Determining the Optimum Timing for the Final Furrow Irrigation on Mid-South Cotton

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Abstract. *A common question from cotton farmers in the U.S. Mid-South is when to stop irrigating the crop. U.S. Cotton growers are adopting COTMAN to monitor crop development and aid in making end-of-season decisions concerning the optimal dates for safe termination of insect control and application of defoliants. The objective of this research was to investigate a similar crop-based recommendation for timing the final irrigation on cotton. Data sets from 28 Mid-South cotton fields conducting irrigation termination studies during the 2000 through 2007 growing seasons were analyzed. Day of year, days after planting, and growing degree days after planting, all until the last irrigation, did not provide a strong enough relationship with yield to guide late-season irrigation decisions. Days after nodes above white flower (NAWF)=5 (DA5) and growing degree days after NAWF=5 (GDDA5) of the last irrigation in the northern portion of the Mid-South did provide a yield impact estimate suitable for developing recommendations, but a relationship for fields south of 34°N latitude could not be established. Based on the resulting equations for a cotton price of \$1.15 kg^{-1} of lint, an irrigation applied after 18 days or 192 GDD, 15.6°C base, after NAWF=5 would not be expected to produce enough additional yield to be profitable. The derived equations can also be used to determine the GDDA5 and DA5 of the last profitable irrigation for a known lint price and diesel cost, allowing the producer to react to his or her individual situation. Six of the fields were harvested twice and a later crop (i.e., a lower % first harvest) was associated with later irrigation, though the differences were not always significant. When fiber quality was measured, significant differences were seldom observed and no consistent trend relating to final irrigation was observed. However, because of the price discounts associated with low or high micronaire and the relationship between micronaire and crop maturity, additional research is needed to refine the fiber-quality relationship for the Mid-South.*

Keywords. *Irrigation, Surface irrigation, Irrigation management, Water management, Cotton production, Crop management.*

One common question from cotton farmers in the U.S. Mid-South is when to stop irrigating the crop. While nobody wants to limit yield by failing to apply water when needed, there are also questions about delaying crop maturity, impacting micronaire enough to get price discounts, and causing muddy field conditions during harvest. Furthermore, the natural inclination late in the season is to watch expenses closely and avoid all non-essential spending. With furrow irrigation, another factor is the need to remove the irrigation tubing from the field and prepare the turnrows for harvest and storing modules.

Knowing when to stop irrigating is not easy because so many factors can affect a cotton crop. Unruh and Silvertooth (1997) compared various planting and irrigation termination date combinations, with the results revealing a larger improvement in yield from an early date of planting and a generally smaller increase in yield from a late irrigation termination date. Comparing early and late irrigation termination treatments with an early planting date, they found an average increase of 93 and 132 kg ha^{-1} of lint for DPL 90 and Pima S-6, respectively. Large increases in lint yield from later termination treatments were usually observed under conditions of very poor fruit retention up to cut-out. Fruit retention can be affected by weather, with periods of cloudy weather frequently impacting Mid-South cotton, as well as by herbicide injury and insect infestation.

Silvertooth et al. (1996) reported that about 333 heat units (HU) (30/13°C upper/lower temperature thresholds) are required to develop a late-season boll from a bloom to a full sized, hard boll when fiber length development is complete. In the Mid-South, HU or growing degree days (GDD) for cotton are typically calculated with a 15.6°C (60°F) lower threshold and upper temperature thresholds are not used, although many researchers believe they would improve the utility of using heat units to describe crop development.

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Silvertooth et al. (1996) also reported that approximately 222 additional HU are required to complete boll maturation and opening, for a total of 555 HU to develop from bloom to open boll. They suggested that irrigation termination decisions should be structured to accommodate development of bolls intended for harvest to the point of full fiber development (333 HU post-anthesis), approximately 21 days in southern Arizona in August and September, and adequate soil moisture must be maintained throughout the period for the last set of bolls intended for harvest.

Climate is quite different between southern Arizona and the Mid-South, with northeast Arkansas and southeast Missouri in the northern extremes of the U.S. cotton belt. While poor fruit retention can be overcome with late irrigation in some areas, there is insufficient time in the northern Mid-South in most seasons to recover from early problems. In addition, Mid-South weather is highly variable and often unpredictable. A system that worked well one year may not be effective the next when conditions are different. Recommendations in some states are based on date; however, factors such as day of the year (DOY) or days after planting (DAP) cannot take into account things that happen during the growing season. GDD after planting (GDDAP) can account for weather differences, but not other factors that affect the development of the crop.

Cotton growers across the Cotton Belt are adopting COTMAN, a COTton MANagement system used to monitor crop development and aid in making end-of-season decisions (Danforth and O'Leary, 1998). The later-season portion of the system is based on monitoring the number of nodes above the uppermost first-position white flower (NAWF) on a plant and Bourland et al. (2001) demonstrated how NAWF can be used to measure maturity differences in cotton. Research has shown that as the developing bolls require more of the plant resources, the addition of new main-stem nodes slows and the first-position white flower progresses toward the plant apex. Bourland et al. (1992) found that a first-position white flower five nodes below the plant terminal represented the last effective flower population. Their work indicated that flowers set after NAWF=5 have a higher shed rate and lower mass, resulting in only a minor contribution to final yield. Based on their findings, NAWF=5 is generally accepted as physiological cutout. However, Viator et al. (2008) determined the last effective flower population for conventionally produced cotton in their study in five states over three years was NAWF=3. Similarly, Bednarz and Nichols (2005) reported that effective flowering can proceed to NAWF=3 for conventionally produced cotton. A better understanding is needed about what impacts the last effective flower population.

The COTMAN system uses a "target development curve" (TDC) as a reference to compare with actual crop development. The TDC assumes first flowers at 60 DAP and NAWF=5 at 80 DAP. Comparisons of actual crop development to the TDC provide indications of the pace of crop development and the maturity of the crop. Early-season stress often results in first flower at a relatively low NAWF value and can result in NAWF=5 occurring earlier than 80 DAP. Factors such as poor fruit retention can delay maturity, resulting in NAWF=5 occurring later than 80 DAP.

Research-based decision guides have been developed to aid in identifying the last effective boll population and determining dates for safe termination of insect control and the application of defoliants based on the accumulation of GDD, 15.6°C base, after NAWF=5 (GDDA5) (Cochran et al., 1999; Benson et al., 2000a). Research projects underway in several cotton-producing states are focused on other ways to use the information from COTMAN to aid in management decisions regarding the crop (e.g., growth regulator applications). One area of cotton production that may benefit from COTMAN is the decision of when to stop irrigating the crop, particularly in the Mid-South. Very little published research is available on irrigation termination under Mid-South conditions and current recommendations are often based on the appearance of the first open boll without consideration of overall crop maturity. Such recommendations typically focus on reducing the risk of boll rot rather than the water needs of the maturing bolls. A recommendation that relates the timing of the final irrigation to physiological cutout should better fit the needs of the crop and follow the approach taken with other management recommendations.

On-farm demonstrations were conducted to validate the COTMAN recommendations for defoliation (Benson et al., 2000b) and insecticide (Cochran et al., 1999). A similar approach was chosen for irrigation and beginning in 2000, irrigation termination studies were conducted in several Mid-South locations (Vories et al., 2001); however, rainfall interrupted many of the studies. Several studies were not completed due to excess rainfall, and several others that were completed were greatly influenced by late-season rainfall. That frequent late-season rainfall is one of the factors that makes the decision of when to terminate irrigation difficult. Additional studies in Texas addressed terminating drip (Biles et al., 2003; Multer et al., 2004) and low energy, precision application (LEPA) sprinkler (Doederlein et al., 2004) irrigation.

Hogan (2005) used economic analyses on the combined data from several Mid-South studies to determine the point at which the cost of additional irrigation was equal to the increased value of additional yield realized over a range of lint prices. He determined that optimal irrigation termination should occur at 336 GDDA5 for market lint prices between 0.77 and 1.65 $ kg^{-1}. He also recommended that further verification was needed. While economics must be considered to develop guidelines for producers, a strong underlying yield relationship must be the basis of the economic analyses.

The overall objective of this project was to investigate a crop-based recommendation for timing the final irrigation on cotton. This report deals with the studies conducted in the Mid-South states of Missouri, Arkansas, Mississippi, and Louisiana.

Materials and Methods

Cotton irrigation studies were sponsored by Cotton Incorporated (CI) in five states (Arkansas, Louisiana, Mississippi, Missouri, and Texas) during the 2000 through 2007 growing seasons to determine the optimal time to terminate irrigation. To make best use of the budget available for the project, a decision was made to include as many individual locations as possible, rather than conducting more detailed studies on a smaller number of sites. Therefore, most of the studies were conducted on producers' fields following the producers' normal practices other than late-season irrigation. Some studies were conducted on university experiment stations when sufficient room was available for large-plot studies. The experimental protocol did not specify soil moisture monitoring (e.g., tensiometers, water-balance models) or any other method of scheduling regular-season irrigation beyond what the producer was already using. The idea was that by working with successful producers the crop would be in good condition at the start of the late-season irrigation treatments and the findings would be directly applicable to other producers. Few producers in the region use irrigation scheduling programs or soil moisture sensors, so a recommendation based only on such methods would likely not be adopted.

For each study, NAWF data were collected weekly from early flower until NAWF<5. With the exception of irrigation termination, cultural practices matched the producers' normal practices and generally followed Cooperative Extension Service (CES) recommendations for the location. The researchers provided advice to the producers when requested, but did not tell them how to manage their crops. For each site, the first termination treatment was generally targeted for an approximate field-average NAWF=5, a value generally associated with physiological cutout (Bourland et al., 1992). An additional treatment was terminated with each subsequent irrigation. Since rainfall and variable weather affected the number of days between irrigations, no uniform number of days or HU between irrigations was specified and the number varied among individual studies. The cotton was planted on 1-m rows and furrow irrigated, a common production system for Mid-South cotton. An assumed gin turnout of 35% was used to calculate lint yield at each location.

Previous analyses (e.g., Vories et al., 2001; 2004) looked at each field separately as a randomized complete block experiment, with date of the final irrigation as treatment. Tests for significant treatment effects were conducted with analysis of variance procedures. However, Hogan (2005) and Vories et al. (2006) used linear regression on a combined data set. Both methods were employed for this report, with irrigation termination data analyzed separately for each field using the ANOVA procedure of SAS (SAS for Windows version 9.2, SAS Institute, Cary, N.C.). Regression analyses were conducted using the MIXED procedure of SAS with the maximum likelihood (ML) method. For the regression analyses, data were fit using a quadratic function:

$$LY = \beta_0 + \beta_1(x) + \beta_2(x^2) \quad (1)$$

where LY is lint yield (kg ha^{-1} assuming a 35% gin turnout); x is an end-of-season parameter describing the timing of the final furrow irrigation; and β_0, β_1, and β_2 are regression coefficients. Plateau-type functions, where yield increases with additional inputs until a maximum is achieved and then remains constant, or asymptotic functions that approach a maximum are often used to describe yield. The quadratic function was used because yield in many of the studies was observed to decrease with later irrigations. Furthermore, the quadratic function could be fit to the data with varying timings and numbers of treatments among the individual studies.

Finally, even if the field was irrigated all season long there is a cost associated with applying additional furrow irrigations that must be paid by increased yield. Typical costs associated with furrow irrigation were obtained from Hogan et al. (2007). They estimated the average costs for irrigating in Arkansas and the conditions there are similar to the rest of the Mid-South cotton producing areas.

Results and Discussion

Data sets were obtained from 28 Mid-South cotton fields during the 2000 through 2007 growing seasons (table 1). Other fields were included in the study; however, rain either precluded the need for late-season irrigation or negated any effect of the final irrigation date and yields were not determined. When data for all late irrigations were analyzed separately for each field, 9 of the 28 fields had a significance level ≤0.05, generally considered significant, for the effect of late-season irrigation on lint yield; 2 other fields had a significance level ≤0.10, and 17 fields a significance level >0.10 (table 2). When irrigations occurring before NAWF=5 were omitted from the data, 19 fields had a significance level >0.10 and another field only received one irrigation after reaching NAWF=5. The large number of study fields without a significant yield effect underscores the difficulty in the Mid-South farmers' decision of when to stop irrigating. However, the goal of this research was to determine, if possible, a recommendation for irrigation termination over a large area. Therefore, the significance levels of the individual studies were of minor importance.

Table 1. Information about the individual studies included in dataset.

Field No.	Year	Location	Predominant Soil Type	Latitude
1	2000	Keiser, Ark.	Silty clay	35.7
2	2000	Manila, Ark.	Sandy loam	35.9
3	2000	Manila, Ark.	Sandy loam	35.9
4	2001	Keiser, Ark.	Silty clay	35.7
5	2001	Manila, Ark.	Sandy loam	35.9
6	2001	Manila, Ark.	Sandy loam	35.9
7	2001	Rohwer, Ark.	Silt loam	33.8
8	2001	Rohwer, Ark.	Silt loam	33.8
9	2002	Mariana, Ark.	Silt loam	34.7
10	2002	Rohwer, Ark.	Silt loam	33.8
11	2002	Rohwer, Ark.	Silt loam	33.8
12	2003	Monette, Ark.	Sandy loam	35.9
13	2003	Keiser, Ark.	Silty clay	35.7
14	2003	Mariana, Ark.	Silt loam	34.7
15	2003	Rohwer, Ark.	Silt loam	33.8
16	2003	Rohwer, Ark.	Silt loam	33.8
17	2004	Mariana, Ark.	Silt loam	34.7
18	2004	Rohwer, Ark.	Silt loam	33.8
19	2004	Rohwer, Ark.	Silt loam	33.8
20	2005	Monette, Ark.	Sandy loam	35.9
21	2005	Rohwer, Ark.	Silt loam	33.8
22	2005	Rohwer, Ark.	Silt loam	33.8
23	2005	Tchula, Miss.	Silt loam	33.2
24	2005	Trumann, Ark.	Silt loam	35.6
25	2005	St. Joseph, La.	Clay	31.9
26	2005	Portageville, Mo.	Silt loam	36.4
27	2006	Trumann, Ark.	Silt loam	35.6
28	2007	Trumann, Ark.	Silt loam	35.6

As a first step in determining a relationship between final irrigation timing and lint yield, all of the data except fields 8 and 26 were fit to equation 1 for the independent variables DOY, DAP, and GDDAP, which are independent of the timing of NAWF=5 and do not reflect any in-season factors other than weather (GDDAP). Field 8 had only 2 irrigation dates and therefore could not be fit to equation 1. Due to insufficient space, field 26 was furrow irrigated until July and then sprinkler irrigation was used to apply the late-irrigation treatments. Since none of the other fields used sprinkler irrigation, the field was not included in subsequent analyses. Separate regression parameters were calculated for each of the 26 fields (table 3). While such a model is impractical for making a regional recommendation, the unrestricted equation was a necessary starting point.

To determine a suitable model with fewer parameters, likelihood ratios were used to compare prospective models with the unrestricted model. The first potential reduction in parameters was a model with one intercept term, one first-order, and one second-order slope. However, with the significance levels <0.0001 and residual yield values correlated due to the fact that different fields had quite different average yields, the model was not acceptable for any of the parameters. To avoid the serial correlation, subsequent models employed a separate intercept for each field.

Because the data from the fields in the northern portion of the Mid-South appeared to respond differently from those in the southern portion, one equation included a separate intercept for each field, and separate linear and quadratic slopes for fields from the northern (latitude > 34°N) and southern (latitude < 34°N) halves of the study region; however, the resulting significance levels were all <0.0001. A first order equation (i.e., no quadratic slope term) resulted in significance levels >0.01 (table 3); however, an equation with separate slope terms for each field is not well suited for developing recommendations. Therefore, the conclusion was that the parameters related only to calendar date (DOY), planting date (DAP), or planting date and weather (GDDAP) were not responsive enough to guide late-season irrigation decisions.

The next step was to test parameters related to NAWF=5: days after NAWF=5 (DA5) and GDDA5. For those analyses, field 12, with only one irrigation later than NAWF=5, was

Table 2. Production information for the fields in the dataset and the results of testing the effectiveness of late-season irrigation.

			NAWF=5		Significance Level[b]	
Field No.	Planting Date	Cultivar[a]	Date	DAP	All Late[c] Irrigations	Irrigations on or after NAWF=5
1	16 May	SG 747	27 July	72	0.078	0.102
2	9 May	DP 425R	10 Aug.	93	<0.001	<0.001
3	13 May	BXN47	12 Aug.	91	0.008	0.295
4	26 April	SG 747	30 July	95	0.120	0.613
5	30 April	Stv 4892 BR	3 Aug.	95	0.015	0.015
6	8 May	Stv 4892 BR	11 Aug.	95	0.165	0.642
7	25 April	DP 451 B/RR	20 July	86	0.020	0.020
8	29 April	Stv 4892 BR	8 Aug.	101	0.467	0.467
9	22 May	PM 1218	6 Aug.	76	0.004	0.004
10	20 April	PM 1218	26 July	97	0.728	0.728
11	29 April	PM 1218	27 July	89	0.958	0.958
12	30 May	DP 451 B/RR	15 Aug.	77	0.416	[d]
13	30 April	SG 105	17 July	78	0.183	0.183
14	10 May	PM 1218	1 Aug.	83	0.278	0.359
15	1 May	Stv 5599 BR	26 July	86	0.014	0.014
16	29 April	DP 451 B/RR	24 July	86	0.353	0.353
17	8 May	PM 1218	11 July	64	0.478	0.478
18	20 April	Stv 5599 BR	20 July	91	0.166	0.166
19	19 April	Stv 5599 BR	24 July	96	0.489	0.489
20	5 May	Stv 5242 BR	31 July	87	0.155	0.155
21	26 April	Stv 5599 BR	31 July	96	0.002	0.002
22	25 April	Stv 5599 BR	26 July	92	0.001	0.001
23	7 May	Stv 5599 BR	20 July	74	0.204	0.311
24	4 May	Stv 5242 BR	22 July	79	0.083	0.132
25	29 April	DP 555 B/RR	28 July	90	0.240	0.491
26	12 May	DP 1218 B/RR	2 Aug.	82	0.438	0.847
27	1 May	Stv 5242 BR	4 Aug.	95	0.797	0.930
28	11 May	DP 444 B/RR	28 July	77	<0.001	0.016

[a] Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.
[b] Probability > F for H_0: yield not affected by timing of final irrigation.
[c] Some irrigations occurred a few days before NAWF=5.
[d] Only one irrigation date later than NAWF=5.

Table 3. Results of regression analyses for the different parameters defining irrigation timing for the study fields.

Parameter[a]	Model[b]	df	-2ln(L)	Likelihood Ratio	df	Significance Level[c]
DOY	26 Int, 26 L, 26 Q	78	5197			
	1 Int, 1 L, 1 Q	3	6185	988	75	<0.0001
	26 Int, 1 L, 1 Q	28	5360	162	50	<0.0001
	26 Int, 1 NL, 1 NQ, 1 SL, 1 SQ	30	5359	162	48	<0.0001
	26 Int, 26 L, 0 Q	52	5242	44	26	0.0140
DAP	26 Int, 26 L, 26 Q	78	5197			
	1 Int, 1 L, 1 Q	3	6170	973	75	<0.0001
	26 Int, 1 L, 1 Q	28	5357	160	50	<0.0001
	26 Int, 1 NL, 1 NQ, 1 SL, 1 SQ	30	5354	156	48	<0.0001
	26 Int, 26 L, 0 Q	52	5242	44	26	0.0140
GDDAP	26 Int, 26 L, 26 Q	78	5198			
	1 Int, 1 L, 1 Q	3	6145	947	75	<0.0001
	26 Int, 1 L, 1 Q	28	5365	167	50	<0.0001
	26 Int, 1 NL, 1 NQ, 1 SL, 1 SQ	30	5363	165	48	<0.0001
	26 Int, 26 L, 0 Q	52	5241	43	26	0.0203
DA5	25 Int, 25 L, 25 Q	75	4522			
	1 Int, 1 L, 1 Q	3	5354	832	72	<0.0001
	25 Int, 1 L, 1 Q	27	4607	85	48	0.0009
	25 Int, 1 NL, 1 NQ, 1 SL, 1 SQ	29	4598	76	46	0.0034
	25 Int, 1 NL, 11 SL, 1 Q	38	4580	58	37	0.0136
	25 Int, 1 NL, 1 NQ, 11 SL, 1 SQ	39	4577	55	36	0.0217
	25 Int, 25 L, 0 Q	50	4555	33	25	0.1286
GDDA5	25 Int, 25 L, 25 Q	75	4523			
	1 Int, 1 L, 1 Q	3	5366	844	72	<0.0001
	25 Int, 1 L, 1 Q	27	4611	88	48	0.0003
	25 Int, 1 NL, 1 NQ, 1 SL, 1 SQ	29	4598	75	46	0.0045
	25 Int, 1 NL, 11 SL, 1 Q	38	4583	60	37	0.0093
	25 Int, 1 NL, 1 NQ, 11 SL, 1 SQ	39	4576	53	36	0.0357
	25 Int, 25 L, 0 Q	50	4555	32	25	0.1468

[a] DOY = day of year, DAP = days after planting, GDDAP = growing degree days, 15.6°C base, after planting, DA5 = days after NAWF = 5, GDDA5 = growing degree days, 15.6°C base, after NAWF = 5.
[b] Int = intercept, L = linear slope, Q = quadratic slope, N = latitude > 34°N, S = latitude < 34°N.
[c] Significance level for testing Ho: model fit equivalent to unrestricted model.

also omitted. As before, separate regression parameters were calculated for each of the 25 fields (table 3) and the first potential reduction in parameters was a model with one intercept term, one first-order and one second-order slope. The resulting significance levels were <0.0001 for both parameters. The next model employed a separate intercept for each field, but one linear slope and one quadratic slope. Although the resulting significance levels were <0.001 for both parameters, they were larger than any observed with parameters unrelated to NAWF=5 except the first order equation.

When an equation was used with a separate intercept for each field, and separate linear and quadratic slopes for fields from the northern and southern halves of the study region, the resulting significance levels were >0.003 for both parameters. However, a larger significance level would be preferable for developing irrigation guidelines; therefore, additional models were tested. Observing the significance levels of the individual terms in the models indicated a stronger relationship for the northern than the southern fields. To attempt to better describe the southern fields, a model was tested with a separate intercept for each field, one linear slope for the northern fields, separate linear slopes for each southern field, and one quadratic slope (table 3). Although the significance levels were increased for both fields, they were <0.02.

The model including a separate intercept for each field, one linear and one quadratic slope for the northern fields, separate linear slopes for each southern field, and one quadratic slope for the southern fields (table 3) resulted in significance levels >0.02 for both parameters. The first order equations resulted in significance levels >0.1; however, as previously stated, a model with a different slope for each field is not well suited for developing recommendations and attempts to simplify the first order equation were not successful. Therefore, only the northern functions were used in subsequent analyses.

The reasons for the differences between the northern and southern fields are unknown. Because almost all of the southern fields were producer fields, less was known about the condition of the crops than some of the fields located on experiment stations. Using large fields was encouraged, since the goal was to develop guidelines that would apply to producers' conditions, and available space on experiment stations was often insufficient for large plot studies. In addition, the range of locations was smaller in the southern fields than the northern, with 9 of 12 fields located in the same area (table 1). Finally, the southern fields experience warmer temperatures and later occurrences of freezing temperatures, allowing for a longer cotton growing season. A better understanding of the factors that affect the last effective flower population may improve the relationship for southern fields.

The resulting equation for the northern portion of the Mid-South (latitude > 34°N) was:

$$LY = -0.00219(GDDA5)^2 + 1.22(GDDA5) + C_{i,dd}$$

$$LY = -0.222(DA5)^2 + 11.7(DA5) + C_{i,d} \qquad (2)$$

where LY is lint yield (kg ha^{-1} assuming a 35% gin turnout); GDDA5 is growing degree days, 15.6°C base, after NAWF=5 when the final furrow irrigation was applied; DA5 is the number of days after NAWF=5 when the final furrow irrigation was applied; and $C_{i,dd}$ and $C_{i,d}$ are unique intercepts for each of the 14 northern fields (fig. 1). Statistical *t*-tests indicated that each of the slope terms was highly significant ($p<0.0001$). The preceding analyses did not indicate that either parameter had a much superior fit than the other. Therefore, using the GDDA5 model when temperature data were available should provide more response to temperature differences; however, the DA5 model would work when temperature data were not available.

Knowing only the day or GDD associated with maximum yield does not consider the cost of irrigation. Even if the field was irrigated all season long there is a cost associated with applying each additional furrow irrigation that must be paid by increased yield. Assuming the irrigation tubing is still useable and a diesel fuel cost of \$0.58 L^{-1}, Hogan et al. (2007) estimated the cost of an additional furrow irrigation at \$16.31 ha^{-1} for fuel, \$1.01 ha^{-1} for labor, and \$1.33 ha^{-1} for repairs and maintenance for a total of \$18.66 ha^{-1} for a 75-mm gross application with a diesel-powered pumping plant and a well depth <37 m, a common situation for the Mid-South region. For a cotton price of \$1.15 kg^{-1} of lint, an irrigation applied after 18 days or 192 GDD after NAWF =5 would not be expected to produce enough additional yield to be profitable. It should be noted that Cochran et al. (1999) and others used a similar value (194 GDD, 15.6°C base, or 350 GDD, 60°F base) for safe termination of insecticide. Figures 2 and 3 show the latest profitable irrigation for a range of lint prices at a diesel fuel cost of \$0.58 L^{-1}, and a range of diesel costs for a cotton price of \$1.15 kg^{-1} of lint, respectively. Furthermore, in most economic scenarios prices and costs must be assumed; however, in the case of the final irrigation, the crop has often been marketed and the price is known.

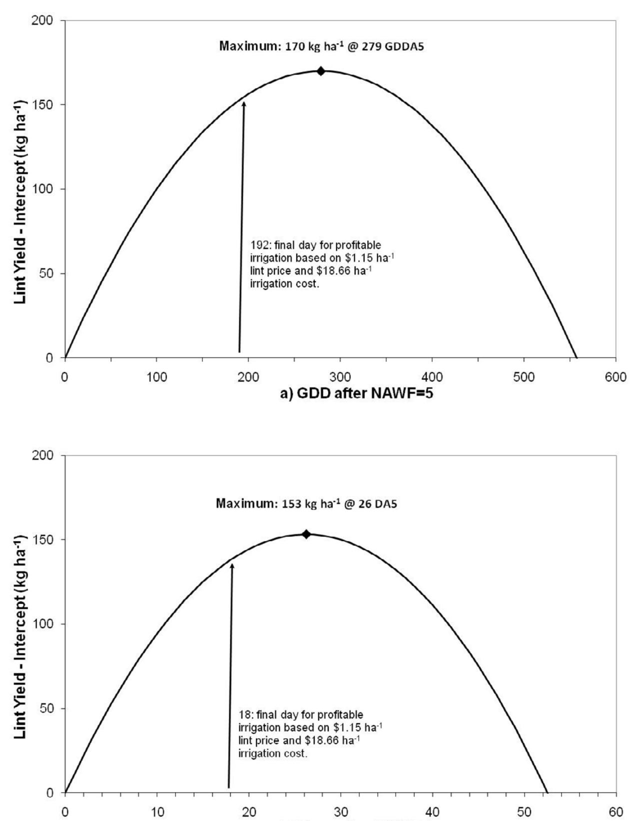

Figure 1. Functions for lint yield vs. timing of the final irrigation for fields > 34°N latitude for (a) growing degree days, 15.6°C base, and (b) days after NAWF=5.

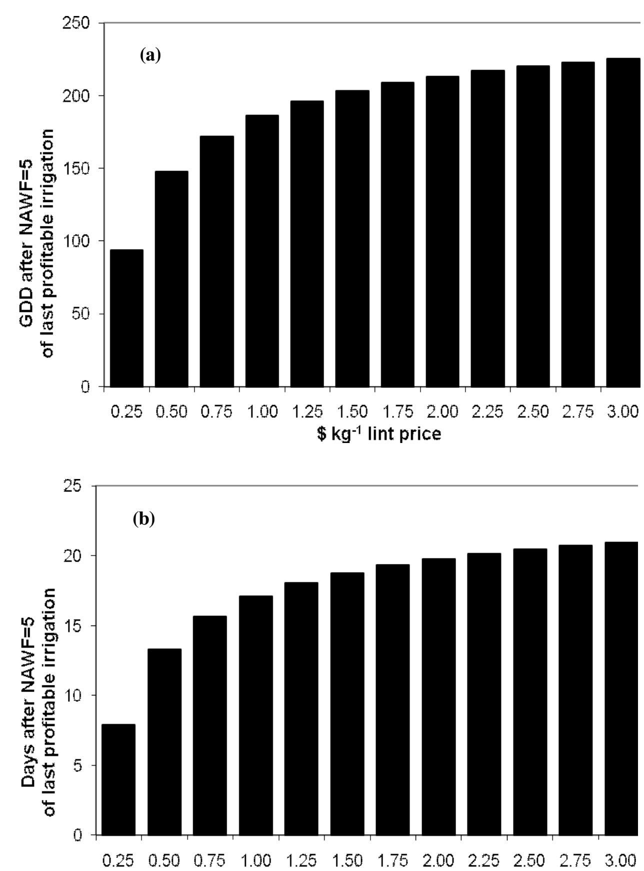

Figure 2. Effect of lint price on timing of the final irrigation for a diesel cost of \$0.58 L^{-1} and fields > 34°N latitude for (a) growing degree days, 15.6°C base, and (b) days after NAWF=5.

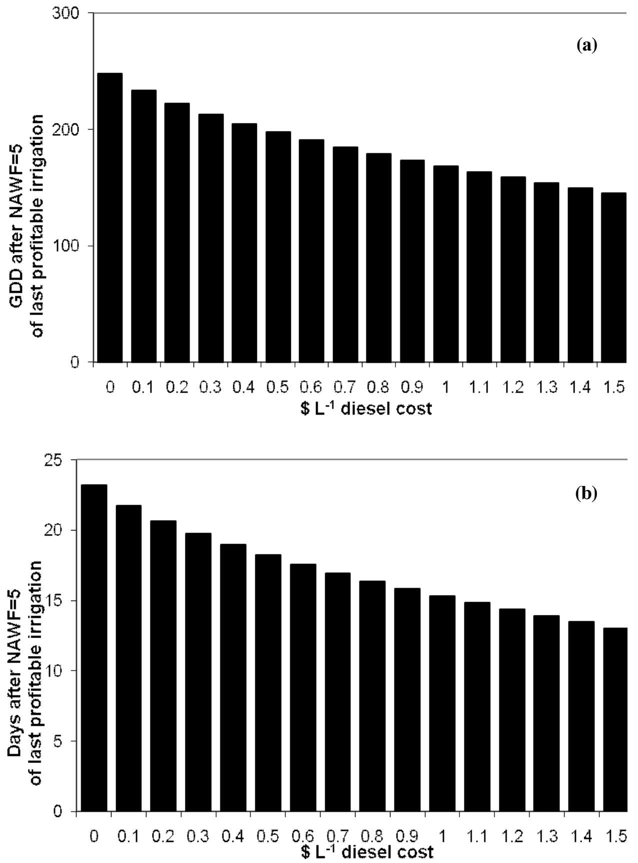

Figure 3. Effect of fuel cost on timing of the final irrigation for a cotton price of $1.15 kg^{-1} of lint and fields > 34°N latitude for (a) growing degree days, 15.6°C base, and (b) days after NAWF=5.

Tables 4 and 5 can be used to determine the GDD and DA5, respectively, of the last profitable irrigation for a known lint price and diesel cost, allowing the producer to consider his or her current situation.

Six of the fields were harvested twice, allowing calculation of % first harvest to indicate differences in maturity among the treatments. A later crop (i.e., a lower % first harvest) was associated with later irrigation, though the differences were not significant for two of the fields (table 6). Hurricanes and other late-season rainfall can prevent Mid-South fields from being harvested and growers must be aware of any impacts on harvest date, therefore delayed maturity is another reason to avoid unprofitable irrigations, especially in the northern portion of the Mid-South where the growing season is shorter.

Finally, High Volume Instrument (HVI) analyses were conducted on lint from many of the fields to investigate possible effects on fiber quality, particularly micronaire. Significant differences were seldom observed and there was no consistent trend relating to final irrigation when differences were significant (data not included). However, because of the price discounts associated with low or high micronaire and the relationship between micronaire and crop maturity, additional research is needed to refine the fiber-quality relationship for the Mid-South.

CONCLUSION

Data sets from 28 Mid-South cotton fields conducting irrigation termination studies during the 2000 through 2007 growing seasons were analyzed. When data for all late irrigations were analyzed, 17 fields had a significance level >0.10 for the effect of late-season irrigation on lint yield. When irrigations occurring before NAWF=5 were omitted from the data, 19 fields had a significance level >0.10 and another only received one irrigation after reaching NAWF=5. The large number of study fields without a significant yield effect underscores the difficulty in the Mid-South farmers' decision of when to stop irrigating.

Parameters related only to calendar date (DOY), planting date (DAP), or planting date and weather (GDDAP) were not responsive enough to guide late-season irrigation decisions. Two variables related to NAWF=5, DA5 and GDDA5, did provide a relationship to yield that could be used to guide irrigation decisions in the northern Mid-South, but not locations south of 34°N latitude. Using the GDDA5 model when temperature data are available should provide more response to temperature differences; however, the DA5 model would work when temperature data are not available.

Table 4. Growing degree days, 15.6°C base, after NAWF=5 of last profitable irrigation in northern (latitude > 34°N) Mid-South for a given combination of fuel cost and lint price.

Lint Price ($ kg^{-1})	Fuel Cost ($ L^{-1}) 0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.4
0.2	205	144	102	69	41	15		
0.4	227	183	154	131	110	92	76	60
0.6	236	201	177	158	141	126	113	100
0.8	242	211	191	174	160	147	135	124
1.0	246	218	200	185	172	161	150	141
1.2	249	224	207	193	181	171	161	153
1.4	251	228	212	199	189	179	170	162
1.6	253	231	216	205	194	185	177	170
1.8	254	234	220	209	199	191	183	176
2.0	255	236	223	212	203	195	188	181
2.2	256	238	225	215	207	199	192	186
2.4	257	240	228	218	210	202	196	190
2.6	258	241	230	220	213	205	199	193
2.8	259	243	231	223	215	208	202	196
3.0	260	244	233	224	217	210	204	199

Table 5. Days after NAWF=5 of last profitable irrigation in northern (latitude > 34°N) Mid-South for a given combination of fuel cost and lint price.

Lint Price ($ kg^{-1})	Fuel Cost ($ L^{-1})							
	0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.4
0.2	19	13	9	5	3	0		
0.4	21	17	14	12	10	8	6	5
0.6	22	19	16	14	13	11	10	9
0.8	23	20	18	16	14	13	12	11
1.0	23	20	18	17	16	15	14	13
1.2	23	21	19	18	17	16	15	14
1.4	24	21	20	18	17	16	15	15
1.6	24	22	20	19	18	17	16	15
1.8	24	22	20	19	18	18	17	16
2.0	24	22	21	20	19	18	17	17
2.2	24	22	21	20	19	18	18	17
2.4	24	22	21	20	19	19	18	17
2.6	24	23	21	20	20	19	18	18
2.8	24	23	22	21	20	19	19	18
3.0	24	23	22	21	20	19	19	18

Table 6. Impact of final irrigation date on crop maturity for the fields included in dataset that were harvested twice.

Field	First Harvest Date	Second Harvest Date	DA5[a]	% First Harvest
1	21 Sept.	4 Oct.	0	89.9
1	21 Sept.	4 Oct.	12	86.0
1	21 Sept.	4 Oct.	21	82.0
1	21 Sept.	4 Oct.	32	81.4
$LSD_{(0.05)}$				3.0
2	27 Sept.	5 Oct.	0	73.7
2	27 Sept.	5 Oct.	5	69.9
2	27 Sept.	5 Oct.	12	63.0
2	27 Sept.	5 Oct.	19	58.5
2	27 Sept.	5 Oct.	26	59.7
$LSD_{(0.05)}$				3.7
3	20 Sept.	5 Oct.	3	80.4
3	20 Sept.	5 Oct.	10	79.0
3	20 Sept.	5 Oct.	17	76.5
$LSD_{(0.05)}$				3.1
4	21 Sept.	9 Oct.	10	82.7
4	21 Sept.	9 Oct.	21	79.1
4	21 Sept.	9 Oct.	31	78.0
$LSD_{(0.05)}$				n.s.
5	26 Sept.	18 Oct.	5	85.3
5	26 Sept.	18 Oct.	11	82.1
5	26 Sept.	18 Oct.	18	78.7
5	26 Sept.	18 Oct.	25	80.4
5	26 Sept.	18 Oct.	32	80.9
$LSD_{(0.05)}$				4.0
25	20 Sept.	8 Oct.	1	86.3
25	20 Sept.	8 Oct.	13	85.6
25	20 Sept.	8 Oct.	26	83.1
$LSD_{(0.05)}$				n.s.

[a] Days after NAWF=5 of the final irrigation.

Based on the equations, for a cotton price of $1.15 kg^{-1} of lint, an irrigation applied after 18 days or 192 GDD after NAWF=5 would not be expected to produce enough additional yield to be profitable. In most economic scenarios, prices and costs must be assumed; however, in the case of the final irrigation, the crop has often been marketed and the price is known, allowing the producer to consider his or her current situation.

Six of the fields were harvested twice and a later crop (i.e., a lower % first harvest) was associated with later irrigation, though the differences were not always significant. When fiber quality was measured, significant differences were seldom observed and no consistent trend relating to final irrigation was observed. However, because of the price discounts associated with low or high micronaire and the relationship between micronaire and crop maturity, additional research is needed to refine the fiber-quality relationship for the Mid-South.

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