantly greater for the 2 m lateral spacing in the third season. These parameters were consistently greater (either numerically or significantly) for the 0.3 m lateral depth in all seasons. Most fiber quality parameters were not significantly different, and no consistent trends were observed. Lint yields ranged from 640 to 1,635 kg ha^{-1}, and net returns ranged from −\$395 to \$1,005 ha^{-1}. The low lint yield and resulting net loss were due to a germination failure in the second season for the alternate furrow spaced laterals. Additional seasons of study are required before conclusions might be drawn concerning the most economic lateral spacing for cotton production in the Trans−Pecos region of Texas, but the 0.3 m lateral depth resulted in greater net returns than the 0.2 m lateral depth.*

Keywords. *Cost benefit analysis, Microirrigation, Texas.*

Texas accounts for about 26% of the 19 million bales of cotton produced in the U.S. annually, ranking Texas first in terms of total cotton production, followed by California at 13% and Mississippi at 11% (USDA−NASS, 2004). About 68% of cotton production in Texas is concentrated in the Southern High Plains and Northern Trans Pecos region (referred to as West Texas herein). Average lint yield per land area (i.e., average of irrigated and dryland) is generally lower than both the state and national averages because rainfall is insufficient and sporadic (average is 380 mm). Atmospheric demand is high (full irrigation requirements for a season can exceed 800 mm) (Wanjura et al., 2002), water resources are insufficient to fully irrigate all arable land, and nearly all irrigation is supplied by pumping from underground aquifers. Where cotton is fully irrigated, however, lint yield and water use efficiency are among the highest in the nation, and cotton production contributes substantially to the Texas economy (TDA−TASS, 2004).

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The authors are **Juan M. Enciso, ASAE Member Engineer,** Assistant Professor and Agricultural Engineering Specialist, Texas A&M University, Texas Cooperative Extension, Texas Agricultural Experiment Station, Weslaco, Texas; **Paul D. Colaizzi, ASAE Member Engineer,** Agricultural Engineer, USDA−ARS Conservation and Production Research Laboratory, Bushland, Texas; and **Warren L. Multer,** Extension Agent−IPM, Texas Cooperative Extension, Glasscock County Extension Office, Garden City, Texas. **Corresponding author:** Paul D. Colaizzi, USDA−ARS, P.O. Drawer 10, Bushland, TX 79012−0010; phone: 806−356−5763; fax: 806−356−5750; e−mail: pcolaizzi@cprl.ars.usda.gov.

Beginning in the early 1980s, cotton producers in West Texas began to install subsurface drip irrigation (SDI) systems to stretch declining groundwater resources. Henggeler (1995) reported that adoption of SDI greatly improved lint yield and water use efficiency for several commercial producers, and noted an average 27% increase in yield over surface (furrow) irrigation, and yield increases greater than 2.5 times over dryland. Yield increases in furrow−irrigated fields were also noted, apparently from water savings from SDI that were reallocated to the furrow−irrigated fields during preplant irrigations. This happened despite SDI generally comprising an average of 11% of the total irrigated area on a given farm. Additional benefits included reduced labor, herbicide, and cultivation requirements; however, no reductions in total water or energy use were documented.

Perhaps the greatest single barrier to the widespread adoption of SDI is the high initial investment, coupled with the absence of general economic guidelines. In a comprehensive review of SDI, Camp (1998) concluded that uncertainties in water resource availability and cost (e.g., energy costs of pumping), commodity prices, and site−specific soil and other physical characteristics make a long−term economic analysis for selecting the most appropriate irrigation system very difficult. He further cited Knapp (1993), who recommended the development of computer programs (see, for example, Srivastava et al., 2003) and extensive site−specific databases, since developing general guidelines are simply infeasible. Nonetheless, a few studies have reported economic analyses between SDI and other irrigation systems. Henggeler (1997) presented a case study of a 195 ha cotton farm in West Texas that converted furrow−irrigated fields to SDI over eight years, and reported a 450% net return on the initial SDI investment over a 16−year period. Bosch et al.

(1992) performed a corn−soybean rotation simulation in Virginia for SDI vs. towable and stationary center pivots, and concluded that SDI gave the greatest returns for parcels less than 30 ha, but towable and stationary center pivots were more economical for parcels greater than 60 and 120 ha, respectively. O'Brien et al. (1998) analyzed continuous corn in western Kansas and found that SDI was more economical than a center pivot only for parcels less than 13.0 ha (about one−quarter of a 51 ha circle typically irrigated by a center pivot) and only if the entire SDI system lasted 10 years or more. They reported that results of their analysis were also greatly affected by the cost of dripline and the market price of corn.

Dripline is a large portion of the initial SDI cost; therefore, drip laterals are most commonly buried beneath alternate furrows rather than under each planted row, resulting in half the number of drip laterals as planted rows (Camp, 1998; Lamm and Trooien, 2003), which can reduce the initial cost by 30% to 40% (Henggeler, 1995; Camp et al., 1997). In regions where rainfall around planting time is fairly reliable, different lateral spacings either have not greatly influenced germination or final yield, or crop yield was not sufficiently reduced to warrant the extra cost of a closer lateral spacing (Powell and Wright, 1993; Camp et al., 1989; Camp et al., 1997; Lamm et al., 1997). In regions such as West Texas, however, where rainfall is unreliable throughout the year, and high atmospheric demand often removes near−surface soil water that is required for seed germination, alternate furrow spacing can potentially require excessive preplant irrigation to sufficiently wet the seed bed (Henggeler, 1995; Howell et al., 1997; Bordovsky and Porter, 2003), or result in poor crop establishment (Charlesworth et al., 1998; Charlesworth and Muirhead, 2003). This can be especially problematic for coarser soils where water movement is dominated more by gravity than capillary forces (Thorburn et al., 2003), or where the soil has a relatively high clay content and shrinking results in large cracks (Howell et al., 1997). Even in locations that normally receive substantial rain, yield variability may increase with lateral spacing (Bosch et al., 1998). Despite the potential problems with lateral spacing in alternate furrows, Hengeller (1995) observed this configuration in 76.2% of SDI installations surveyed in West Texas, where cotton is commonly planted in raised beds spaced 1.0 m apart and drip laterals are spaced 2.0 m apart.

There is recent renewed interest in installing drip laterals beneath each planted bed. This may be related to the widespread drought over most of the western U.S., which has required greater irrigation amounts for seed germination, along with the continued decline in groundwater aquifers and increasing energy costs. In addition, drip laterals installed beneath each planted row are thought to expedite the movement of salts away from the root zone and toward the surface of the raised bed. Electro−conductivities (EC) of some irrigation wells in the region have been observed as high as 5.8 dS m^{-1} and sodium adsorption ratios (SAR) as high as 7.0. The objective of this article is to evaluate the costs and returns of cotton production in West Texas for two drip lateral spacings (alternate furrows and each planted bed) at two installation depths (0.2 and 0.3 m).

MATERIALS AND METHODS

A field experiment was conducted on a cooperating producer's farm in St. Lawrence, Texas, during the 2001, 2002, and 2003 seasons. The area is semi−arid and receives an average of 380 mm rainfall per year. The soil at the site was a well−drained Reagan clay loam (thermic Ustolic Calciorthids) with 29% sand, 42% silt, and 29% clay, and 0% to 1% slope. Cotton (*Gossypium hirsutum* L., cv. 458 Deltapine) was planted at a density of 13 plants m^{-2} on raised beds spaced 1 m apart. The cotton variety was genetically modified with *Bt* traits to limit insect damage and its influence on the experiment. A subsurface drip irrigation (SDI) system was installed to supplement crop water demand not met by rainfall. Liquid nitrogen (urea ammonium nitrate 32−0−0) was injected into the irrigation water in two applications. Other agronomic practices were similar to those used for high−yield cotton production on commercial farms in the area (table 1).

The experimental design consisted of a complete randomized block with four treatments. Treatments consisted of two factors (drip lateral spacing and lateral installation depth) at two levels each. Drip lateral spacing was either 1 m (beneath every planted bed) or 2 m (beneath alternate furrows) (fig. 1). Lateral depths were shank−injected either 0.2 m or 0.3 m beneath the soil surface, which is typical of most installations in West Texas (Henggeler, 1995). Camp (1998) noted that lateral installation depth was seldom a treatment variable, so little information is available. Most lateral installation depths for permanent SDI systems reflect practical experience and are a trade−off between tillage practices and soil hydraulic conductivities; however, installation depths can also be constrained by soil texture and availability of field equipment. Each plot had eight planted rows and was 290 m long, and all plots in the field were adjacent to each other. Plots were replicated four times, and total field area was 3.79 ha. In 2001 and 2002, wheel traffic was allowed in the furrows containing dripline (2 m spacing, fig. 1b), but in 2003 wheel

Table 1. Dates of planting, first and last irrigation, nitrogen injection, irrigation, and rainfall amounts for each season.

Operation	2001	2002	2003
Planting date	14 May	30 May	12 May
First in−season irrigation	3 June	6 June	8 June
First N injection	25 June (49.3 kg ha^{-1})	10 June (63.9 kg ha^{-1})	1 July (51.6 kg ha^{-1})
Second N injection	17 July (53.8 kg ha^{-1})	17 July (53.8 kg ha^{-1})	20 July (51.6 kg ha^{-1})
Last irrigation	7 Sept.	10 Sept.	16 Sept.
Harvest date	17 Oct.	2 Oct.	21 Oct.
Preplant irrigation (mm)			
Subplot 1 (SS1)	130	18	114
Subplot 2 (SS2)	180	18	161
In−season irrigation (mm)			
Subplot 1 (SS1)	324	288	245
Subplot 2 (SS2)	272	288	245
Total irrigation (mm)			
Subplot 1 (SS1)	454	306	359
Subplot 2 (SS2)	452	306	406
Rainfall (mm)			
Received in−season	149	107	144
For the calendar year	521	361	227

traffic was restricted to the non−dripline furrows due to a germination problem that will be discussed shortly.

Plots were further divided into two adjacent 4−row subplots (designated SS1 and SS2), where irrigation water applied could be an additional treatment variable, as each subplot was equipped with a solenoid−controlled irrigation valve, flowmeter, and flow volume totalizer (table 1). Preplant irrigation amounts were determined from gravimetric sampling before planting. In 2001, the SS2 subplot received 180 mm of preplant irrigation (determined from gravimetric sampling), and the SS1 preplant amount was reduced by 50 mm. The SS1 in−season amount was then increased by 50 mm, so the total irrigations for SS1 and SS2 were equal. In 2002, irrigation amounts were not varied between SS1 and SS2. In 2003, the SS2 subplot received 161 mm of preplant irrigation (again, determined from gravimetric sampling), and the SS1 preplant amount was reduced by 47 mm. In−season irrigation amounts were the same, so that total irrigation for SS2 was 47 mm greater than SS1.

Dripline was Netafim Python (Netafim USA, Fresno, Cal.), with a 12.5 mil thickness, 0.61 m emitter spacing, and a 0.91 L h^{-1} nominal discharge per emitter. This resulted in irrigation application rates of 1.46 and 0.73 mm h^{-1} for the 1 and 2 m lateral spacing, respectively. Irrigations to each plot were scheduled daily using a Rain Bird automatic irrigation controller (Rain Bird Corp., Glendora, Cal.). The plots were irrigated from a nearby well having a flow capacity of 1.9 L s^{-1}. This limited flow rate permitted each plot to receive a maximum of 4.3 mm d^{-1}. Peak−season crop water demands, however, can exceed 8 mm d^{-1}; therefore, in−season irrigations were scheduled on the basis of equitable distribution of water to each plot, and additional crop water demand was met by mining water stored in the soil profile. This is common practice in water−limited regions such as West Texas since it is not always possible to maintain the soil water profile above a specified level during the irrigation season.

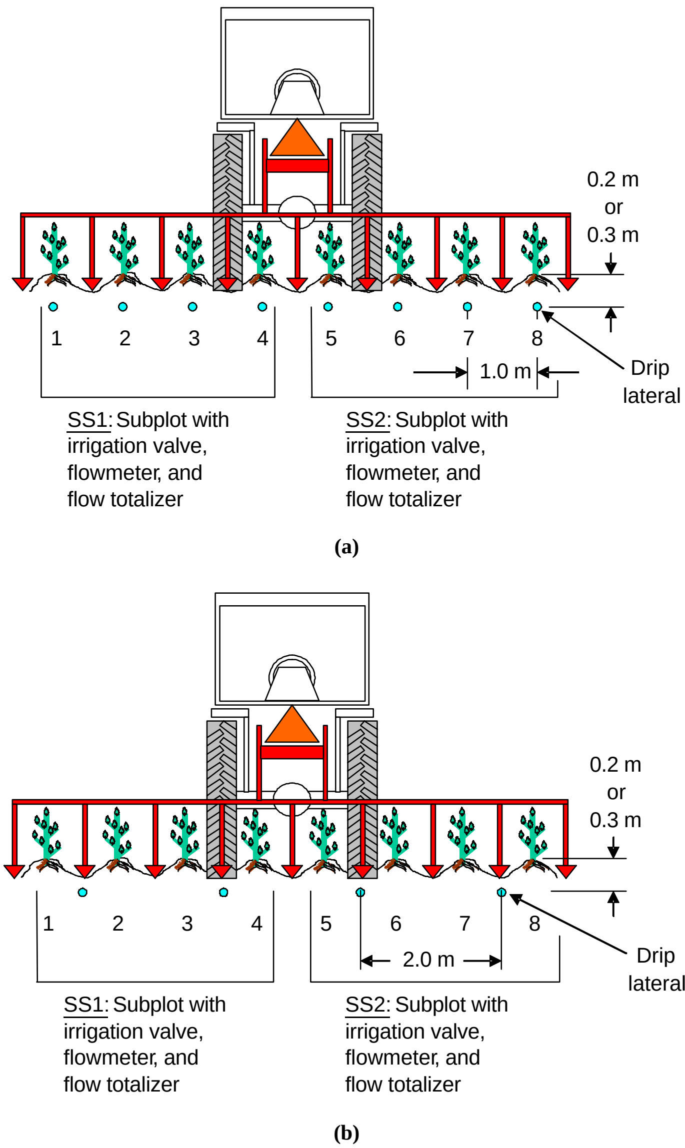

Figure 1. Drip lateral spacing, position of tractor wheels and cultivation tools, and row numbers for each main plot: (a) laterals under every planted bed (1 m spacing), and (b) laterals under alternate furrows (2 m spacing), as shown for the 2001 and 2002 seasons. In 2003, the tractor wheels were moved over one row.

Harvest data were gathered from within each plot mechanically by harvesting four rows. Seed cotton was weighed for each replicate, and a portion (about 0.6 kg) was ginned at the Texas A&M Agricultural Research and Extension Center in Lubbock, Texas. Lint was analyzed for fiber quality at the International Textile Center of Texas Tech University in Lubbock. Fiber quality parameters (which influence final loan values and gross returns) included length, micronaire, strength, and uniformity.

Lint yield, seed mass, fiber length, micronaire, fiber strength, fiber uniformity, final loan value (base price adjusted for fiber quality), gross return, and net return (gross return − fixed costs − variable costs) were tested for differences for each season and all seasons combined using the SAS mixed model (Proc Mixed; Littell et al., 1996). In Proc Mixed, fixed and random effects are specified separately. Fixed effects included lateral spacing, lateral depth, and irrigation amounts (2001 and 2003 only), and replication was the random effect. The different irrigation amounts did not have a statistically significant effect on lint yield or other performance parameters (data not shown). Irrigation amounts (subplots) were then excluded from the fixed effects (Model statement) in all years, and yield and fiber quality data from subplots were taken as subsamples of main plots. To specify subsamples in Proc Mixed, the random effect was specified as replication × subsample, rather than just replication (S. Duke, personal communication). Differences of fixed effects (lateral spacing and installation depth only) were tested using least square means ($\alpha \leq 0.05$), and means were separated by letter groupings using a macro by Saxton (1998). An additional Proc Mixed model was run to test for differences using least square means ($\alpha \leq 0.05$) of each parameter between years.

Results and Discussion

Climate and Irrigation

Climatic conditions for each growing season were similar, with warm, mostly dry weather prevailing and two distinct periods of heightened in−season precipitation occurring during May and August −September (fig. 2). Rainfall for the calendar year 2001 was slightly below average until two large events (13 and 26−27 November) brought the annual total to 521 mm. Sufficient soil water was stored in the profile by the following spring, so very little, if any, preplant irrigation was required. However, a small amount (18 mm) was applied to check for proper system operation and to detect leaks (table 1). Rainfall in 2002 was near average (361 mm) and below average in 2003 (227 mm). Planting dates in 2001 and 2003 were near the historical average (14 May and 12 May, respectively), but in 2002 planting was delayed until 30 May by several large rainfall events.

Cumulative growing degree days (15.9°C base temperature) since planting were very similar in 2001 and 2002, but slightly less in 2003 (fig. 3). The cotton crop was harvested at 1,400 to 1,650 degree days (°C), and this is within the range expected for full maturity cotton in the Southern High Plains (Peng et al., 1989). In 2001 and 2002, physiological maturity was reached around the latter part of September. In 2001, light but frequent rainfall during September and early October delayed harvest until 17 October. September rainfall was less frequent the following year, and harvest occurred on 2 October. In 2003, physiological maturity was reached around the middle of October, with harvest on 21 October.

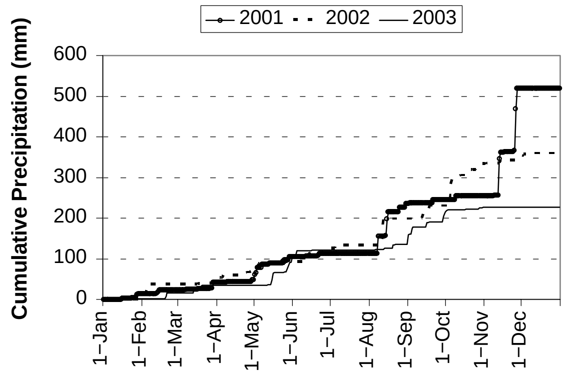

Figure 2. Cumulative precipitation at the study site for 2001, 2002, and 2003.

Preplant irrigations were varied between subplot 1 and subplot 2 (SS1 and SS2 in table 1) in 2001 and 2003, but not in 2002. In 2001, in−season irrigations were also varied between subplots, so the total irrigation amount for the season for the subplots was nearly the same (average of 453 mm). In 2003, only the preplant irrigations were varied (114 and 161 mm for SS1 and SS2, respectively), resulting in different total irrigations for the season (359 and 406 mm for SS1 and SS2, respectively). In−season irrigations were similar for each year (except for SS1 in 2001, which was greater in order to compensate for the reduced preplant irrigation amount). Atmospheric demand during the growing season was slightly less in 2003 than in 2002 or 2001, which is reflected in the in−season irrigation amounts (table 1) and the cumulative heat units (fig. 3).

Germination Failure in 2002

In 2002, very little, if any, germination occurred for rows 3 to 6 in all plots with alternate furrow (2 m) lateral spacing. Limited resources did not permit replanting, and only rows 1−2 and 7−8 were harvested that year. Consequently, final yield for the plots with 2 m lateral spacing was only about half of its potential. Rows 3 to 6 were adjacent to the furrow where the tractor wheels passed, and this furrow also contained drip laterals (fig. 1b). We suspect that the germination failure was related to soil compaction in the furrow as the tractor wheels passed during 2001, which was exacerbated by relatively wet

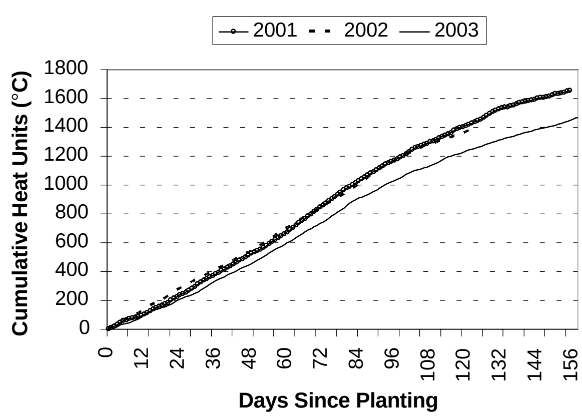

Figure 3. Cumulative heat units of cotton (15.9°C base temperature) for 2001, 2002, and 2003.

conditions surrounding the drip lateral. The compaction may have collapsed the drip lateral and impeded flow or resulted in reduced hydraulic conductivity of the soil surrounding the lateral, and by 2002, antecedent soil water was inadequate for germination (recall that only 18 mm of preplant irrigation was applied). After harvest in 2002, soil in all furrows was loosened with a sweep plow to a depth carefully maintained to about 0.1 m (to avoid damaging the buried SDI laterals), and the beds were then re−listed. In 2003, tractors were driven only in furrows without SDI laterals (i.e., for plots with alternate furrow lateral spacing, between rows 2−3 and 4−5 in fig. 1b). Germination in 2003 appeared uniform in all rows, and yield was greatly improved, exceeding even the plots with laterals under every bed, which will be discussed further.

Fixed and Variable Costs

Fixed and variable input costs ($ ha^{-1} basis) varied mainly by drip lateral spacing and were averaged over the three seasons (table 2). Fixed costs consisted of the annual payment for financed SDI materials and installation, the annual land lease, and the annual depreciation of the SDI system. Finance terms consisted of a 5.00% interest rate amortized over 10 years (the minimal life for an entire SDI system to be cost competitive for low−value crops) (O'Brien et al., 1998). The annual payment (financed materials + installation) for alternate furrow lateral spacing (2 m) was $210 ha^{-1}, 38% less than $337 ha^{-1} for the 1 m lateral spacing, and this is within the range of cost differences reported by Camp et al. (1997) and Henggeler (1995). Annual depreciation was computed using the straight−line method over ten years, where dripline was assumed unsalvageable but other system components (e.g., filters, valves, pipelines, etc.) were assumed to have a 50% salvage value because they are often still serviceable after ten years. Variable costs were those associated with cotton production, and were assumed identical for each lateral spacing (since planted row spacing was 1 m in both cases). An exception was in 2002 for the plots with 2 m lateral spacing, where only one−half of the rows were harvested due to germination failure. Harvest costs per ha were the same, but total harvest costs were reduced by one−half in that case. The total costs (fixed + variable) were deducted from gross returns to compute net returns for each treatment.

Table 2. Annual fixed and variable costs ($ ha^{-1}) averaged for three seasons.

Component	Drip Lateral Spacing 1 m	2 m	2 m[a] (2002)
Fixed costs			
SDI materials (dripline)	$494	$247	
SDI materials (all other components)	$198	$198	
SDI installation	$1,914	$1,173	
Total financed	$2,606	$1,618	
Interest rate	5.00%	5.00%	
Finance term (years)	10	10	
Annual payment for SDI system	$337	$210	
Annual depreciation[b]	$59	$35	
Land lease	$124	$124	
Total fixed costs	$520	$369	
Variable costs			
Seed	$87	$87	
Fertilizer	$63	$63	
Chemicals	$81	$81	
Irrigation (energy cost)	$378	$378	
Insurance	$44	$44	
Labor	$47	$47	
Fuel	$30	$30	
Custom application	$9	$9	
Interest	$24	$24	
Gin, bag, tie, haul modules	$245	$240	$120
Harvest (fuel, lube, repair, chemicals)	$60	$60	$30
Total variable costs	$1,068	$1,063	$913
Total costs (fixed + variable)	$1,588	$1,432	$1,282

[a] Variable costs of the 2002 harvest were the same per ha, but total harvest costs were reduced by one−half due to germination failure.
[b] Computed using the straight−line method over ten years, where dripline was assumed unsalvageable but other components retained a 50% salvage value.

Effect of Lateral Spacing and Installation Depth

In 2001, lint yield, seed mass, and gross returns were significantly greater for the 1 m lateral spacing, and these parameters were numerically greater for the 0.3 m lateral depth (table 3, "2001" block). Loan values (base market price adjusted for fiber quality parameters) were not significantly different for any treatment, although there were small differences in fiber length, micronaire, fiber strength, and uniformity. Net returns for the 1 m lateral spacing were significantly greater than for the 2 m lateral spacing at the 0.2 m lateral depth, and numerically greater for the 0.3 m lateral depth.

In 2002, these trends were more pronounced for lint yield, seed mass, gross returns, and net returns due to the germination failure in plots with the 2 m lateral spacing (four out of eight rows failed to germinate), and net returns showed a loss (table 3, "2002" block). However, loan values for the 2 m lateral spacing were generally numerically greater than those for the 1 m lateral spacing. Of the rows that were harvested in 2002 in the 2 m lateral spaced plots, lint yield and seed mass per unit row length were nearly identical to those in the 1 m lateral spaced plots, possibly because plants that successfully germinated in the 2 m lateral spaced plots had less competition for water and nutrients (data not shown). The 0.3 m lateral depth numerically outperformed the 0.2 m depth for both the 1 m and 2 m lateral spacing.

In 2003, the 2 m lateral spacing showed more favorable performance than the 1 m lateral spacing in terms of lint yield, seed mass, fiber length, and returns, and most differences were significant (table 3, "2003" block). Although lateral spacing trends were reversed in 2003 compared to 2001 and 2002, lateral depth trends remained consistent, with the 0.3 m lateral depth again numerically outperforming the 0.2 m depth for both the 1 m and 2 m lateral spacing (except for lint yield at the 1 m spacing, where the difference was significant). The highest lint yield, seed mass, gross and net return for the three seasons occurred in 2003 for the 2 m lateral spacing at the 0.3 m depth. The successful germination for the 2 m lateral spacing in 2003 (compared to 2002) may have been related to no longer allowing wheel traffic in dripline furrows; however, control of wheel traffic does not necessarily explain why the 2 m lateral spacing outperformed the 1 m lateral spacing in 2003 and vice versa in 2001.

Table 3. Parameter differences for lateral spacing and installation depths.
Numbers followed by the same letter are not significantly different (α = 0.05).

Year	Lateral Spacing (m)	Lateral Depth (m)	Lint Yield (kg ha^{-1})	Seed Mass (kg ha^{-1})	Fiber Length 32^{-1} in	Micro−naire Value	Fiber Strength (g tex^{-1})	Uni−formity (%)	Loan Value ($ kg^{-1})	Gross Return ($ ha^{-1})	Net Return ($ ha^{-1})
2001	1.0	0.2	1,445 a	2,263 a	35.1 ab	4.68 a	30.7 a	78.8 a	$1.20 a	$2,010.44 a	$416.28 ab
		0.3	1,518 a	2,425 a	35.5 ab	4.63 a	27.7 a	78.5 a	$1.18 a	$2,078.51 a	$484.35 a
	2.0	0.2	1,235 b	1,995 b	35.6 a	4.40 b	31.0 a	78.7 a	$1.20 a	$1,719.15 b	$284.58 b
		0.3	1,307 b	2,086 b	35.0 b	4.55 ab	30.6 a	77.7 a	$1.20 a	$1,810.49 b	$375.92 ab
2002	1.0	0.2	1,290 a	1,896 b	33.6 a	4.55 a	29.7 a	80.7 a	$1.13 ab	$1,696.27 a	$102.11 a
		0.3	1,344 a	1,993 a	33.4 a	4.63 a	29.6 a	80.5 a	$1.12 b	$1,750.30 a	$156.14 a
	2.0	0.2	640 b	970 c	33.9 a	4.60 a	29.9 a	81.1 a	$1.15 a	$855.63 b	−$429.11 b
		0.3	670 b	1,035 c	33.9 a	4.58 a	29.6 a	80.9 a	$1.15 ab	$894.26 b	−$390.48 b
2003	1.0	0.2	1,420 c	2,132 c	33.8 b	5.00 a	27.7 a	81.2 a	$1.12 a	$2,046.38 c	$452.22 b
		0.3	1,525 b	2,172 bc	34.1 b	4.99 a	27.6 a	81.5 a	$1.13 a	$2,177.36 bc	$583.20 b
	2.0	0.2	1,570 ab	2,358 ab	35.1 a	5.00 a	27.9 a	81.5 a	$1.15 a	$2,298.71 ab	$864.14 a
		0.3	1,635 a	2,444 a	35.1 a	4.96 a	27.8 a	81.5 a	$1.16 a	$2,404.63 a	$970.06 a
All three seasons	1.0	0.2	1,385 a	2,097 a	34.2 b	4.74 a	29.4 a	80.2 a	$1.15 ab	$1,917.70 a	$323.54 a
		0.3	1,462 a	2,197 a	34.3 b	4.75 a	28.3 a	80.1 a	$1.14 b	$2,002.06 a	$407.90 a
	2.0	0.2	1,148 b	1,774 b	34.9 a	4.67 a	29.6 a	80.4 a	$1.17 a	$1,624.50 b	$239.87 a
		0.3	1,204 b	1,855 b	34.7 a	4.70 a	29.3 a	80.0 a	$1.17 a	$1,703.13 b	$318.50 a
2001 and 2003 only	1.0	0.2	1,432 ab	2,198 a	34.4 c	4.84 a	29.2 a	80.0 a	$1.16 a	$2,028.41 a	$434.25 b
		0.3	1,521 a	2,298 a	34.8 bc	4.81 a	27.6 a	80.0 a	$1.16 a	$2,127.93 a	$533.78 ab
	2.0	0.2	1,402 b	2,176 a	35.4 a	4.70 b	29.5 a	80.1 a	$1.18 a	$2,008.93 a	$574.36 ab
		0.3	1,471 ab	2,265 a	35.1 ab	4.76 ab	29.2 a	79.6 a	$1.18 a	$2,107.56 a	$672.99 a

When all three seasons were combined, overall trends were similar to those observed in 2001. Performance parameters were significantly or numerically better using the 1 m lateral spacing, and numerically better using the 0.3 m lateral depth (table 3, “All three seasons” block). However, when 2002 was eliminated from the analysis, spacing and depth had different influences on the performance parameters (table 3, “2001 and 2003 only” block). Lint yield, seed mass, and gross returns were more influenced by depth than by spacing, where again results were better for the 0.3 m depth. Fiber quality parameters (length, micronaire, strength, and uniformity) and resulting loan values were better for the 2 m spacing. The overall result was that net returns were numerically greater for the 2 m spacing, and the net return using the 2 m spacing and 0.3 m depth was significantly greater compared to the 1 m spacing and 0.2 m depth. Had the germination failure not occurred in 2002, net returns might have been significantly greater using the 2 m spacing when all three seasons were considered.

The data were tested for differences of lateral depth only, where lateral depth was the fixed effect and all other effects were treated as random. The tests included all three seasons (table 4, “All three seasons” block) and exclusion of the 2002 data (table 4, “2001 and 2003 only” block). Again, the 0.3 m depth resulted in better performance than the 0.2 depth, although differences were numerical rather than significant. Lint yield, however, was significantly greater for the 0.3 m lateral depth compared to the 0.2 m depth when the 2002 data were excluded. From tables 3 and 4, lateral depth appeared to have a greater influence on lint yield and seed mass than fiber quality parameters. Regardless of the season or lateral spacing, the deeper (0.3 m) lateral depth may have encouraged a greater root volume to develop early in the season, allowing the plant to extract a greater amount of soil water during reproductive stages that are more sensitive to water stress.

Effect of Successive Seasons

The effects of lateral depth were clearly consistent over all three seasons of this study, but the effects of lateral spacing were reversed from the first (2001) to the third (2003) season. This raises the question whether the 2 m lateral spacing would continue to outperform the 1 m spacing in future seasons, which cannot be answered presently, but we can nonetheless examine how performance parameters varied over the three successive seasons. Considering only the 1 m plots between years (table 5, “1.0” block), lint yields, seed mass, gross return, and net return were not significantly different between 2001 and 2003, but these parameters were significantly less in 2002. For the 2 m plots (table 5, “2.0” block), these parameters were significantly greater in 2003 than in 2001. This suggests that parameter variability between years in the 1 m plots may have been influenced primarily by climate, whereas additional factors, such as

Table 4. Parameter differences for lateral installation depths. Numbers followed by the same letter are not significantly different (α = 0.05).

Year	Lateral Spacing (m)	Lateral Depth (m)	Lint Yield (kg ha^{-1})	Seed Mass (kg ha^{-1})	Fiber Length 32^{-1} in	Micro−naire Value	Fiber Strength (g tex^{-1})	Uni−formity (%)	Loan Value ($ kg^{-1})	Gross Return ($ ha^{-1})	Net Return ($ ha^{-1})
All three seasons	−−	0.2	1,267 a	1,936 a	34.5 a	4.70 a	29.5 a	80.3 a	$1.16 a	$1,771.10 a	$281.70 a
	−−	0.3	1,333 a	2,026 a	34.5 a	4.72 a	28.8 a	80.1 a	$1.15 a	$1,852.59 a	$363.20 a
2001 and 2003 only	−−	0.2	1,417 b	2,187 a	34.9 a	4.77 a	29.3 a	80.0 a	$1.17 a	$2,018.67 a	$504.31 a
	−−	0.3	1,496 a	2,281 a	34.9 a	4.78 a	28.4 a	79.8 a	$1.17 a	$2,117.75 a	$603.38 a

Table 5. Parameter differences between years by lateral spacing. Numbers followed by the same letter are not significantly different (α = 0.05).

Year	Lateral Spacing (m)	Lateral Depth (m)	Lint Yield (kg ha^{-1})	Seed Mass (kg ha^{-1})	Fiber Length 32^{-1} in	Micro−naire Value	Fiber Strength (g tex^{-1})	Uni−formity (%)	Loan Value ($ kg^{-1})	Gross Return ($ ha^{-1})	Net Return ($ ha^{-1})
2001	1.0	−−	1,481 a	2,344 a	35.3 a	4.65 b	29.2 a	78.6 b	$1.19 a	$2,044.47 a	$450.31 a
2002		−−	1,317 b	1,944 c	33.5 c	4.59 b	29.7 a	80.6 a	$1.12 b	$1,723.29 b	$129.13 b
2003		−−	1,472 a	2,152 b	33.9 b	4.99 a	27.6 a	81.3 a	$1.13 b	$2,111.87 a	$517.71 a
2001	2.0	−−	1,271 b	2,040 b	35.3 a	4.48 c	30.8 a	78.2 b	$1.20 a	$1,764.82 b	$330.25 b
2002		−−	655 c	1,002 c	33.9 b	4.59 b	29.8 ab	81.0 a	$1.15 b	$874.94 c	−$409.80 c
2003		−−	1,603 a	2,401 a	35.1 a	4.98 a	27.9 b	81.5 a	$1.15 b	$2,351.67 a	$917.10 a

changes in soil structure and wetting patterns, may have influenced parameter variability in the 2 m plots.

We hypothesized that by the third season, sufficient time had elapsed since the soil was disturbed during the drip lateral installation, and the soil structure in the plots with 2 m lateral spacing may have been conducive to a wider and more uniform distribution of soil water compared to previous seasons. This would have made more soil water available to plants during early root development by 2003. Thorburn et al. (2003) reported that wetting patterns were more dependent on soil structure than texture, contrasting with the previous assumption that wetting patterns were mainly dependent on soil texture. They concluded that optimal emitter spacing (and lateral spacing and depth) depended on site−specific field structure, and should not be based on soil texture alone. Many producers report that seed germination and overall performance using SDI improves with subsequent seasons, which corroborates the authors' practical experience on commercial farms, especially with drip laterals installed in alternate furrows.

In addition, a wider distribution of soil water in 2003 could conceivably have resulted in slightly greater soil temperature in the plant beds compared to the 1 m plots, which is critical for early season cotton development (Wanjura et al., 1996). Soil water in the 1 m plots may have been more concentrated in the plant beds, since irrigation durations were one−half those of the 2 m plots per irrigation event, but application rates were doubled (i.e., 1.46 and 0.73 mm h^{-1} for the 1 m and 2 m plots, respectively), resulting in a lower soil temperature. Longer−term studies are clearly warranted, especially since ten years or more are generally required to recoup the initial investment of a subsurface drip irrigation system. The USDA Agricultural Research Service in Bushland, Texas, is presently conducting detailed studies on the influence of lateral spacing on near−surface soil water and soil temperature distribution over successive seasons.

CONCLUSION

The most economical SDI lateral spacing was 1 m (every row) in the first season of this study, but it was 2 m (alternate furrows) by the third season. Previous experience suggests that near−surface soil structure and hydraulic conductivity change over time after the initial installation, which may explain relative differences of lint yield and net returns in the present study for every row vs. alternate furrows from the first to the third season. However, there is clearly a greater risk associated with drip laterals installed in alternate furrows because water is required to travel a longer distance from the emitter to the seed bed early in the season. We believe that the catastrophic germination failure in the second season was due to wheel traffic in the furrows containing laterals, which may have flattened laterals and/or compacted the soil structure and impeded the wetting front movement. This was alleviated in the third season, probably by loosening the soil in the furrows with a sweep plow and restricting wheel traffic to non−lateral furrows. Additional seasons of study, particularly those with below−average preplant precipitation, are therefore required before conclusions can be drawn concerning the most long−term economic lateral spacing for cotton production in the Trans−Pecos region of Texas. We do conclude, however, that a 0.3 m lateral depth is better than a 0.2 m lateral depth for the Reagan clay loam soil common to the region.

The wide bed, or twin row bed design, where twin plant rows are placed on either side of a drip lateral in a wide bed, should also be evaluated, along with laterals installed in alternate furrows and each bed. This design has been used successfully in the southeastern U.S. for corn (Phene, 1974; Phene and Beale, 1979) and in Israel for cotton (Oron, 1984), but has not yet been widely adopted in West Texas. It may be advantageous for germination because seed beds are much closer to the drip lateral. Research is presently underway at the USDA Agricultural Research Service laboratory in Bushland, Texas, to evaluate germination and crop response where drip laterals are installed in every row, alternate furrows, and wide beds for a clay loam soil. Near−surface soil water and temperature will be monitored throughout the season. This further research aims to expound some of the inconclusive results of the present study.

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