The *Journal of Cotton Science 13:227–237 (2009)*
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AGRONOMY & SOILS

Subsurface Drip Irrigation and Fertigation for North Alabama Cotton Production

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ABSTRACT

Cotton (*Gossypium hirsutum* L.) yield fluctuations in the Tennessee Valley of north Alabama are usually related to drought or irregular growing season rainfall. In 1998, a seven-year study was established on a Decatur silt loam to evaluate cotton yield and performance of drip irrigation tape products under conventional fertilizer application and fertigation compared to dryland cotton. The study encompassed three objectives: 1) compare the long-term *in situ* flow rate characteristics for various commercially available tape products; 2) compare cotton yield with supplemental irrigation to dryland cotton and, 3) compare fertilizer application (conventional surface-applied versus fertigated) in subsurface drip irrigated systems in terms of seed cotton yield and profitability. Irrigated systems consistently yielded more than the dryland system over the course of the study; the latter had a strong positive return only when early-season rainfall was above the 30-yr norm. No emitter clogging, root intrusion, tape collapse or crushing was found in any subsurface drip irrigation (SDI) tape product during the seven year study, indicating that these SDI products should perform in excess of 10 years. Surface drip tape on the other hand, although effective in increasing yield, had to be replaced after three years under the conditions of this experiment. No significant difference between the performance of individual drip tape products was observed. Fertigation offered no clear advantage over surface fertilization because the 7-yr average return of $ 207 ha^{-1} was close to the return of $ 212 ha^{-1} for comparable surface fertilized SDI. Irrigation increased 7-yr net returns, exceeding dryland systems by $ 400 ha^{-1}.

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The southeastern U.S. typically has sufficient rainfall available for crop production on an average annual basis. However, large inter-annual variability in rainfall and frequent dry periods during the growing season make purely rain-fed agriculture a poor competitor to the efficiency of irrigated agriculture (Dougherty et al., 2007). Sheridan et al. (1979) reported that crop yields in the southeastern coastal plain are impacted about every other year because of poor rainfall distribution and/or coarse-textured soils. During a seven-year period (1998 to 2004) in northern Alabama, rainfall during the May - August cotton growing season ranged from over 100% excess of the 30-yr monthly normal in May 2002 to a 94% deficit for August 1999 (Figure 1). This region in the eastern highland rim of the interior plateau of northern Alabama has a 30-yr normal annual rainfall of 1405 mm with a range of 1054 – 1747 mm yr^{-1} (AWIS, 2008). Supplemental irrigation designed to meet crop water requirements thus safeguards against yield loss during periods of moisture stress.

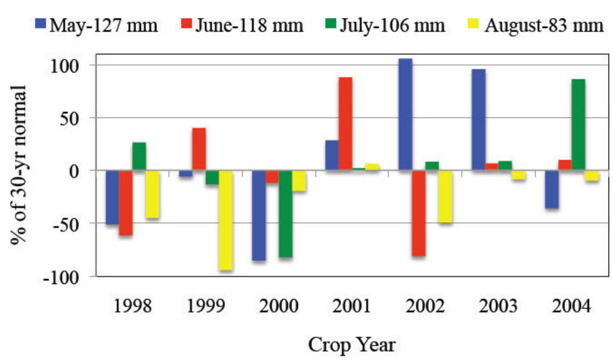

Figure 1. Monthly rainfall totals at Belle Mina, AL for 1998-2004 relative to the 30-yr normal rainfall provided in the figure legend.

Previous studies in the southeastern U.S. and elsewhere have shown that drip and sprinkler irrigation increased seed cotton yield compared to dryland cotton yield (Camp et al., 1994; Camp et al., 1997; Bronson et al., 2001; Pringle and Martin 2003; Sorensen et al., 2004; Kalfountzos et al., 2007). However, a four-year study conducted on loamy sand in the southeastern coastal plain found that cotton did not respond to drip irrigation in two seasons likely due to the small amounts of irrigation applied (Camp et al., 1997 and Bauer et al., 1997). Similarly, Camp et al. (1999) reported that subsurface drip irrigation (SDI) near Florence, North Carolina did not increase cotton yield and attributed the absence of response to soil compaction that restricted root growth above the SDI lines.

The profitability of drip irrigation is impacted by the design life of the system, the spacing and placement of laterals, and the method by which irrigation and fertilization is scheduled and applied. SDI systems can have a long economic life when properly designed, installed, and managed. Compared to center pivot irrigation systems, however, SDI systems have a shorter design life which means that annualized depreciation costs must increase to provide for more frequent system replacement (Lamm, 2002; Lamm et al., 2007). Using a 20-year design life for center pivot sprinklers, O'Brien et al. (1998) reported that SDI was less profitable than center pivot irrigation for an SDI life of less than 10 years. However, as energy and corresponding pumping costs continue to increase and longer SDI operational life is documented, lower pressure SDI systems become more cost effective. In many parts of the country including northern Alabama, it is the relative high capital investment and lack of experience with SDI that has kept producers from adopting this method of irrigation over center pivot, big gun, or furrow irrigation.

In an SDI system, improved profitability and reduced environmental contamination is possible because of the ability to manage small applications of water and N fertilizer as needed by the crop (Camp et al., 1997). Application of fertilizer nutrients through irrigation systems (fertigation) has been found to increase seed cotton yield, water use efficiency, and nutrient uptake by researchers in Syria (Janat and Somi 2001a, 2001b; Janat**,** 2004), Texas (Enciso-Medina et al., 2007), and India (Thind et al., 2008). Irrigation systems permit multiple small dose fertilizer injections at different intervals, reducing the risk of leaching compared to fertilizers applied in a single application. Notwithstanding, Hunt et al. (1998) near Florence, South Carolina found that N fertigation using a single drip-application produced the highest seed cotton yield compared with five split drip-applications. Similar results were reported by Hou et al. (2007) for N applied at the beginning of the irrigation cycle rather than in more frequent, smaller doses throughout the irrigation cycle. Alternatively, Bauer et al. (1997) determined that N application method (single versus five split drip-applications) through SDI had no significant effect on cotton yield.

Although there have been a number of studies reporting the effect of dripline spacing and irrigation scheduling on cotton growth, combined studies that evaluate the effect of drip tape performance and fertilizer method on long-term profitability do not currently exist. Therefore, the objectives of this study were to (1) compare long-term *in-situ* flow rate characteristics for commercially available tape products; (2) compare seed cotton yield under surface and subsurface drip irrigation to dryland cotton, and (3) evaluate the effects of drip irrigation systems and fertilizer application methods (conventional surface-applied versus fertigated) on seed cotton yield and profitability.

MATERIALS AND METHODS

Experiment Design. A SDI study was initiated in 1998 at the Alabama Agricultural Experiment Station's Tennessee Valley Research and Extension Center (TVREC) in Belle Mina, AL (86 ˚ 52' 30" W, 34 ˚ 41', 00" N) on a Decatur silt loam (fine, kaolinitic, thermic, Rhodic Paleudult). The treatment design was an augmented factorial of SDI tape designs (Table 1) and fertilizer application methods (surface-fertilization vs. fertigation). A surface tape and a dryland (non-irrigated) treatment, both with surface applied fertilizer, served as controls. The surface T-Tape treatment was discontinued after 2001 because of extensive damage from wildlife.

The experiment design was a randomized complete block (r = 4) with a split plot restriction on randomization. Drip tape design was the main plot factor and supplemental fertilization treatment the subplot factor. The two control plots occupied a single main plot. The dimension of a main plot was 113 m x 8 m accommodating 8 rows of cotton at 1-m row spacing. Each subplot consisted of 4 rows with the center two rows harvested for yield.

Irrigation. The irrigation system was installed in April 1998 before cotton planting. A single row of drip tape was installed in the middle of each four-row subplot similar to an agricultural field using an alternate-row drip tape spacing of 2.0 m. Surface tape was installed manually using a tractor-mounted reel. Subsurface drip tapes were installed between 30- and 38-cm deep using a heat-treated shank with installation tube on the backside (Andros Engineering, Paso Robles, CA) mounted on a standard toolbar behind a 100-kW agricultural tractor. The toolbar assembly was equipped with an integrated reel carrier and platform for handling the self-feeding reels. During the study, the irrigation system operated at a nominal pressure of 69 kPa with individual emitter flows ranging from 1.13 to 1.47 L h^{-1} (Table 1).

Tape performance. Flow meters were used to monitor total flow and run times for each tape section throughout the study. The average clean water flow rate of each drip tape product was evaluated twice per year typically at the beginning and end of the growing season, after regular system flushing and cleaning (Table 1). Coefficient of variation (CV) between individual emitters was not measured during the study period as this would have required destructive testing. Rather, measured flow rate per meter (L h^{-1} m^{-1}) was used to measure the variation in average flow between years and tape products. Standard maintenance and cleaning operations were performed throughout the duration of the study.

Irrigation scheduling. Daily pan evaporation was downloaded from the Alabama Weather Information Service (AWIS, 2008). The daily irrigation requirement, ET, was calculated using the following equation:

$$ET = 0.90 \text{ x } PAN \text{ x } CC$$

where evapotranspiration, ET (mm day^{-1}) was calculated from 90% pan evaporation, PAN (mm day^{-1}) adjusted for fractional canopy cover, CC. Canopy cover was determined weekly by measuring the open canopy distance (cm) between rows with a tape measure. Fractional canopy cover was calculated using the following formula; (row width - open canopy distance)/row width. Canopy closure measurements were a critical component used in this study to determine the daily amount of irrigation water.

Fertility management. Fertilization of all study plots, including the dryland control, was determined annually based on soil tests and standard agronomic recommendations from the Soil Testing Laboratory at Auburn University. Fertility and cultivar changes were made as directed by the lead agronomist and

Table 1. Sources of irrigation tape, product specification, and annual flow rate evaluation for drip tapes evaluated at Belle Mina, AL from 1998-2004.

Source	T-Systems International, Inc., San Diego, CA, USA		Rainbird, Inc., Azusa, CA, USA	Netafim, Inc., Fresno, CA, USA	Eurodrip, Inc., USA, Madera, CA, USA
Type	T-Tape	T-Tape	RainTape	Typhoon 13	Euro-Tape
Placement	Surface	------------------------- Sub-Surface ------------------------------			
Cost (1998), $ m^{-1}	0.038	0.102	0.102	0.075	0.052
Wall thickness, mm (mil)	0.10 (4)	0.38 (15)	0.36 (14)	0.33 (13)	0.38 (15)
Emitter spacing, cm	30.5	61.0	61.0	61.0	61.0
Emitter flow rate, L h^{-1}	1.1	1.3	1.3	1.5	1.3
Tape flow rate, L h^{-1} m^{-1}	3.7	2.1	2.2	2.4	2.1
Year	Field measured flow rate per meter, L h^{-1} m^{-1}				
1998	2.7	2.3	2.0	2.1	1.9
1999	^{z}	2.1	1.9	2.1	1.9
2000	3.9	2.7	2.5	2.6	2.4
2001	discontinued	2.8	2.5	2.6	2.4
2002		2.7	2.4	2.6	2.4
2003		^{z}	^{z}	^{z}	^{z}
2004		2.6	2.4	2.4	2.3
CV_{Min} ^{y}		0.1	5.6	6.1	0.3
CV_{Max} ^{y}		4.0	15.1	9.1	3.6

^{z} **Flow rate was not measured.**

^{y} **The minimum and maximum CV refer to the coefficients of variation calculated from two evaluations per crop year.**

reflected ongoing changes in recommended farm management practices. The study area was planted using conventional tillage from 1998 through 2002. In 2003, the test was converted to conservation tillage using wheat (*Triticum aestivum* L.) planted as a winter cover crop for the 2003 and 2004 cotton growing seasons. Preplant nitrogen or cover crop N fertilizer was broadcast applied using ammonium nitrate in all years. Two different irrigation fertilizers were used during these testing periods. In 1998 and 1999 a 10-0-10-7S fertilizer was used which was a combination of 32% liquid N plus ammonium thiosulfate. Beginning in 2000, a 6.2-4.14-0 fertilizer was used which was a combination of feed grade urea and potassium nitrate. Total nitrogen and potassium fertilizer rates varied slightly during the study (Table 2). Dryland N rates varied from 67 to 101 kg N ha^{-1} and irrigated N rates from 135 to 168 kg N ha^{-1}. Potassium fertilizer was applied at a rate of 67 kg ha^{-1} (56 kg K ha^{-1}) each year except in 2004 when a 90 kg ha^{-1} (75 kg K ha^{-1}) was applied. The N fertilizer rate for cotton was increased by 33 kg ha^{-1} in 2003 and 2004 when cotton was no tilled into wheat stubble based on N requirements for conservation tillage cotton with cover crops on these soils (Brown et al., 1985). This cover crop treatment represented the best management practice (BMP) for cotton production in the Tennessee Valley region of Alabama. Supplemental fertilizer (subplot factor) was applied to the subsurface irrigated (non-fertigated) plots as a single conventional surface sidedress application at early to mid-square and in eight equal weekly subsurface applications for the fertigated treatments beginning at early to mid-square (Table 2). Conventional sidedressed fertilizer was applied approximately 10 cm from the row using a 4-row dribble applicator. The control plot received only the surface sidedress application.

Crop. Cotton (Table 2) was planted in the second or third week of April each year using a 4-row planter with a 1-m row spacing and a seeding rate of 13-17 seeds m^{-1}. Plots were end-trimmed by 1 m to eliminate edge effects just before picking. The two center rows of each subplot were harvested with a 2-row cotton picker and weighed using a boll buggy equipped with electronic load cells to measure accumulated seed cotton yield per subplot. Average post-harvest turnout from the gin was used to determine lint yield for subsequent economic analysis.

Economic analysis. A partial budget was developed to compare the profitability of irrigated surface fertilized, fertigated, and dryland treatments in this study. The analysis tested whether irrigation and fertigation provided a net return advantage over dryland cotton. Not all costs are accounted for in this economic analysis. For example, partial budgeting does not identify costs associated with startup management, especially for farmers unfamiliar with SDI systems. Net returns presented included allocated overhead and operating costs. The economic analysis was calculated on a pre-tax basis; therefore taxable deductions associated with depreciation were not included. This analysis results in a more conservative estimate of profitability.

Gross receipts and operating costs. Gross receipts for cotton were calculated on an annual basis as the sum of cotton lint and cotton seed receipts less ginning costs. Historic cotton prices and operating costs were obtained from the National Cotton Council of America, which were developed for the

Table 2. Cotton cultivars and fertility regime for the 7-yr study at Belle Mina, AL.

Crop year	Cotton cultivar	All plots			N for irrigated plots	N for dryland plots
		N^z	K	S		
			------------------------ kg ha^{-1} ------------------------			
1998	DPL 33B	78	56	47	67	0
1999	DPL 33B	78	56	47	67	0
2000	DPL 428B	34	56	0	101	45
2001	DPL 428B	34	56	0	101	45
2002	DPL 451BR	34	56	0	101	45
2003	DPL 451BR	67	56	0	101	0
2004	DP 444BG/RR	34	75	0	134	67

[z] Preplant or cover crop N.

Southern Seaboard using a 1997 survey base year (NCCA, 2008). Operating costs for cotton production included seed, fertilizer, chemicals, custom operations (harvest, spraying, and fertilizer application), fuel, lube, electricity, repairs, and interest on above operating inputs. These non-irrigation operating costs for production were assumed the same for all treatments since fertilizer and basic fuel costs for planting and harvesting are similar. It is recognized that on farms with SDI fertigation, pre-plant surface nitrogen and phosphorus may be applied as part of routine agronomic management.

Irrigation operating costs. Irrigation operating costs were calculated separately on a dollar per ha-cm H_2O basis. Cost of electricity for pumping was assumed constant at $0.10 per kWh from 1998 to 2004, resulting in $1.85 per ha-cm pumping costs using a 25 kW motor. Additional operating costs allocated to irrigation system operation include estimated repairs ($1.06 per ha-cm H_2O) and labor ($0.10 per ha-cm H_2O). Total operating costs for irrigation are $3.01 per ha-cm H_2O. The cost of irrigated water is assumed to be zero. Tyson and Curtis (2007) reported total operating costs of $9.13 per ha-cm for a 56-ha center pivot supplied by a 75 kW diesel engine pumping plant using $ 0.79 L^{-1} diesel.

Capital investment and design considerations. A hypothetical 40-ha rectangular field was used to estimate the annual profitability of dryland versus irrigated and fertigated cotton. Approximately 200,000 m of dripline was assumed to irrigate the 40-ha cotton field split into two zones. Each irrigation zone had a design capacity to operate up to 11 hours per day at a maximum application rate of 7.6 mm d^{-1}. Capital costs for the SDI system were acquired from O'Brien et al. (1998) with the exception of historic dripline costs which were available from dripline manufacturers in this study (Table 1). Capital costs for the irrigation pump and electric motor were estimated separately.

Capital recovery of irrigation equipment was annualized based on expected design life. Subsurface drip lines were assumed to have a minimum 10-year life similar to O'Brien et al. (1998). This value is considered conservative, with a longer assumed design life further improving the economics for SDI. The surface tape product was analyzed using the 3-year service life observed in this study and is also considered a conservative value. No salvage value was assigned at the end of the design life for any tape product (Lamm et al., 2007).

Allocated overhead costs. Allocated annual overhead costs for cotton production from 2000 to 2004 were taken from the National Cotton Council of America (NCCA, 2008). Overhead costs included hired labor, farm machinery and equipment, opportunity cost of land, taxes, insurance, and general farm overhead. Overhead costs and historic cotton prices for 1998 and 1999 were estimated using available 2000 and 2001 NCCA data. Allocated annual overhead for the irrigation pumping station was calculated at $ 24.06 per ha assuming a 25-kW electric motor and pump with a 20-yr life at 5% interest.

Statistical analysis. Canopy closure data were modeled through logistic regression and DAP of 25, 50, 75, 100% canopy closure predicted. Yield data were analyzed using mixed models methodology as implemented in SAS® PROC GLIMMIX (SAS, 2009). To compare irrigated plots to the dryland control, we analyzed the experiment as a RCB with a split plot in time restriction on randomization where tape x fertilizer application (treatment) represented main plots. The error structure for this analysis has three members: block x treatment interaction serving as the appropriate error term for treatment main effects, block x year interaction serving as the error term for year main effect, and the residual term as the appropriate error term for three-way interaction means. We employed R-side modeling to account for heterogeneous variances. Equal SEDs in Table 4 indicated which years had homogeneous variances. Irrigated treatments were compared to the dryland control using Dunnett's test.

We then dropped the dryland control and the surface tape treatments from the data and analyzed the data as a complete factorial. The design can now be described as a RCB (r = 4) with a split plot – split plot in time restriction on randomization. Tape design (main plot factor), fertilizer application method (subplot factor), year (sub-subplot factor), and all their interactions were considered fixed treatment effects and block as the single random effect relating to the design structure. The error structure thus consisted of five random effects: main plot error (Block x Tape design), subplot error (Block x Tape design x Fertilizer application method), sub-subplot error (Block x Year), sub-sub-subplot error (Block x Tape design x Year), and the residual error term. The analysis followed a repeated models approach where we modeled the covariance structure of the residual term (R-side modeling) to account for correlated and heterogeneous variances. An unstructured variance model gave the best model fit (lowest AICC value). Because the 3-way interaction was significant, pair-wise comparisons among tape products within fertilization method and year were calculated using the SLICEDIFF option in PROC GLIMMIX and the simulation option to account for Type I error rate inflation. Single degree of freedom contrasts were used to compare fertilization method within tape design x year. Finally, a multivariate canonical discriminant analysis using the combination of tape product by fertilization method as a class variable was also conducted and classes compared on the basis of Mahalanobis (D^2) distance. We used an evidence-based approach to *P*-values, with an upper limit of $P = 0.10$ to indicate non-significant differences. The lower the *P*-value the stronger the evidence that a particular effect or difference was important.

RESULTS AND DISCUSSION

Drip tape performance. All SDI tapes used in this study performed in a similar manner over time, with average flow rates close to the listed specifications within the first two years after installation. Average flow rates for each product then stabilized at 14-29% above the initial for the remainder of the study (Table 1). Patel and Rajput (2007) observed a similar, non-significant post-installation increase in SDI tape flow rate over time. In spite of the observed increase in apparent emitter flow over time, calculated CV values for average annual flows for all tape products (Table 1) did not fluctuate from the range of good (CV < 10%) or average (CV < 20%) for line source emitters (ASAE, 2003; James, 1988; Boswell, 1990). The RainTape had the highest CV of the four products tested, exceeding 10% for five out of seven years but was still < 20%. The field performance of the surface T-tape was unacceptable because of damage and leaks from wildlife (rodents, coyotes, deer) and insects. Excluding the surface T-tape, flow performance results indicated that with proper maintenance and cleaning, continued service life well past the seven-year study period can be expected. No emitter clogging, root intrusion, tape collapse or crushing was found in any buried tape during the study, indicating that in the absence of inversion or subsurface tillage operations these buried tape products should perform in excess of 10 years. These results confirm what is known about the longevity of subsurface drip irrigation lines that are maintained according to manufacturer's recommendations on a routine, seasonal basis (Lamm et al., 2007).

Rainfall, irrigation and canopy closure. There was no 'normal' rainfall year during the duration of the study. Crop years 1998-2000 were characterized by a strong moisture deficit almost through the entire growing season, 2001 by excess moisture in May and June followed by an average season, 2002 by alternating wet and dry months, 2003 by above average moisture in May followed by near normal conditions, and 2004 by early and late season moisture deficits (Figure 1).

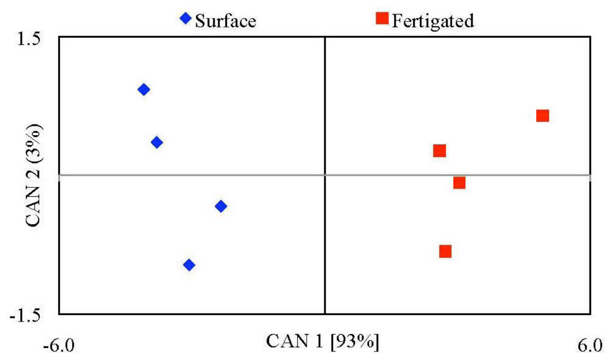

Figure 2. Plot of centroid means for the first and second canonical variates using tape x fertilization method as the class variable.

The first irrigation event varied from 39 DAP (Table 3) in 2000, a year characterized by extreme early season rainfall deficit (Figure 1) to 91 DAP in 2003, which only had a small rainfall deficit in August. In three out of seven years (1999, 2000, 2004) irrigation was necessary before mid-June. These were years with a moisture deficit in May. During the two years with a high rainfall deficit in June (1998, 2002), irrigation was initiated during the last two weeks of that month. In 2001 and 2003 irrigation began during the first 10 days of July. Irrigation typically ended between the last week of August and the first week of September.

Table 3. Duration of irrigation and canopy closure dates, estimated by logistic regression from periodic measurements of canopy data.

Crop year	Planting date	Irrigation		Day of canopy closure			
		Start	End	25%	50%	75%	100%
		---- DAP ----		------------ DAP ------------			
1998	1-May	57	117	50	58	66	92
1999	21-Apr	52	136	55	61	68	88
2000	19-Apr	39	129	52	61	69	98
2001	19-Apr	79	135	29	41	53	92
2002	17-Apr	62	131	62	71	79	96
2003	9-Apr	91	153	z	z	z	98
2004	22-Apr	51	125	52	55	60	76

[z] Only late season canopy data were collected.

The 25% canopy closure date ranged from 29 DAP in 2001 to 62 DAP in 2002 but was reached in the majority of years about 50 DAP (Table 3). One hundred percent closure was generally reached approximately 90 DAP. The correlation among adjacent canopy percentage classes (25, 50, 75) was high (r > 0.95) but had little predictive value for complete canopy (100%) closure.

Yield response. Seed cotton yield of all irrigated treatments exceeded the dryland control in every crop year ranging from a minimum of 210 kg ha^{-1} (6%) for the fertigated RainTape treatment in 2001 to a maximum of 2830 kg ha^{-1} (150%) for the fertigated RainTape treatment in 1999 (Table 4). During 1998, 1999, 2000, 2002, and 2004 all treatments differed significantly ($P < 0.0001$) from the dryland control. In 2001, only the surface fertilized treatments differed significantly ($P \leq 0.0034$) from the dryland control, whereas the fertigated treatments, although numerically greater, did not differ from the dryland control except for the Typhoon 13 and Euro-Tape products ($P \leq 0.0638$). In 2003, half of the treatments did not differ significantly from the dryland control. These results confirmed the positive cotton yield response to irrigation that has been reported by other researchers in the southeastern coastal plain (Camp et al., 1994; Sorensen et al., 2004), on the western high plains (Bronson et al., 2001), Mississippi alluvial plain (Pringle and Martin 2003) and in Larissa, Greece (Kalfountzos et al., 2007). It was clear from these results that irrigation is important to offset insufficient growing season rainfall and to maintain optimum and consistently high seed cotton yields.

In the analysis of the complete factorial, the year x fertilization method ($P < 0.0001$) was significant. The year x tape x fertilization method was significant ($P = 0.0933$), but less so. Not surprisingly, the year effect was highly significant ($P \leq 0.0001$) due to varying rainfall during the growing seasons. None of the other effects involving tape or method were significant ($P \geq 0.3127$).

Table 4. Means of tape design x fertilization method x year interaction for seed cotton yields, kg ha^{-1}. Fertilization contrasts give the percent change in yield of surface fertilization relative to the yield of fertigated.

Irrigation tape	Fertilization	1998		1999		2000		2001		2002		2003		2004	
		Yield	Dunnett's	Yield	Dunnett's	Yield	Dunnett's	Yield	Dunnett's	Yield	Dunnett's	Yield	Dunnett's	Yield	Dunnett's
		kg ha^{-1}													
Dryland control	Surface	2744		1859		1750		3307		1960		2941		2276	
T-Tape surface	Surface	3637	<0.0001	4499	<0.0001	3786	<0.0001	z		z		z		z	
T-Tape	Surface	3992	<0.0001	3435	<0.0001	4174	<0.0001	3947	0.0006	3824	<0.0001	3393	0.5398	3843	<0.0001
T-Tape	Fertigated	3972	<0.0001	4435	<0.0001	3979	<0.0001	3560	0.4664	3732	<0.0001	3491	0.3254	3299	<0.0001
RainTape	Surface	4377	<0.0001	3105	<0.0001	4136	<0.0001	4195	<0.0001	3796	<0.0001	4054	0.0022	3791	<0.0001
RainTape	Fertigated	4226	<0.0001	4689	<0.0001	4001	<0.0001	3516	0.6681	3994	<0.0001	3600	0.1606	3181	<0.0001
Typhoon 13	Surface	4073	<0.0001	3540	<0.0001	4206	<0.0001	3872	0.0034	3930	<0.0001	3780	0.0377	3867	<0.0001
Typhoon 13	Fertigated	4147	<0.0001	4309	<0.0001	4131	<0.0001	3716	0.0638	3970	<0.0001	3518	0.2774	3309	<0.0001
Euro-Tape	Surface	3994	<0.0001	3275	<0.0001	4271	<0.0001	4153	<0.0001	3977	<0.0001	3998	0.0041	3793	<0.0001
Euro-Tape	Fertigated	4196	<0.0001	4553	<0.0001	4093	<0.0001	3732	0.0492	3986	<0.0001	3672	0.0939	3451	<0.0001
SED[y]		159		301		159		117		301		117		136	
Fertilization Contrast		Pct[x]	*P*-value	Pct	*P*-value	Pct	*P*-value	Pct	*P*-value	Pct	*P*-value	Pct	*P*-value	Pct	*P*-value
T-Tape		1	0.9137	-23	<0.0001	5	0.4567	11	0.0298	2	0.4862	-3	0.7890	16	<0.0001
RainTape		4	0.4153	-34	<0.0001	3	0.6055	19	0.0003	-5	0.1410	13	0.2152	19	<0.0001
Typhoon 13		-2	0.6898	-18	<0.0001	2	0.7737	4	0.3684	-1	0.7543	7	0.4727	17	<0.0001
Euro-Tape		-5	0.2761	-28	<0.0001	4	0.4952	11	0.0189	0	0.9494	9	0.3723	10	0.0025

[z] Surface T-Tape discontinued due to damage.

[y] SED = standard error of a difference between means in a column.

[x] Pct indicates the percentage change in yield of the fertigated treatment relative to the surface fertilizer application with tape design.

Differences among irrigation tapes were minor; only three pair wise differences among a total of 42 possible within year x fertilization method comparisons were significant (P ≤ 0.05) with the largest difference of 435 kg seed cotton ha^{-1}. This assessment was supported by results from the multivariate canonical discriminant analysis using the eight tape x fertilization methods (excluding surface tape and dryland) as class variables. The first canonical axis accounted for 93% of the multi-variance among the seven annual yield variables and all pair wise Mahalonobis distances (D^2) between classes sharing the same fertilization method were non-significant ($P > 0.17$), whereas all distances between fertilization classes were significant ($P \leq 0.0018$), irrespective of tape design (Figure 2).

Contrasts for fertilization method were significant only during crop years 1999, 2001, and 2004 (Table 4). During 2001 and 2004, seed cotton yield of surface-fertilized treatments exceeded the yield of fertigated treatments by at least 10% and were significant. In 1999, extremely dry conditions in the upper layer of the soil profile (Curtis et al., 2004) made conventionally surface-applied fertilizer less available resulting in significant yield reduction of at least 18% compared to treatments where fertilizer was applied through the subsurface drip irrigation system.

Although the surface tape treatment was discontinued after three seasons, seed cotton yields obtained with the surface tape were statistically similar to yields obtained with SDI products in surface-fertilized and fertigated treatments during this period (Table 4). Kalfountzos et al. (2007) in Larissa, Greece also found that surface and SDI systems produced similar seed cotton yields except during a dry year. Camp et al. (1993) found in the southeastern Coastal Plain that cotton grown with surface laterals placed alternate-row (2-m spacing) had yields equivalent to cotton with surface laterals placed every-row (1-m spacing). French et al. (1985) found in a coarse-textured Arizona soil that cotton yields were comparable for laterals placed every row (1-m spacing) or every other row (2-m spacing), but were reduced 30% for laterals placed every third row (3-m spacing).

Economic analysis. Average capital and operating costs to irrigate 40 hectares of cotton with SDI was $ 270 ha^{-1} (Table 5). Therefore, the additional cost to irrigate was approximately 24% above the average dryland cotton production costs of $ 1135 ha^{-1} estimated in this study (Table 5). The capital cost of dripline (not shown) accounted for between 26 and 69% (average 50%) of total installation costs, excluding the pump and motor. In their economic analysis of SDI irrigation field sizes from 32.4 ha to 64.8 ha, O'Brien et al. (1998) found that, excluding irrigation pump and motor, dripline costs comprised between 46 and 49% of total installation costs.

Production costs and cash receipts taken from NCCA (2008) represent survey values for farms along the southern seaboard. As such, estimated net returns reported in this study may not represent individual farms in the Tennessee Valley of northern Alabama.

Table 5. Average annual irrigation and production costs for treatments in this study[z].

Year	Capital costs for Irrigation system ($/ha)	Irrigation depth (cm)	Irrigation operating cost ($/ha-cm)	Operating cost for irrigation system ($/ha)	Cost of irrigation (capital + operating) ($/ha)	Crop production costs (excluding irrigation) ($/ha)	Cost of SDI as a percent of total crop production %
1998	167.52	28.27	3.01	85.09	252.61	1185.31	21.3
1999	167.52	46.10	3.01	138.85	306.37	1185.31	25.8
2000	167.52	43.15	3.01	129.88	297.40	1153.91	25.8
2001	167.52	26.70	3.01	80.37	247.89	1216.47	20.4
2002	167.52	32.72	3.01	98.49	266.01	1197.54	22.2
2003	167.52	28.35	3.01	85.33	252.85	975.84	25.9
2004	167.52	33.78	3.01	101.68	269.20	1028.82	26.2
7-yr mean	167.52	34.15	3.01	102.81	270.33	1134.74	23.9

[z] Per ha irrigation system capital cost annualized over 10 years at 5%, with exception of surface tape (3 years). Per ha drip irrigation pump/motor capital cost ($12,000) annualized over 20 years at 5%. Cotton production costs from National Cotton Council (2008).

Nevertheless, both irrigated systems evaluated had strong positive net returns in 1998, 2000, and 2003 ranging from $ 523 to 658 ha^{-1} (Table 6). These results were similar to Sheridan et al. (1979) who reported that crop yields in the southeastern coastal plain are impacted about every other year because of poor rainfall distribution and/or coarse-textured soils.

There was no clear advantage of either fertilization scheme, although the fertigated system had four years of positive returns > $ 300 ha^{-1} versus three for the surface-fertilized system (Table 6). The dryland system was characterized by a negative net return in five out of seven years (1999, 2000, 2001, 2002, and 2004), suggesting that under reported market, yield, and weather conditions, dryland cotton production may not be economically viable. Net positive returns for dryland were found only for 1998 and 2003, years which had the highest gross receipts (Table 6) due to high dryland yields and high prices paid for cotton. There was a long-term average advantage of irrigated systems that can be seen from the 7-yr mean of plus $ 212 ha^{-1} for irrigated systems versus a negative $ 210 ha^{-1} for dryland. O'Brien et al. (1998) reported net returns for SDI corn (*Zea mays* L.) in the midwest ranging from $ 138 - 185 ha^{-1}. Durham (2005) reported net profits for irrigated cotton (pivot and SDI) in the southeast USA ranging from $ 250 - 346 ha^{-1}.

The strong positive net returns from SDI indicated in three of the seven study years provided an average 7-year net return gain of $ 420 ha^{-1} over dryland cotton (Table 6). These results indicate that subsurface drip irrigation of cotton with or without fertigation provides an effective safeguard against consistent losses during seasons of moisture stress.

Table 6. Average net return for irrigated treatments and profit gain for irrigated treatments over dryland.

Year	Treatment Description	Yield (kg/ha)	Gross Receipts ($/ha)	Total production costs (irrigation + crop) ($/ha)	Net Return (Loss) ($/ha)	Profit Gain Over Dryland ($/ha)
1998	Irrigated	4015	2,029	1438	591	445
	Fertigated	4135	2,096	1438	658	511
	Dryland	2744	1,332	1185	147	0
1999	Irrigated	3571	1,397	1492	(95)	447
	Fertigated	4497	1,804	1492	313	854
	Dryland	1859	644	1185	(542)	0
2000	Irrigated	4115	2,068	1451	616	981
	Fertigated	4051	2,033	1451	582	946
	Dryland	1750	789	1154	(365)	0
2001	Irrigated	4042	1,282	1464	(183)	20
	Fertigated	3631	1,132	1464	(333)	-130
	Dryland	3307	1,014	1216	(203)	0
2002	Irrigated	3882	1,390	1464	(74)	482
	Fertigated	3921	1,405	1464	(59)	497
	Dryland	1960	642	1198	(556)	0
2003	Irrigated	3806	1,885	1229	656	236
	Fertigated	3570	1,751	1229	523	103
	Dryland	2941	1,395	976	420	0
2004	Irrigated	3824	1,270	1298	(28)	345
	Fertigated	3310	1,066	1298	(232)	141
	Dryland	2276	656	1029	(373)	0
7-yr mean	Irrigated	3894	1617	1405	212	422
	Fertigated	3874	1612	1405	207	417
	Dryland	2405	925	1135	(210)	0

CONCLUSIONS

1. No significant performance difference between individual drip tape products, in terms of emitter flow rate over time, was found over the course of the study.
2. The SDI systems evaluated are expected to have a design life in excess of 10 years with proper maintenance; surface tapes, although effective in increasing yield, would have to be replaced after three years under the conditions of this experiment.
3. Irrigated systems consistently yielded higher than the dryland system; the latter had a strong positive return only when early-season rainfall was above the 30-yr norm.
4. Fertigation offered no clear advantage because the 7-yr average return of \$ 207 ha^{-1} was close to the return of \$ 212 ha^{-1} for comparable surface fertilized, irrigated systems.
5. Irrigation increases net returns because the average 7-yr return was positive and exceeded the dryland system by \$ 400 ha^{-1}.

ACKNOWLEDGEMENT

Grants from Alabama Cotton Commission and The Tennessee Valley Authority along with contributions of drip tape products from private industry for this research were appreciated. Comments from three peer reviewers are acknowledged.

DISCLAIMER

Mention of a trade name does not imply endorsement by the authors or Auburn University.

ABBREVIATIONS

BMP (best management practice) DAP (days after planting); SDI (subsurface drip irrigation); SED (standard error of the difference between means); CV (coefficient of variation)

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