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AGRONOMY AND SOILS

Lint Yield and Crop Maturity Responses to Irrigation in a Short-Season Environment

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ABSTRACT

Cotton (*Gossypium hirsutum* L.) responses to supplemental irrigation need to be reassessed in humid, short-season environments. We conducted a 4-year study on a Typic Hapludalf at Jackson TN, to measure yield and maturity responses of contemporary cultivars to supplemental irrigation; to describe boll retention and distribution patterns associated with maturity responses; and to estimate the percentage of years in which yields may respond to irrigation. Treatments consisted of three rates of supplemental drip irrigation (nominally 3.81, 2.54, and 1.27 cm wk^{-1}, adjusted for rainfall and prior irrigation), plus a non-irrigated check. Irrigation increased lint yields significantly in 3 of 4 years, with quadratic rate responses. The average yield increase was 38% at the 2.54-cm wk^{-1} rate. Yields were maximized with 35 to 37 cm of total water (irrigation + rainfall) between 40 and 120 days after planting. Yields were limited more by the accumulation of heat units than water supply in 2009. Irrigation delayed crop maturity by an average of 0.56 days for every additional cm water from irrigation or rainfall. Full irrigation expanded the effective fruiting zone on the plant from about 6.6 to 8.5 sympodial branches, increasing first position boll retention, but it delayed crop maturity mainly by shifting the location of the highest harvestable boll. Response to water supply showed that a yield response to irrigation could be expected in years with <28 cm rainfall between 40 and 120 days after planting. Assuming a planting date of 3 May, this condition occurred in 60% of years of historical rainfall data for this environment.

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According to the 2007 Census of Agriculture (USDA-NASS, 2009), only 2.3% of Tennessee cotton acres were irrigated. By contrast, producers in neighboring states such as Arkansas and Mississippi irrigated a much larger proportion of their cotton acres (80% and 45%, respectively). Certainly, many factors play into a producer's decision to invest in an irrigation system. One important factor is available technical information on crop responses to supplemental irrigation in the region. Based on a 13-yr cotton irrigation study in Tennessee, Parks et al. (1978) reported that irrigation significantly increased yield in only 7 of 18 site-years in which irrigation was applied. In two of the 18 site-years, irrigation significantly decreased yield. They concluded that irrigation generally delayed maturity and picking time, increased insect control problems, sometimes caused plants to lodge, and required a higher level of management than non-irrigated cotton. Given this discouraging prospectus, there is an obvious need to revisit cotton responses to supplemental irrigation in Tennessee and similar short-season environments.

Much of our understanding of short-season cotton response to irrigation comes from the semi-arid High Plains of Texas, where water supply limits crop productivity under rain-fed conditions (Morrow and Krieg, 1990). Where supplemental irrigation is applied, growing season length (measured in heat units) often becomes a yield limiting factor. In a 2-yr study on a clay loam, Peng et al. (1989) achieved maximum lint yields with a total seasonal water supply of 55 cm and heat-unit accumulation of 1450 degree-days (DD, base 15.6°C). In an 11-yr irrigation study on clay loam, Wanjura et al. (2002) found a quadratic yield response of stripper cotton to water supply, with maximum yields achieved with seasonal water input of 74 cm (58 cm from irrigation). However, maximum lint yields achieved with irrigation were linearly related to heat-unit accumulation, indicating that heat units limited yields when moisture was adequate. Their findings highlight the importance of earliness of maturity in attaining high yields in short-season environments.

Response to supplemental irrigation has also been studied in the humid coastal plains of the U.S. cotton belt, where season length does not usually limit yields. In Georgia, Whitaker et al. (2008) found that drip irrigation increased lint yield by an average of 39% in 2 of 3 site-yrs relative to non-irrigated cotton. Their data indicated that the optimum total water supply for yield ranged from 65 to 70 cm at one location, and about 59 cm at another location, both with loamy sand soils. Irrigation that increased water supply above 70 cm did not further increase yields. In Mississippi, Pettigrew (2004) found that furrow irrigation increased lint yield about 35% in 2 of 4 yrs on a sandy loam soil, mainly due to increased number of bolls per unit ground area. In Alabama, Balkcom et al. (2006) found a quadratic yield response to sprinkler irrigation in 2 of 3 yrs on a silt loam, with yields maximized in regimes that supplied 43.4 cm of water from rainfall plus irrigation from June through September in one year, and 60.7 cm during the same time period in another year. Variability in yield response among these studies was expected, given the differences in irrigation regimes, soils, and rainfall distribution. However, a common feature of these studies was a lack of yield response to supplemental irrigation in a sizeable proportion of site-years. Quadratic yield response functions to water supply suggest the possibility of using local rainfall records to estimate the percentage of years in which a positive yield response to supplemental irrigation may be expected in a given location. This information would be useful in estimating long-term returns on investment in a supplemental irrigation system for cotton.

Delayed crop maturity due to supplemental irrigation has been reported for many years (e.g., Spooner et al., 1958; Parks et al., 1978). Pettigrew (2004) reported that irrigation delayed cutout (cessation of flowering) by an average of 6 days, relative to non-irrigated cotton, due to production of additional mainstem nodes and fruiting sites. Therefore, irrigated plants produced more bolls at higher nodes (>node 10) and at distal sites on fruiting branches than non-irrigated plants. Whitaker et al. (2008) indicated that irrigation delayed maturity, but the number of days of delay were not reported. Their non-irrigated cotton had 1 or 2 fewer nodes above white flower between 79 and 97 days after planting than drip-irrigated cotton in two site-years where total water supply >65 cm, but not in a site-year where total water supply <60 cm.

While predictions of crop maturity can be made from flowering data, late-season maturity measurements are more directly related to timing of defoliation and harvest. One maturity benchmark, used to determine readiness for defoliation, is the time when plants have four mainstem nodes from the highest first-position cracked boll to the highest harvestable boll (Kerby et al., 1992). In irrigated cotton, Plant et al. (2000) found a positive correlation between nodes above cracked boll (NACB) with the normalized difference vegetation index (NDVI) of the crop canopy, measured concurrently in late season. Gwathmey et al. (2010) found positive correlations between canopy NDVI in late-season (>1000 DD after planting) with DD from planting to open boll in non-irrigated cotton. These reports suggest that late season NDVI may be used to compare maturity status of cotton grown under different irrigation regimes, but additional research is needed to validate this approach.

Yield and maturity responses to irrigation are related both to the production of additional fruiting sites on the plant, and to retention of bolls set by the last effective bloom date. Without irrigation, plant water deficits induced by low soil water (or high evaporative demand) reduce the number of fruiting sites proportionally to shoot growth (Jordan, 1986). Water deficits in early flowering tend to increase shedding of squares, while late-season deficits reduce flowering rate and boll retention (Jordan, 1986). Pettigrew (2004) reported that vegetative growth during flowering continued longer in irrigated than non-irrigated cotton, delaying cutout (NAWF=5) by about 6 d. Therefore, irrigated plants produced more bolls at higher nodes (>node 10) and at distal fruiting sites than non-irrigated plants. Data reported by Ritchie et al. (2009) showed similar boll load at lower nodes (5-9) and topmost nodes (>18) between drip irrigated and non-irrigated cotton, but a greater boll load at nodes 10-17 with irrigation. These reports highlight the importance of boll load on yield, and of boll distribution on earliness. Understanding maturity and yield responses would be advanced by determining irrigation effects on position of the highest harvestable boll on the plant, and on boll retention below this position.

Objectives of this research were to measure lint yield and maturity responses of contemporary cultivars to supplemental irrigation in context of rainfall and heat-unit accumulation; to describe boll retention and distribution patterns associated with maturity responses; determine the relationship of late-season NDVI with crop maturity; and to estimate the percentage of years in which yields may respond to supplemental irrigation in a short-season environment.

MATERIALS AND METHODS

Cotton response to supplemental irrigation was evaluated in a 4-year field study at the West Tennessee Research & Education Center, Jackson TN (35.624°N; 88.845°W). The soil was a Memphis silt loam (fine-silty, mixed, active, thermic Typic Hapludalf). The Memphis series consists of deep (>0.81 m), moderately permeable, well drained soils on terraces and uplands of the Coastal Plain (USDA-NRCS, 2002). The field was planted to winter wheat (*Triticum aestivum* L.) in the fall of each year. Prior to planting cotton each year, the winter cover crop was killed, and fertilizers supplying either 15 or 29 kg P ha^{-1}, and 56 or 84 kg K ha^{-1}, were applied in accordance with soil test recommendations.

The field was planted to 'DP143B2RF' on 24 April 2006 and 27 April 2007, and to 'PHY375WRF' on 21 May 2008 and 13 May 2009. The crop was planted with no tillage each year except 2008, when the field was disced and harrowed for replanting after an earlier planting produced an inadequate stand. Row spacing was 97 cm. Plant population densities averaged between 10 and 12.5 plants m^{-2} each year. Nitrogen fertilization supplied 90 kg N ha^{-1} as ammonium nitrate between 10 and 37 days after planting (DAP) in 2006 and 2007, and urea-ammonium nitrate solution (320 g N kg^{-1}) between 9 and 19 DAP in 2008 and 2009. Crop and pest management followed Extension recommendations.

Prior to appearance of first squares each year, the field was divided into 8-row plots for irrigation treatments, consisting of three rates of supplemental irrigation (nominally 3.81, 2.54, and 1.27 cm wk^{-1}) plus a non-irrigated check. These treatments are referred to here as 150%, 100%, 50% and 0%, respectively. Treatments were arranged in a randomized complete block design with four replications, and plot assignments were re-randomized each year. Irrigation was applied by drip tapes (T-tape by T-Systems, San Diego, CA) calibrated to apply flow rates of 0.58, 0.39, and 0.20 cm hr^{-1}, respectively, at 69 kPa regulated line pressure. Drip tape was placed on the soil surface beside every row in irrigated plots, and fed from a municipal water source. Irrigation treatments were initiated when half of the plants had their first squares. Irrigation was applied two times each week in which <2.54 cm rain fell during the previous 7 d. The amount of water applied every 3 or 4 days was based on irrigation and rainfall during the previous 7-d. If the 7-d rainfall was <2.54 cm, then irrigation applied to the 100% treatment was 1.27 cm (half of the 7-d amount), minus the total rainfall plus irrigation applied to that treatment during the previous 7 d. Irrigation amounts were adjusted by varying the run time, with other treatments receiving a proportional amount by differences in drip tape flow rates. No irrigation was applied when rainfall was ≥2.54 cm in the previous 7 d. Irrigation was terminated in all plots when at least half of the plants in irrigated plots had an open boll.

Soil moisture tension was monitored in three replicate sets of plots in 2007 and 2008, using electrical resistance granular matrix sensors (Model 200SS, Irrometer Co., Riverside CA) embedded at 23 and 61 cm depth at the time of drip system installation. Sensors were placed within 10 to 20 cm of an interior row segment of each plot. Moisture tension was read and recorded two times each week, just prior to irrigation (if any), with a Watermark meter (Irrometer Co., Riverside CA). Readings from the two depths in each plot were averaged to estimate soil moisture potential on each date.

Weather data were collected at 0700 h daily at a standard NOAA weather observation station within 400 m of the test site. Data collected for this study included daily rainfall, maximum and minimum air temperatures, and pan evaporation. Historical rainfall records for this weather station were obtained from the NCDC (2010).

The cotton crop was managed by following Extension guidelines for cotton production in Tennessee, including plant growth regulator applications. Accordingly, a total of 110, 123, and 147 g ha^{-1} of mepiquat chloride (N,N-dimethylpiperidinium chloride) was uniformly applied by self-propelled, high-clearance sprayer to all plots in 2006, 2007, and 2008, respectively. In 2009, 345 g ha^{-1} of mepiquat pentaborate (N,N-dimethylpiperidinium pentaborate) was similarly applied.

Canopy NDVI data were collected from two interior rows of each plot using a hand-held sensor (GreenSeeker Model 505, NTech Industries, Ukiah CA), equipped with a data logger. These data were collected on a 2-wk interval starting mid-bloom, following procedures of Gwathmey et al. (2010). The sensor was oriented vertically over the center of each row, 76 to 91 cm above the canopy. The sensor used light emitting diodes to project pulses of red (656 nm) and near-infrared (NIR, 774 nm) light towards the canopy. Light reflected in each waveband was measured by a photodiode in the sensor head. Internal software calculated NDVI as the difference between NIR and red reflectance, divided by the sum of NIR and red reflectance (NTech Industries, 2009). About 200 data points were recorded from ~15 m of interior row length in each plot on each date. Average NDVI values were calculated for each plot and date. Given the results of Gwathmey et al. (2010), only late-season data, collected after accumulation of 1000 DD after planting, were used for this study.

After all plants had started opening bolls, data on nodes above cracked boll (NACB) were collected from 10 plants plot^{-1} on a 6- to 8-d interval. Numbers of mainstem nodes above the highest first-position cracked boll to the highest potentially harvestable boll were counted to measure NACB. A closed boll was considered potentially harvestable if it was turgid and >2 cm diameter. Days from planting to NACB=4 was calculated for each plot by linear interpolation to measure earliness of maturity and readiness for defoliation (Kerby et al., 1992; Whitaker et al., 2008). Prior to defoliation in 2007, 2008, and 2009, growth and development data were collected from six representative plants in two interior rows of each plot. These data included final plant height, number of sympodial branches, location of the lowest and highest harvestable bolls at first-position fruiting sites, and boll retention at first-position fruiting sites. Boll location was determined by counting nodes up the mainstem from the first sympodial branch.

When the latest maturing plots reached NACB<4 each year, harvest aids were applied to all plots. All defoliants and boll opening chemicals were uniformly applied per Extension recommendations. Between 14 and 20 days after defoliation each year, the four center rows (35.3 m^2) of each plot were harvested with a 2-row cotton picker. All seedcotton harvested from each plot was weighed at picking. A sample of seedcotton was collected from each plot, weighed, and air dried to equilibrate moisture content. Gin turnout was determined for each sample using a 20-saw gin assembly equipped with a stick machine, incline cleaners, and two lint cleaners. Lint yields were calculated from seedcotton weights, gin turnouts, and plot areas harvested.

Repeated observations of soil moisture tension were analyzed with the Mixed procedure of SAS 9.2 (SAS Institute, Cary, NC), with observation date as a repeated measure in each year. Other multiyear data were first analyzed to determine the relative magnitude of main effects of treatments and year-by-treatment interactions by ascribing fixed effects to years and to treatments. Year-by-treatment interactions were considered non-negligible (per Littell et al., 2006) in cases where P(F) <0.05 and F values were higher than those of corresponding main effects. In these cases, the Mixed procedure was applied to individual year data with replications as random effects. Otherwise, the Mixed procedure was applied to multiyear data with years and replications as random effects. Least square means were separated by independent t-tests of all possible pairs of means, using the "pdiff" option at the 0.05 level of significance. Linear and quadratic responses to irrigation rates were tested by single-df contrast arguments. Regression analysis of yield and maturity data was performed in SigmaPlot 11 (Systat Software, Inc., San Jose, CA). Terms in polynomial response functions were retained where *p*-values of coefficients <0.05; otherwise, the polynomials were reduced to linear functions and re-tested for significance.

RESULTS AND DISCUSSION

Heat-unit accumulation, rainfall distribution, and cumulative pan evaporation differed considerably among years (Fig. 1). Morrow and Krieg (1990) established 1250 DD as the minimum heat-unit accumulation for lint yield potential >1000 kg ha^{-1}. In this study, over 1250 DDs accumulated between planting and harvest in all years except 2009. Over 40 cm of rain fell between planting and harvest in all years except 2007, when fewer than 2.5 cm fell between 80 and 130 DAP. In 2007, cumulative pan evaporation was 374% of total rainfall, indicating strong vapor pressure deficit. By contrast, cumulative pan evaporation in 2009 was just 131% of total rainfall.

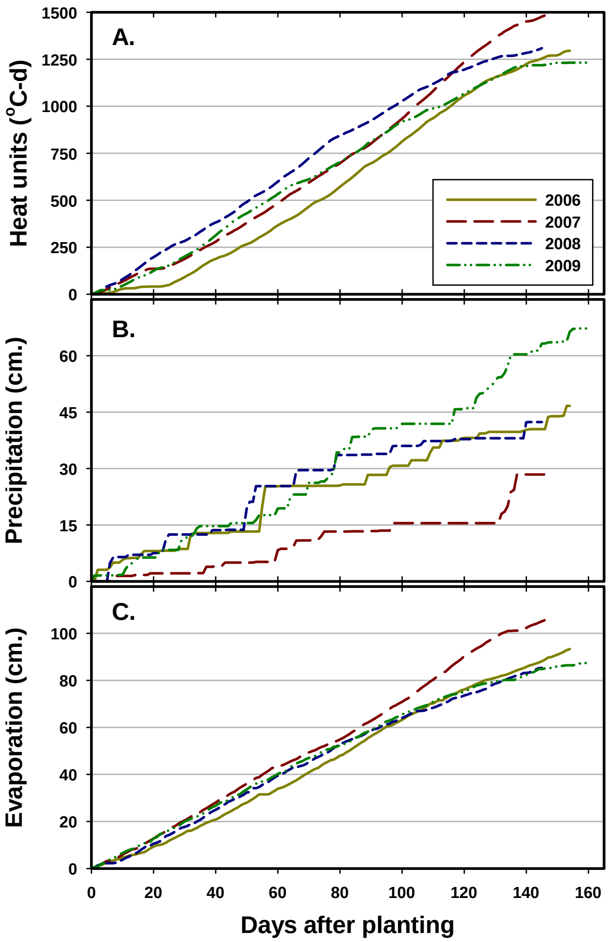

Fig. 1. Yearly heat-unit accumulation (base 15.6°C), cumulative precipitation, and pan evaporation between planting and harvest of cotton in irrigation studies at Jackson TN, 2006-09.

Table 1. Total irrigation and rainfall amounts from planting to harvest in the cotton irrigation study, 2006-09, Jackson TN.

	Irrig. Regime[z]	2006	2007	2008	2009
		------------------ cm ------------------			
Total irrigation	50%	6.8	8.7	7.1	5.8
	100%	13.6	17.4	14.1	11.7
	150%	20.3	26.1	21.2	17.5
Total irrigation + rainfall	0%	46.7	28.4	42.4	67.3
	50%	53.4	37.1	49.4	73.1
	100%	60.2	45.8	56.5	78.9
	150%	67.0	54.5	63.6	84.7
		------------------- % -------------------			
Percent of water from irrigation	50%	13	23	14	8
	100%	23	38	25	15
	150%	30	48	33	21

[z] Percentage of water applied to nominal 2.54 cm wk^{-1} plots (adjusted for rainfall and prior irrigation).

In 2007, a total of 17.4 cm of irrigation was applied in the 100% treatment, comprising 38% of the total water supplied to the crop in that year (Table 1). By contrast, a total of 11.7 cm of irrigation was applied in the 100% treatment in 2009, comprising 15% of the total water supply. In the four years of study, total water supplied to the crop ranged from 28.4 cm in the non-irrigated treatment in 2007, to 84.7 cm in the 150% treatment in 2009 (Table 1).

Patterns of soil moisture depletion and replenishment differed markedly between 2007 and 2008 (Fig. 2). In 2007, soil moisture potential declined below -100 kPa between 80 and 92 DAP in all irrigation regimes, and reached -200 kPa in the non-irrigated plots by 112 DAP. Significant differences in soil moisture due to irrigation occurred on 11 of 23 dates of observation in 2007. In 2008, soil moisture potential varied between -30 and -100 kPa from 55 to 105 DAP for all irrigation regimes except the non-irrigated check (Fig. 2). The greatest variation in soil moisture tension was observed in the non-irrigated plots in 2008 due to rainfall events, but average moisture potential remained above -160 kPa throughout the season. Significant differences due to irrigation were observed on 9 of 22 dates in 2008.

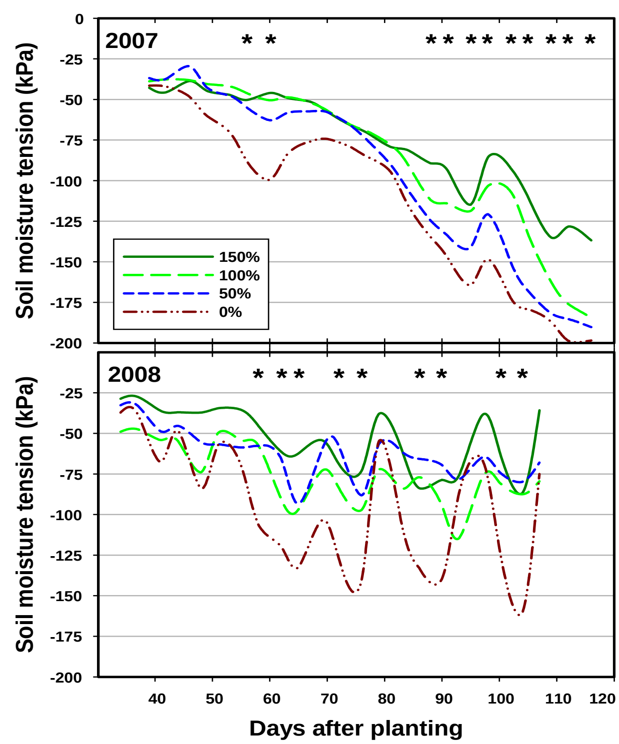

Fig. 2. Mean soil moisture potentials in four cotton irrigation regimes during 2007 and 2008, Jackson TN. Irrigation treatments are percentages of water applied to plots designated 2.54 cm wk^{-1} (minus 7-d rainfall plus irrigation). Asterisks (*) indicate dates on which significant (p<0.05) differences between treatments were observed.

Gin turnout and yield. Multi-year analysis of variance indicated that year-by-treatment interactions were not negligible (per Littell et al., 2006) for gin turnout and lint yield. Therefore these responses were analyzed for each year of the study (Table 2). Irrigation had no significant effect on gin turnout in 2006 or 2009, but it had opposite effects in 2007 and 2008. In the drought year of 2007, the unexpectedly higher gin turnout with irrigation was attributed to a higher percentage of motes (unfertilized or undeveloped ovules) in the non-irrigated seedcotton. The motes were subsequently removed during the ginning process, reducing gin turnout. The 2008 response was consistent with Parks et al. (1978), who found a reduction in gin turnout with irrigation in some years, due to larger seed size.

Table 2. Effects of supplemental irrigation on gin turnout and lint yields of cotton by year, 2006-09, Jackson, TN.

Year	Irrigation		Gin Turnout	Lint Yield
	Tmt. [z]	Total		
		cm	%	kg ha^{-1}
2006	150%	20.3	36.8	1938 b[y]
	100%	13.6	37.7	1988 ab
	50%	6.8	38.1	2093 a
	0%	0.0	37.0	1755 c
Pr > F			0.115	0.004
p (linear)			0.553	0.062
p (quadratic)			0.026	0.002
2007	150%	26.1	37.2 a	1892 a
	100%	17.4	37.2 a	1894 a
	50%	8.7	35.7 ab	1509 b
	0%	0.0	35.0 b	1035 c
Pr > F			0.035	<0.001
p (linear)			0.007	<0.001
p (quadratic)			0.453	0.001
2008	150%	21.2	36.5 b	2265 ab
	100%	14.1	39.5 a	2463 a
	50%	7.1	40.2 a	2445 a
	0%	0.0	40.2 a	2092 b
Pr > F			0.013	0.017
p (linear)			0.004	0.128
p (quadratic)			0.059	0.004
2009	150%	17.5	37.9	1197
	100%	11.7	37.7	1207
	50%	5.8	37.4	1209
	0%	0.0	38.0	1246
Pr > F			0.434	0.639
p (linear)			0.878	0.266
p (quadratic)			0.164	0.636

[z] Percentage of water applied to nominal 2.54 cm wk^{-1} plots (adjusted for rainfall and prior irrigation).

[y] Letters separate means within groups at *p*=0.05 by independent paired comparisons. Letters omitted where Pr(F)>0.05.

Irrigation increased lint yields significantly in 3 of 4 years of this study, but the rate responses were more quadratic than linear (Table 2). Lint yield responses to total water supply (irrigation plus rainfall from planting to harvest) followed quadratic functions in 2006, 2007, and 2008 (Fig. 3A). Lint yields were maximized with total water supply of 58.3, 52.3, and 54.4 cm in each of these years, respectively. In 2009, however, lint yields did not respond to total water supply ranging from 67.3 to 84.7 cm (Fig. 3A). Non-irrigated cotton received more water between planting and harvest than any irrigated cotton received in earlier years of the study. Quadratic yield response to water supply was also found by Wanjura et al. (2002), who maximized yields on the Texas High Plains with seasonal water supply of 74 cm, of which irrigation supplied 58 cm. However, Morrow and Krieg (1990) determined that water supply during the fruiting period was more critical to yield formation than water supply prior to fruiting. In this study, the irrigation season began at appearance of the first square and ended at first open boll. Total water supply during this period may provide a more precise estimate of yield response than total seasonal water. Quadratic regression of lint yield on water supply (rainfall + irrigation) between 40 and 120 DAP (Fig. 3B) showed that yields were maximized with 37.0, 35.4, and 36.2 cm water in 2006, 2007, and 2008, respectively. There was no significant relationship between 40-120 DAP water supply and lint yields in 2009.

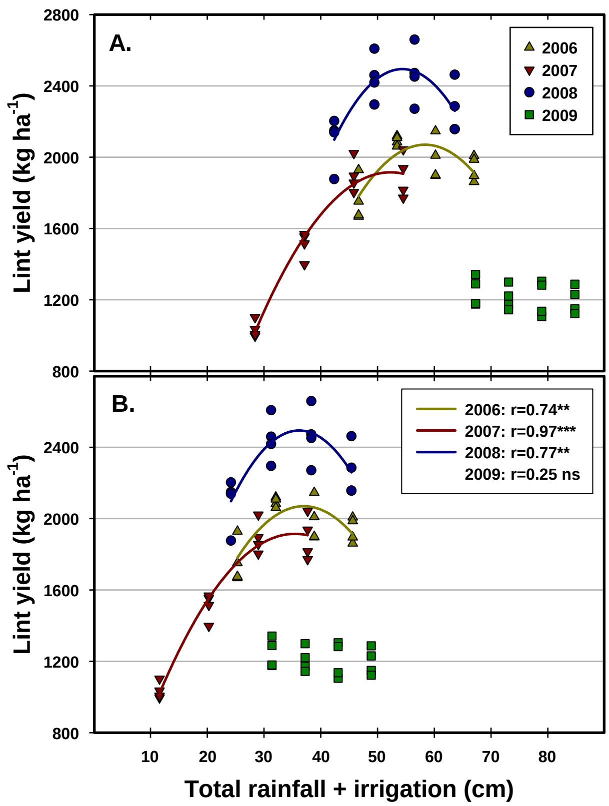

Fig. 3. (A.) Relationships between cotton lint yield and total water supply (rainfall + irrigation) from planting to harvest, Jackson TN, 2006-09; (B.) Relationships between lint yield and water supply (rainfall + irrigation) between 40 and 120 days after planting, Jackson TN, 2006-09. Asterisks (, ***) indicate significance of regressions at *p*=0.01, and 0.001, respectively; ns= not significant (*p*>0.05).**

Earliness and plant mapping . Year-by-treatment interactions were negligible for earliness and plant mapping data, so these data were analyzed across years. Increasing water supply with irrigation increased the number of days from planting to NACB=4, the maturity measure in this study. Irrigation delayed crop maturity in every year of the study, including 2009 when lint yields did not respond to irrigation. Irrigating at the 150% rate delayed maturity by 10 days on average, compared to non-irrigated cotton (Table 3). Across years, days from planting to NACB=4 had a positive linear response to total water supply, delaying maturity by 0.56 days for every additional cm water applied (Fig. 4). Differences in earliness of maturity were also detected with late-season NDVI (Table 3), and NDVI was linearly correlated (p<0.001) with days to NACB=4 in three of four years (Fig. 5). The range of NDVI values was more limited in 2006, when no significant relationship was found between NDVI and NACB=4, even if an outlier was omitted from the linear model for that year. In 2007-09, however, the number of days to NACB=4 increased between 5.3 and 8.6 days for each 0.1 unit increase in late-season NDVI (Fig. 5). Results suggest that irrigation effects on maturity could be detected with late-season NDVI as effectively as with NACB counts, but refinement of the NDVI method is needed.

Table 3. Earliness responses of cotton to four irrigation regimes, 2006-09, Jackson TN.

Irrigation Regime[z]	Days to NACB4[y]	Late season NDVI[x]
	d	
150%	133 a[w]	0.754 a
100%	129 b	0.736 ab
50%	127 c	0.710 b
0%	123 d	0.649 c
Pr > F	<0.001	<0.001
p (linear)	<0.001	<0.001
p (quadratic)	0.824	0.033

[z] Percentage of water applied to nominal 2.54 cm wk^{-1} plots (adjusted for rainfall and prior irrigation).

[y] NACB4 = four nodes above cracked boll.

[x] NDVI = normalized difference vegetation index, measured >1000 DD after planting.

[w] Letters separate means in each column at *p*=0.05 by independent paired comparisons.

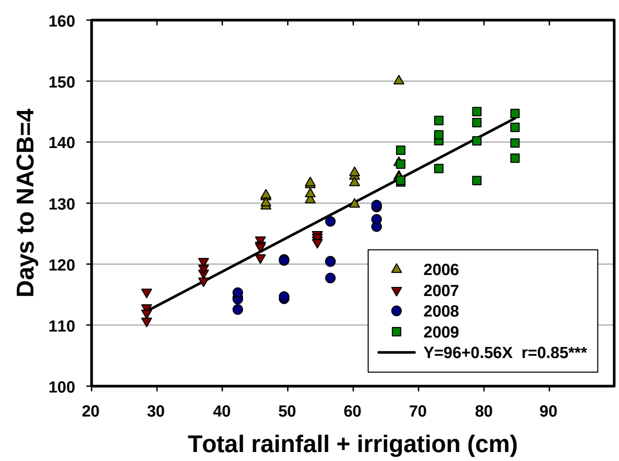

Fig. 4. Relationships between earliness of maturity (as days from planting to four nodes above cracked boll [NACB=4]) and total water supply from planting to harvest, Jackson TN, 2006-09, and coefficient of correlation of curve fitted to combined data. Asterisks (***) indicate significance of linear regression (*p*<0.001).

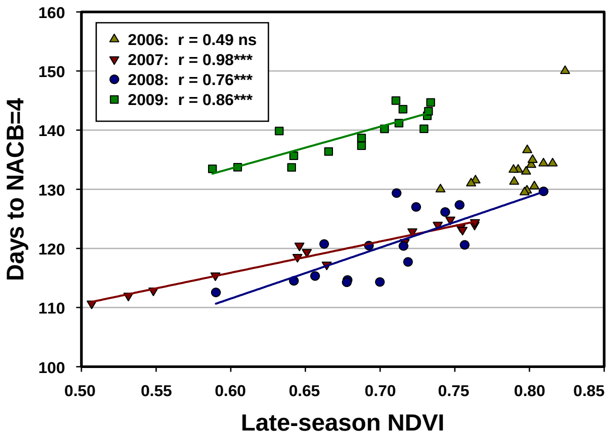

Fig. 5. Relationships between normalized difference vegetation index (NDVI) observed in late season (>1000 DD after planting), and earliness of maturity (days from planting to four nodes above cracked boll [NACB=4]), and coefficients of correlation (r) of curves fitted to yearly data, Jackson TN, 2006-09. Asterisks (***) represent significance of linear regressions (*p*< 0.001); ns = not significant (*p*>0.05).

Insight into earliness responses was provided by late-season plant mapping data (Table 4). Across years, final plant height increased linearly (about 7 to 9%) with successive amounts of irrigation. Irrigation at the 100% rate increased the number of sympodial branches by about one, relative to non-irrigated cotton. Location of lowest harvestable boll (LHB) was moved up only 0.2 sympodial branches with irrigation at 100% or 150% rates. However, location of the highest harvestable boll (HHB) was moved up by one sympodial branch for each successive amount of irrigation up to 100% (Table 4). Thus the effective fruiting zone on the plant was expanded vertically from about 6.6 to 8.5 sympodial branches with irrigation at the 100% rate, but did not increase further with 150% irrigation. Relative to non-irrigated cotton, overall first-position boll retention was increased by irrigation (Table 4), as expected from research by Guinn and Mauney (1984) and by Pettigrew (2004). However, boll retention below the HHB decreased with irrigation at 100% or 150% rates, compared to non-irrigated cotton (Table 4). Possibly, the feedback effects described by Guinn and Mauney (1984) caused the boll load below the HHB to be limited by stresses other than water supply at the higher irrigation rates. Reduced boll retention at lower fruiting sites would be expected to shift carbohydrate partitioning towards more vegetative growth and to bolls set on higher sympodia (Table 4), effectively delaying crop maturity (Table 3).

While first-position boll distribution data reported here help to explain the earliness response, they do not fully account for the yield response to irrigation. Boll numbers m^{-2} accounted for most of the yield response in a study by Pettigrew (2004), but irrigation significantly increased bolls m^{-2} at second- and third-position fruiting sites, not at first-position sites. Although first-position bolls on sympodial branches account for the majority of total yield (Jenkins et al., 1990), compensatory boll set at distal fruiting sites on branches in our study may have contributed to yield responses to supplemental irrigation.

Table 4. Plant growth and development responses of cotton to four irrigation regimes, 2007-09, Jackson TN.

Irrigation regime[z]	Final plant height[y]	Sympodial Branch[x]			First-position boll retention	
		Total	LHB[w]	HHB[v]	Overall	Below HHB[v]
	cm	no.	no.	no.	%	%
150%	118 a[u]	13.3 a	1.3 a	10.1 a	60 a	77 bc
100%	110 b	12.8 a	1.3 a	9.8 a	59 a	75 c
50%	102 c	12.2 b	1.1 b	8.8 b	59 a	81 ab
0%	93 d	12.0 b	1.1 b	7.7 c	54 b	82 a
Pr > F	<0.001	<0.001	0.005	<0.001	0.005	0.011
p (linear)	<0.001	<0.001	0.001	<0.001	0.003	0.003
p (quadratic)	0.729	0.474	0.670	0.134	0.085	0.308

[z] Percentage of water applied to nominal 2.54 cm wk^{-1} plots (adjusted for rainfall and prior irrigation).

[y] Data collected in 2006 through 2009.

[x] Branch number, counting upward from first sympodial branch.

[w] LHB = Lowest harvestable boll.

[v] HHB = Highest harvestable boll.

[u] Letters separate means in each column at *p*=0.05 by independent paired comparisons.

Lack of yield response to irrigation in 2009 (Fig. 3) was not attributable to boll set, but rather to rainfall and heat-unit distribution (Fig. 1) that delayed maturity in all irrigation regimes in that year (Fig. 4). Fewer than 1250 DD accumulated between planting and harvest in 2009, below the minimum needed to realize yield potential in short-season environments (Morrow and Krieg, 1990). Fewer than 17 DD accumulated after harvest-aid application in 2009, compared to accumulations of 48 to 115 DD after harvest-aid application in other years of the study (Fig 1A). This result underscores the importance not only of total heat units, but also of heat-unit distribution for short-season cotton.

Assuming that heat-unit requirements of an adapted cultivar are met, then the percentage of years in which cotton may respond to supplemental irrigation can be roughly estimated from historical weather data and water amounts associated with yield response in this study. In years with adequate heat units, lint yields were maximized with 35 to 37 cm of total water between 40 and 120 DAP (Fig. 3B), and at least 7 cm of irrigation were required to produce a significant yield response (Table 2). Therefore, yield response to irrigation may occur in years with <28 cm rainfall between 40 and 120 DAP. Assuming a planting date of 3 May, an 80-day irrigation season would occur between 12 June and 31 August in this environment. Fifty-year rainfall records for this location (NCDC, 2010) indicated that about 60% of years received <28 cm rainfall between these dates (Fig. 6). For comparison, rainfall between 40 and 120 DAP in this study ranged from 11.6 to 25.3 cm in 2006-08, and totaled 31 cm in 2009. Yield responses in this study thus fit the 28-cm criterion. In the study by Parks et al. (1978), the average 80-d (12 June to 31 August) rainfall totaled 18.3 cm in years in which irrigation elicited a positive yield response. The average rainfall totals for the same time period in site-years with no significant response or a negative yield response were 28 and 31 cm, respectively. Relative to the present study, Parks et al. (1978) irrigated less frequently (10-15 d interval) when soil moisture reached -200 kPa, with larger amounts (~5.1 cm) per irrigation. Chu et al. (1995) demonstrated that applying the same total water volume in smaller, more frequent irrigations during cotton fruiting reduced water deficits and increased lint production.

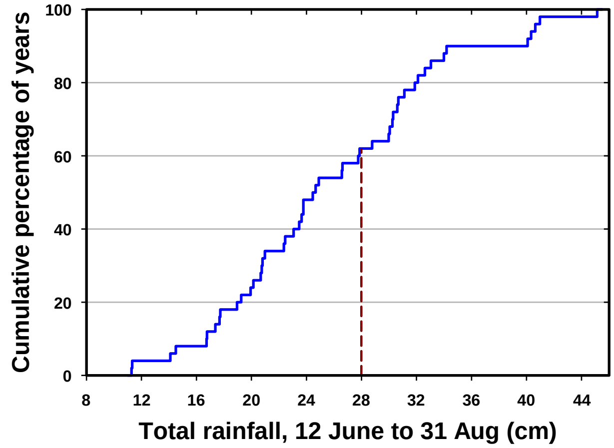

Fig. 6. Cumulative percentage of years that received less than given amounts of total rainfall during a hypothetical cotton irrigation season between 12 June and 31 August, based on rainfall records for Jackson TN from 1956 to 2005 (NCDC, 2010). Vertical dashed line represents rainfall level (28 cm) below which a yield response to supplemental irrigation may be expected in this environment.

Available water holding capacity of a Memphis soil similar to this study was estimated at 22.7 cm m^{-1} soil depth (Parks et al., 1978). The Memphis series is deeper than most other loess-derived upland soils in the region (USDA-NRCS, 2002). Yield response to irrigation may be expected in a greater percentage of years on shallower or coarser-textured soils than the Memphis series.

CONCLUSIONS

An earlier assessment of supplemental irrigation in cotton found that positive yield responses occurred in <40% of site-years in this humid, short-season environment. The present research indicates that a positive yield response may be expected in years with <28 cm rainfall between 40 and 120 days after planting. Assuming a planting date of 3 May, this condition occurred in 60% of years of historical rainfall data. With contemporary cultivars, drip irrigation at 2.54 cm wk^{-1} (adjusted for rainfall and prior irrigation) between first square and first open boll increased yield an average of 38% in three of four years, relative to non-irrigated cotton. There was no yield response to irrigation in a year when <1250 DD accumulated between planting and harvest. In all years, however, maturity was delayed by an average of 0.56 days for every additional cm water supply between first square and first open boll. Irrigation effects on maturity were detected with late-season

NDVI as effectively as with NACB, but refinement of the NDVI method is needed. Producers who wish to profit from the yield response to irrigation should apply appropriate earliness management practices for similar short-season environments.

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