Furrow diking and the economic water use efficiency of irrigated cotton in the Southeast United States

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Abstract

Cotton (*Gossypium hirsutum* L.) production in the Southeast United States can be limited by periodic drought. Irrigation and furrow diking tillage may improve economic yield and water use efficiency of cotton. Timing of rainfall may interfere with the efficiency of irrigation. Field studies were conducted during 2001 to 2010 near Shellman, Georgia to examine four irrigation rates based on Irrigator Pro for Cotton consisting of 100, 66, 33, and 0%. The objectives were to determine the value of irrigation and the economic water use efficiency of irrigation among irrigation rates over years. In-season rainfall ranged from 270 to 760 mm and irrigation volume ranged from 110 to 455 mm. Total water applied (rainfall + irrigation) ranged between 560 and 870 mm. In all but 2003, irrigation improved yield by 247-645 kg lint ha^{-1}. Years with average or below average rainfall had incrementally higher yields as irrigation rate increased except for 2007. Water use efficiency for irrigation was highest for the 33% rate in 2001 and 2002 and higher in 2004 and 2007 for the 66% rate. In severe drought years, the 33% rate did not sufficiently relieve drought stress. Irrigation provided profit in all but one year of the study. Although 100% irrigation is not the most efficient irrigation level, it often provides the most economic return. Furrow diking improved yield and water use efficiency in 3 of 6 years tested.

Keywords: furrow diking, irrigation, water use efficiency, tillage, cotton, Gossypium hirsutum.

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1 Introduction

Cotton (*Gossypium hirsutum* L.) production has had a major historical impact in the Southeast United States. In 2010, cotton was planted on 4.4 million ha in the US and on 526,000 ha in Georgia. The recent United States Census of Agriculture, reports that 59% of cotton in Georgia is irrigated (USDA-NASS [1]). Current agricultural water issues and the need for reduced input costs in farming operations add importance to making sound water use decisions to ensure efficient management of resources as well as ensuring stable profitability for growers. The Southeast US production region receives an average precipitation of 1,300 mm annually which is usually delivered in high intensity storms; however periodic drought is also frequent (Sheridan *et al.* [2]; Bosch *et al.* [3]). Limited soil infiltration during intense storms often limits soil water capture and storage during precipitation making supplemental irrigation necessary to match crop water use during these periods to achieve high stable yields. Sorensen *et al.* [4] reported a 10 to 50% cotton yield improvement with irrigation compared to non-irrigated cotton in Georgia. In North Carolina, Nuti *et al.* [5] showed that cotton yield improved between 15 and 50% with irrigation compared to non-irrigated cotton. Limited or reduced rate irrigation may be used to reduce the amount of fresh water used in agriculture. With current predictions for population expansion and the reduction in land available for agricultural production, production efficiency and capacity must increase to meet demand.

Depending on the level of discussion, water use efficiency (WUE) has many definitions. At the plant cellular level, WUE is considered to be the units of water transpired per unit of carbon gain. For irrigation, WUE is the amount of water applied compared to the harvestable crop produced. On an agricultural economic basis, WUE is the ratio between the cost per unit of water applied in relation to the value of the crop produced (Lamb *et al.* [6]).

Furrow diking tillage creates a series of basins and dams between crop rows to increase infiltration opportunity time and reduce runoff of both rain and irrigation water (Lyle and Dixon [7]; Nuti *et al.* [8]; Jones and Stewart [9]). If a greater portion of rainfall was captured in the field, irrigation requirements have the potential to be reduced, thus improving agronomic WUE and lower energy use associated with irrigation. Nuti showed that furrow diking reduced irrigation requirements and improved crop value with furrow diking in one of 3 years. The objectives of these field studies were to [1] measure the agronomic and economic value of cotton produced among multiple rates of irrigation compared to non-irrigated cotton, [2] quantify the value that irrigation has on a unit basis in terms of cotton production over multiple years, and [3] evaluate furrow diking tillage among irrigation rates over years. The irrigation rate experiment is reported for 2001 to 2008 to address objectives 1 and 2. The furrow diking over irrigation rate study is reported for 2005 to 2010 to address objective 3.

2 Materials and methods

In 2001 to 2010, four irrigation rates were evaluated on cotton at the USDA-ARS Multicrop Irrigation Farm near Shellman, Georgia (84° 36′ W, 30° 44′ N) on a Greenville fine sandy loam (fine, kaolinitic, thermic Rhodic Kandiudults) with 0-2% slope. Cotton was produced under conventional tillage with best management practices (Brown *et al.* [10]). Cultivar 'DP 458' (Delta and Pine Land Company; Scott, Mississippi) was used in 2001 and 2002 and cultivar 'DP 555BG/RR' was planted in 2003-2010. Irrigator Pro for Cotton was used to schedule irrigation timing (Nuti *et al.* [8]; Davidson *et al.* [11]). The model is designed to avoid crop stress while triggering irrigation at the most efficient timing and volume to avoid over-irrigation [10]. Irrigator Pro for Cotton is based on daily soil water potential (Watermark soil moisture sensor, Irrometer; Riverside, California) at 0.2, 0.4, and 0.6 m. The software uses a weighted system over the 3 depths where the sensor at 0.2 m contributes 43% of the average compared to 32% at 0.4 m and 25% at 0.6 m depths. When this weighted average reaches -50 kPa, the software will recommend irrigation. Soil water potential was corrected using a common 50 mm soil temperature recorded at 04:00 daily.

Table 1: Seasonal rain accumulation and irrigation totals for irrigated cotton near Shellman, Georgia.

Year	Rainfall†	Irrigation‡	Total water	Irrigation cost§
	mm			— $ ha^{-1} —
2001	551	267	818	260
2002	274	285	559	277
2003	729	137	866	133
2004	673	152	825	148
2005	762	109	871	106
2006	414	455	869	443
2007	270	410	680	399
2008	589	246	835	239
2009	907	152	1059	148
2010	414	305	719	297

†Reported rainfall totals are the annual accumulation from planting to crop termination.
‡Irrigation rate and timing were dictated by Irrigator Pro for Cotton and are shown at the full amount recommended.
§Irrigation cost shown is for the full rate recommended by Irrigator Pro for Cotton at \$0.973 ha^{-1} mm.

A three tower linear overhead irrigation system was used that had separate nozzle packages on each tower to achieve different irrigation rates under the same pressure. The non-irrigated treatment was planted in a range beyond the irrigation system. The four rates applied were 100, 66, 33, and 0% of the full rate recommended by Irrigator Pro for Cotton. Irrigation, at respective rates, was applied to all plots at the same time. Irrigation treatments were replicated three times and were arranged in a strip-plot design (Gomez and Gomez [12]). In 2005, furrow diking was added to the experiment in each of the irrigation treatments. In 2005 to 2010, irrigation rate was the main-plot factor and furrow diking was the sub-plot factor within each irrigation rate. The furrow diked and non-furrow diked sub-plots were 3.6 x 30.5 m. Furrow dikes were established after crop emergence each year. Rainfall, irrigation, total water, and the cost of application are shown for the 100% irrigation treatment in Table 1.

Cotton was machine picked from the middle two rows for the full length of each sub-plot and a sub-sample (200 g) of seedcotton was ginned to determine lint turnout. Lint yield was used to calculate crop value at \$1.595 kg^{-1} of lint. Irrigation costs were calculated considering that the energy required for applying 1 mm of water ha^{-1} was \$0.973. Net returns were calculated assuming the production costs between treatments other than irrigation rate were equal. For the purposes of these studies, other production costs are not reflected in the net return values and are assumed to be equal among treatments. In each respective replication in each year, the non-irrigated yield was subtracted from each of the irrigated yields to calculate the yield and crop value gained by each irrigation rate and furrow diking treatment, less the respective irrigation and/or furrow diking costs. This yield was then used to calculate the irrigation use efficiency by dividing the additional yield by the amount of water applied to the respective irrigation rate treatments for each year.

Data for each of these studies were combined over years and analyzed in SAS (version 9.1) under the general linear model and means were separated using Fisher's Protected LSD at $\alpha \leq 0.05$. A significant year × irrigation rate interaction was present for yield in the irrigation rate study during 2001 to 2008, so years are reported separately. In the furrow diking by irrigation rate study during 2005 to 2010, further statistical analysis was carried out to identify years with similar responses in order to draw more concise conclusions in which 3 groups were identified.

3 Results and discussion

Rainfall, irrigation, and total water applied during the growing season to the 100% irrigation rate treatment are reported in Table 1. The irrigation costs for the full irrigation rate ha^{-1} were calculated based on the energy required to apply water at \$0.973 ha^{-1} mm.

3.1 Irrigation rate study: 2001 to 2008

3.1.1 Lint yield and irrigation

A positive response was observed to irrigation in the 8 years of the study except in 2003, which received more than average precipitation (Table 2). In 2005, also a wet year, the 3 irrigation rate treatments produced similar yields which were 25% greater than non-irrigated cotton. In the remaining 6 years studied, increased irrigation rates were generally associated with increased cotton yield.

Table 2: Effect of irrigation rate on cotton lint yield over years near Shellman, Georgia.

Irrigation Rate	2001	2002	2003	2004	2005	2006	2007	2008
	kg ha^{-1}							
0%	645 C†	241 D	1022 A	354 D	1118 B	450 D	415 C	540 C
33%	1060 B	887 C	988 A	635 C	1365 A	949 C	797 B	842 BC
66%	1123 AB	1084 B	972 A	1331 B	1404 A	1393 B	1600 A	1134 AB
100%	1225 A	1290 A	1060 A	1572 A	1426 A	1610 A	1770 A	1365 A

†Means in a column followed by the same letter are not statistically different according to Fisher's Protected LSD at $\alpha = 0.05$.

In 2002, 2004, and 2006, each irrigation rate produced significantly more cotton than the next lower rate. In each of these respective years, the 100% irrigation rate treatment produced 5.4, 4.4, and 3.6 times more cotton than the non-irrigated treatment. In 2001, Cotton irrigated at 33% had a similar yield to cotton irrigated at 66%, which was similar compared to the full irrigation rate. In 2007, the lowest irrigation rate produced 92% more lint than the non-irrigated treatment, but still yielded less than 50% of the 2 higher irrigation rates. It was obvious that yield limiting stress was not avoided in the 33% irrigation rate treatment in 2007. Although 2008 received greater than 2 times the rainfall that was received in 2007, the 100% irrigation rate produced 30% less lint compared to the same treatment in 2007. Non-irrigated yield ranged between 241 and 1,118 kg ha^{-1} over the 8 years. Considering that the two highest non-irrigated yields were achieved with an average of 745 mm rainfall in 2003 and 2005, one would assume that the non-irrigated yield in 2004 with 673 mm rainfall during the growing season would have been much greater than 354 kg ha^{-1}. It would certainly not be assumed that an 11% increase in rainfall between 2004 and the average of 2003 and 2005 could allow a 3 fold increase in yield as was found in this study. These yield results indicate that cotton yield stability without irrigation is very poor in the region studied.

3.1.2 Irrigated crop value in excess of non-irrigated yield

To evaluate the value of cotton produced by irrigation rates compared to the non-irrigated potential each year, the non-irrigated yield was subtracted from the yield produced by each irrigation rate (Table 3). In 2003, a net loss of \$74 to \$222 ha^{-1} was measured among irrigation rates compared to non-irrigated cotton. In 2001 and 2005, irrigated cotton produced similar average crop values of \$613 and \$377 ha^{-1}, respectively, in addition to the non-irrigated yield, regardless of irrigation rate. An incremental increase in crop value was observed among irrigation rates in 2002 with an average of a 22% increase in value between irrigation rates. In 2004, the same trend was observed, but the difference between the 33 and 66% irrigation rates was 3.7 times the value compared to a 23% increase between the 66% rate and full irrigation. The 66 and 100% irrigation rates produced similar crop values in each of 2006 and 2007, which

Table 3: Effect of irrigation rate on net return to irrigation rate over years near Shellman, Georgia.†

Irrigation Rate	2001	2002	2003	2004	2005	2006	2007	2008
	$ ha^{-1}							
33%	576 A‡	946 C	-99 A	395 C	358 A	660 B	480 B	413 B
66%	593 A	1166 B	-222 A	1458 B	388 A	1221 A	1626 A	796 AB
100%	670 A	1401 A	-74 A	1791 A	385 A	1416 A	1760 A	1080 A

†Net return to irrigation rate is calculated as the value of lint produced by irrigation above non-irrigated yield considering lint value at $1.595 kg^{-1} and the cost of irrigation was $0.973 ha^{-1} mm.
‡Means in a column followed by the same letter are not statistically different according to Fisher's Protected LSD at $\alpha = 0.05$.

were 2 and 3.5 times greater than the crop value increase over non-irrigated cotton produced by the 33% irrigation rate in each respective year. In 2008, the lowest irrigation rate produced $413 ha^{-1} more crop value than non-irrigated cotton that year and the full irrigation rate produced 2.6 times the crop value compared to non-irrigated cotton.

3.1.3 Crop value per unit of water application cost

The variable rainfall, irrigation requirements, and yields over years warrants investigation into which irrigation rates may have the highest economic irrigation WUE. The dollar value of lint produced by each irrigation rate in addition to the next lower irrigation rate was divided by the amount of water applied to achieve the yield (Table 4). Since negative returns were observed in 2003, negative WUE values were also observed. The 33% rate lost $0.91 ha^{-1} mm applied compared to non-irrigated cotton in 2003, simply because it produced lower yield than the non-irrigated cotton. The 100% rate only lost $0.24 ha^{-1} mm, because the yield was numerically higher than non-irrigated cotton, however the amount spent on irrigation was not enough to justify irrigation in that year. In 2001, 2002, 2005, 2006, and 2008, the general trend was that the 33% irrigation rate was the most effective at producing crop value per unit of water used. In 2004 and 2007, irrigation applied at 66% was the most efficient at producing crop value. The greatest economic irrigation WUE was achieved by the 2 higher irrigation rates in 2004 ($4.72 to $5.91 in crop value ha^{-1} mm). This result was possible because the non-irrigated yield in 2004 was the second lowest behind 2002, and the 100% irrigation rate yield was third highest in the study. The second greatest display of economic irrigation WUE was by the 33% irrigation rate in 2002 and 2005 ($4.06 to $4.09 in crop value ha^{-1} mm). In 2002, this was a result of a very low non-irrigated yield (241 kg ha^{-1}) associated with a good response to the low rate of irrigation, a 3.7 fold increase over non-irrigated cotton. In 2005, the 33% irrigation rate had a significant yield improvement over non-irrigated cotton (247 kg ha^{-1} or 22%) with only 36 ha^{-1} mm irrigation applied resulting in a high efficiency in producing crop value per unit of water applied.

Table 4: Value of cotton lint produced per unit of irrigation water applied over years near Shellman, Georgia.†

Irrigation Rate	2001	2002	2003	2004	2005	2006	2007	2008
	$\$$ mm^{-1} water ha^{-1}							
33%	2.68 A‡	4.09 A	-0.91 A	3.15 C	4.06 A	1.77 A	1.42 B	2.05 A
66%	1.38 B	2.52 B	-1.02 A	5.91 A	2.02 A	1.65 A	2.44 A	1.97 A
100%	1.02 B	2.00 C	-0.24 A	4.72 B	1.46 A	1.26 A	1.73 B	1.77 A

†Value of lint per unit of water applied is net return to irrigation over mm of water applied considering water cost at \$0.973 ha^{-1} mm and lint value at \$1.595 kg^{-1}.
‡Means in a column followed by the same letter are not statistically different according to Fisher's Protected LSD at $\alpha = 0.05$.

3.2 Furrow diking and irrigation rate study: 2005 to 2010

3.2.1 Lint yield

In 2005 to 2010, there was a significant interaction between years for yield. Years were grouped by yield response and rainfall patterns to establish environmental groups. The groups were 2005 and 2009 (wet), 2007 (dry), and 2006, 2008, and 2010 (moderate). When analyzed by groups, there were no interactions for yield among years within a group, thus results are reported according to these environmental groups. There was no interaction between irrigation rate and furrow diking and the response to furrow diking is reported over irrigation rate for each environmental group (Table 5). In both wet and dry years, there was no yield benefit to furrow diking. In moderate years, furrow diked cotton averaged 150 kg ha^{-1} more lint than conventionally tilled cotton. This 16% increase is averaged over irrigation rates and occurred every other year during the study.

Table 5: Effect of furrow diking on cotton lint yield in various environmental groups of years near Shellman, Georgia.†

Environmental group	Wet	Dry	Moderate
	kg ha^{-1}		
Furrow diked	1100 A†	1110 A	1080 A
Non-furrow diked	1140 A	1105 A	930 B

†Means in a column followed by the same letter are not statistically different according to Fisher's Protected LSD at $\alpha = 0.05$.

3.2.2 Water use efficiency

The ratio of lint produced per unit of water applied is expressed as WUE in Table 6. Furrow diking did not affect WUE in wet or dry years, however it did improve WUE by 100 g mm^{-1} of water in moderate years. The excess water available through rainfall in wet years reduced WUE by an average of 370 g mm^{-1} of water. Water use efficiency was high in dry years because water was limited and runoff was minimal. Furrow diked cotton in moderate years was more efficient because surface applied water was retained and available for plant use (Truman and Nuti [13]).

Table 6: Effect of furrow diking on water use efficiency in various environmental groups of years near Shellman, Georgia.†

Environmental group	Wet	Dry	Moderate
	g lint mm^{-1} water†		
Furrow diked	640 A‡	1030 A	820 A
Non-furrow diked	660 A	1020 A	720 B

†Total of rainfall and irrigation applied during the season.
‡Means in a column followed by the same letter are not statistically different according to Fisher's Protected LSD at $\alpha = 0.05$.

4 Conclusions

The variability in cotton yield, value ha^{-1}, and economic WUE in response to irrigation rates over years shows that irrigation is necessary for long term yield and profit stability to cotton growers in the Southeast US. Although irrigation was not necessary for achieving significantly greater yield and profit in 1 of 8 years of the irrigation rate study, having the option to irrigate reduces overall risk and improves profit potential when used in the other years. Best management practices for irrigation should emphasize accurate irrigation scheduling to maximize economic WUE and profit. As reported here, higher WUE may be achieved by reducing irrigation rates, however the greatest profit per unit land area remains the goal of growers and must be achieved. Non-irrigated cotton produced yield above a breakeven threshold of $1,500 ha^{-1} in only 2003 ($1,630 ha^{-1}) and 2005 ($1,783 ha^{-1}) during this study. The greatest yield potential was present in 2004, 2006, and 2007, which were years that required irrigation to provide an overall profit. In 2001, 2002, 2004, 2006, and 2008, the upper limit of economic potential ha^{-1} was not reached leaving the opportunity to increase yield with more intense water management. For non-irrigated cotton production, management should be driven to reduce production costs to make the breakeven threshold more attainable.

Furrow diking provided a significant benefit in 3 of the six years tested. This benefit was achieved by taking advantage of surface applied water from rainfall and irrigation. The 3 years that furrow diking did not provide a benefit had either an abundance of rain or severe drought. The positive side is that the average benefit of furrow diking outweighed the cost of the practice for the years without a yield benefit. Furrow diking is a practice that may aid in improving economic WUE and reduce risk in cotton production in the Southeast United States.

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