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AGRONOMY AND SOILS

Response to Defoliation Timing Based on Heat-Unit Accumulation In Diverse Field Environments

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ABSTRACT

Defoliation timing affects lint yield and quality of cotton (*Gossypium hirsutum* L.). A timing method based on heat-unit accumulation was evaluated in replicated field plots in Georgia, Louisiana, Tennessee, and Texas during a 3-year period. Objectives were to evaluate effects of different intervals of heat-unit accumulation prior to defoliation in diverse environments on yield and fiber quality. Defoliation timing treatments were aimed at 361, 417, 472, and 528 degree-days (base 15.6°C) after five nodes above white flower (NAWF=5) at all locations. There were additional treatments at some locations. The control treatment aimed to defoliate at 472 degree-days (DD15) after NAWF=5. Crop maturity, as measured by boll opening at the time of control treatment, varied widely across site-years. A seed cotton sample from each plot was ginned to determine lint yield and fiber properties. The control treatment produced yields that were not significantly different from the maximum yield in 9 of 16 site-years. In four environments where the control treatment was too early, yield loss averaged 18.5%. In four other environments where control treatment was too late, lost time averaged 4 days to harvest. Across environments, heat-units after NAWF=5 required to reach the earliest maximum yield at each site-year was associated with yield level, as each increment of 100 kg lint ha^{-1} was associated with 12 more DD15. Fiber properties were less sensitive than yield to defoliation timing by heat-unit accumulation in this study with significant effects on micronaire, fiber strength and length in 9, 4, and 1 site-years, respectively. To achieve consistent results, the heat-unit approach is best used in conjunction with traditional methods of defoliation timing. The existing heat-unit model could be improved for use in diverse environments by incorporating a yield predictor.

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Cotton lint yield and quality are influenced by defoliation and harvest timing (Bednarz et al., 2002; Larson et al., 2002). Several methods exist to determine crop maturity and defoliation readiness, including determining percentage open bolls, counting nodes above the highest cracked boll, and examining the highest harvestable bolls to determine their maturity (Brecke et al., 2001). None of these methods provide sufficiently early prediction of crop maturity for producers to plan defoliation and harvest operations in advance.

Methods to predict crop maturity and schedule harvest-aid application based on heat units were developed in Arkansas during the 1980s and 90s. Bourland et al. (1992) suggested that defoliation timing could be based on the number of heat units needed for development of the last effective flowers into harvestable bolls. They determined a critical value of five nodes above the highest first-position white flower (NAWF=5) as the last effective boll population to contribute to economic yield, based on Arkansas field research. The last effective flower or boll population was defined as those having high probability of retention and adequate size (Oosterhuis et al., 1996). They identified this boll population by whichever occurred first; the occurrence of physiological cutout (NAWF=5.0), or the latest possible cutout date for the location. They stated that 850 degree-days based on 60°F (472 degree-days, base 15.6°C; DD15) were required to mature the last effective bolls in Arkansas. Bourland et al. (1997) recommended that 850 degree-days based on 60°F (472 DD15) accumulate after the last effective flowering date prior to defoliation. These principles were incorporated into the COTMAN decision-aid system (Bourland et al., 1997; Cochran et al., 1998) to help producers schedule cotton fields for defoliation, and plan defoliation and harvest operations in advance of crop maturity.

Defoliation timing by COTMAN rules (472 DD15 after NAWF=5) has been repeatedly validated in Arkansas (Benson et al., 2000; Robertson et al., 2003), but reports from other parts of the U.S. Cotton Belt have shown inconsistent yield responses with this method. In central Texas, defoliation at 472 DD15 after NAWF=5 significantly reduced lint yield relative to defoliation at 528 or 583 DD15, in a single harvest 14 d after each harvest-aid application (Whitten and Cothren, 2002). In coastal Texas, yield was not significantly different when defoliation was initiated at 417 DD15 after NAWF=5 or later (Fromme, 1999). In Tennessee, defoliation at 472 DD15 after NAWF=5 significantly reduced lint yields relative to 528 DD15 for the first harvest at 14 d after treatment and in the total lint from two harvests (Larson et al., 2002).

These reports also varied with respect to fiber quality responses to defoliation timing. There was no difference in fiber quality from defoliation timing ranging from 367 to 527 DD15 after NAWF=5 (Benson et al., 2000). Robertson et al. (2003) indicated that loan values associated with fiber quality were greatest with the 472 DD15 timing in Arkansas. Loan value was reduced by defoliation earlier than 583 DD15 after NAWF=5 due to fiber quality discounts (Whitten and Cothren, 2002). Micronaire was reduced by defoliation at 417 DD15 after NAWF=5 or earlier, relative to later defoliation timing in Texas (Fromme, 1999). Micronaire values increased with DD60 accumulation prior to defoliation in Tennessee, but price differences due to fiber quality did not differ significantly in cotton defoliated between 417 and 528 DD15 after NAWF=5 (Larson et al., 2002).

Adoption of the COTMAN system would be fostered by validation of its defoliation timing rules across a wider range of field environments. A regional project was initiated to evaluate the effects on yield and fiber quality of different intervals of heat-unit accumulation prior to defoliation (Holman et al., 2000). This paper assembles the results across locations from this 3-yr study, and discusses possible reasons for differences in results in contrasting environments.

MATERIALS AND METHODS

A field study was conducted from 1998 through 2000 at Tifton, GA; St Joseph LA; Jackson, TN, and multiple locations in coastal Texas. A uniform protocol called for a well-adapted cotton cultivar to be planted and managed according to local extension recommendations for each location. Agronomic data from each location are presented in Table 1. Row spacing ranged from 0.91 to 1.02 m at the different locations. Crop development was monitored using methods described by Cochran et al. (1998) to determine the date when the crop reached five nodes above white flower (NAWF=5). A time course of NAWF counts was used to calculate the average date of NAWF=5 at each site-year. Starting on that date, daily heat-unit (HU) accumulation was calculated as described by Bourland et al. (1997), using air temperature data from the nearest cooperative weather station. At all locations, a core set of harvest-aid timing treatments were targeted at 361, 417, 472, and 528 degree-days, based on 15.6 °C (650, 750, 850, and 950 DD60s), after NAWF=5. Additional timing treatments were applied at some sites as noted below.

Defoliation timing treatments were applied to 4-row plots arranged in a randomized complete block design with four replications at each location. Plots were arranged so that each plot could be mechanically harvested without affecting other plots. Dates of treatment application at the different locations and years, and actual degree-day accumulations on those dates are listed in Table 2. A tank mixture of tribufos (Def 6; Bayer Corp., Kansas City, MO; or Folex 6EC; Rhone Poulenc Ag. Co.; Research Triangle Park, NC), thidiazuron (Dropp 50WP; AgrEvo USA, Co.; Wilmington, DE), and ethephon (Prep; Rhone Poulenc Ag. Co.; Research Triangle Park, NC; or Super Boll; Griffin LLC., Valdosta, GA) was applied in aqueous solution to individual plots. Rates of these harvest-aids were locally adjusted within labeled ranges to produce optimal response for the crop condition and prevailing weather. Tribufos rates ranged from 0.21 to 0.67 kg ha^{-1}, thidiazuron rates ranged from 0.056 to 0.112 kg ha^{-1}, and ethephon rates ranged from 0.84 to 1.68 kg ha^{-1}. Harvest-aids were applied with a high-clearance sprayer in Georgia, Louisiana, and Tennessee and with a CO_2-pressurized backpack sprayer in Texas.

On the day of treatment, boll counts were made in a 1-m segment of row in each plot to calculate percentage open bolls, and the number of nodes above the uppermost first-position cracked boll to the highest harvestable boll was counted. All data were collected from the two center rows of each plot. In Georgia, Louisiana, and Tennessee, seedcotton was harvested from the two center rows of each plot with a 2-row spindle picker and weighed. In Georgia, plots were picked one time at 14 ± 1 d after each treatment. In Louisiana, plots were picked at 7 and 14 ± 1 d after each treatment. In Tennessee, plots were picked at 14 ± 1 d after each treatment and again between 147 and 150 d after planting. In Texas, a 4.05 m^2 area of each plot was hand-harvested 10 to 12 days after each treatment. In all locations, a sample of seedcotton from each plot was ginned for lint yield calculation based on the total harvest from each plot. A subsample of lint from each plot was analyzed by high volume instrument (HVI) testing procedures to determine fiber properties (USDA, 2001).

Due to differences in degree-day accumulation until treatment and numbers of treatments at different locations, data from each location and year were analyzed separately using the Mixed procedures of SAS (SAS Institute; Cary, NC). Replications were considered random, and treatment dates were fixed variables. Means were separated by performing all possible pair-wise *t*-tests at $P = 0.05$.

RESULTS AND DISCUSSION

Dates for all NAWF=5 occurred before the latest possible dates in which 472 DD15 could be accumulated in the remainder of the growing season in half of the years, based on historical weather data for the test locations (Bourland et al., 1997), so defoliation timing was based on heat-unit accumulation after NAWF=5 in all site-years (Table 1).

In addition to the four core treatments applied in all site-years, earlier treatments were applied in Georgia, and later treatments applied in Georgia, Louisiana, and Texas in all three years (Table 2). The nearest treatment to the target of 472 DD15 after NAWF=5 was considered a control treatment for each site-year. Actual degree-days accumulated after NAWF=5 ranged from 451 to 484 DD15 for these control treatments (Table 2). Differences between target and actual treatment timing were mostly due to weather events. Between NAWF=5 and the control treatment,

Table 1. Edaphic and agronomic features of the regional defoliation timing study conducted in four states over three years

Year	Location	Soil type [y]	Irrigation	Cultivar [z]	Planting	NAWF=5
1998	Tifton, Georgia	Tifton loamy sand	yes (pivot)	SG 501	27 Apr.	24 Jul.
1999			yes (pivot)	DPL 33B	10 May	30 Jul.
2000			yes (pivot)	DPL 33B	1 May	30 Jul.
1998	St. Joseph, Louisiana	Commerce silt loam	No	STV 474	5 May	31 Jul.
1999			No	STV 474	7 May	31 Jul.
2000			No	STV 474	9 May	17 Jul.
1998	Jackson, Tennessee	Calloway silt loam	yes (boom)	STV 474	15 May	24 Jul.
1999			yes (boom)	STV 474	3 May	23 Jul.
2000			yes (boom)	STV 4892BR	11 May	25 Jul.
1998	Wharton, Texas (Beard)	Lake Charles clay	No	DPL 20	30 Mar.	8 Jun.
1998	El Maton, Texas (Hans.)	Laewest clay	No	DPL 50	22 Mar.	1 Jun.
1998	Vanderbilt, Texas (Sapp.)	Laewest clay	No	PM 1220BG/RR	20 Mar.	6 Jun.
1999	Wharton, Texas (Fairgr.)	Lake Charles clay	No	DPL 20B	10 Apr.	1 Jul.
1999	El Maton, Texas (Hans.)	Laewest clay	No	DPL 50	22 Mar.	23 Jun.
1999	Palacios, Texas (Batch.)	Laewest clay	No	DPL 50	20 Mar.	19 Jun.
2000	El Campo, Texas (Emsh.)	Lake Charles clay	No	DPL 20	27 Mar.	20 Jun.

[y] Tifton is a fine-loamy, kaolinitic, thermic Plinthic Kandiudults; Commerce is a fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts; Calloway is a fine-silty, mixed, active, thermic Aquic Fraglossudalfs; Laewest and Lake Charles are fine, smectitic, hyperthermic Typic Hapluderts.

[z] SG = SureGrow (Delta Pine and Land Company; Scott, MS); DPL = Deltapine (Delta Pine and Land Co.; Scott, MS); STV = Stoneville (Stoneville Pedigreed Seed Co.; Memphis, TN); and PM = Paymaster (Delta Pine and Land Co.; Scott, MS).

Table 2. Degree-day accumulation at the date of harvest-aid application and treatment and harvest dates in the four states in 1998, 1999, and 2000

Location [y]	1998			1999			2000		
	Cumul. DD15.6 [z]	Treatment date	Harvest date	Cumul. DD15.6	Treatment date	Harvest date	Cumul. DD15.6	Treatment date	Harvest date
Tifton, Georgia	196	8/11	8/25	329	8/26	9/9	264	8/22	9/10
	279	8/18	9/1	388	9/1	9/17	354	8/30	9/20
	357	8/25	9/9	*463*	*9/8*	*9/22*	*459*	*9/11*	*9/25*
	451	*9/1*	*9/15*	536	9/17	9/30	498	9/15	9/28
	523	9/8	9/22	562	9/22	10/6	526	9/20	10/3
	581	9/15	9/29	612	9/30	10/14	584	9/27	10/10
	654	9/22	10/6	643	10/6	10/19	619	10/3	10/18
St. Joseph, Louisiana	364	8/27	9/10	365	8/27	9/10	367	8/14	8/28
	437	9/1	9/15	425	9/1	9/15	413	8/18	9/1
	484	*9/5*	*9/19*	436	9/2	9/16	*457*	*8/21*	*9/5*
	549	9/10	9/24	*487*	*9/6*	*9/20*	513	8/25	9/8
	596	9/16	9/30	532	9/10	9/24	589	8/30	9/14
	645	9/20	10/4	586	9/16	9/30	639	9/2	9/18
	721	9/26	10/10	636	9/24	10/8	--	--	--
	809	10/3	10/17	700	10/5	10/19	--	--	--
Jackson, Tennessee	361	8/28	9/11	361	8/23	9/7	367	8/28	9/11
	412	9/2	9/16	430	8/29	9/13	423	9/1	9/15
	475	*9/8*	*9/22*	*472*	*9/3*	*9/17*	*473*	*9/5*	*9/19*
	527	9/15	9/29	532	9/8	9/22	522	9/11	9/26
Wharton, Texas	357	7/5	7/16	361	7/29	8/8	--	--	--
	412	7/9	7/20	422	8/3	8/13	--	--	--
	469	*7/13*	*7/24*	*474*	*8/7*	*8/17*	--	--	--
	513	7/16	7/27	524	8/11	8/21	--	--	--
	570	7/20	7/31	566	8/14	8/24	--	--	--
El Maton, Texas	367	6/29	7/10	359	7/23	8/2	--	--	--
	432	7/4	7/15	419	7/28	8/7	--	--	--
	472	*7/7*	*7/18*	*468*	*8/1*	*8/11*	--	--	--
	526	7/11	7/22	533	8/6	8/16	--	--	--
	569	7/15	7/26	582	8/10	8/20	--	--	--
Three Loc's, Texas	375	7/4	7/15	359	7/17	7/27	361	7/19	7/26
	416	7/7	7/18	412	7/22	8/1	427	7/24	7/31
	471	*7/11*	*7/22*	*470*	*7/27*	*8/6*	*476*	*7/28*	*8/4*
	514	7/14	7/25	532	8/1	8/11	522	8/1	8/8
	571	7/18	7/29	583	8/5	8/15	568	8/5	8/13

[y] At Wharton, Texas, the location was the Beard farm in 1998; Fairgrounds in 1999. At Three Loc's, Texas, the location was Vanderbilt, Texas in 1998; Palacios, Texas in 1999; and El Campo, Texas in 2000.

[z] Cumulative degree-days, base 15.6 C, from NAWF=5 until treatment. *Italics* indicate control treatment.

rates of heat-unit accumulation ranged between 10.3 and 11.6 DD15 per day in the Georgia and Tennessee site-years, and between 12 and 13.5 DD15 per day in the Louisiana and Texas site-years.

Table 3 summarizes temperature and precipitation recorded at the closest NOAA weather station to each site during months of flowering and boll maturation, along with departures from normal (DFN) data for each site-year (NOAA, 2004). Weather in St. Joseph, LA, and Palacios, TX, was generally warmer and drier than normal during these months in 1998 and 2000. Only Tifton, GA, in 2000 had cooler than normal temperatures during these months. Average temperatures were normally cooler in Jackson, TN, than other sites in all 3 yr. Results are consistent with heat-unit accumulation rates for these site-years.

The relationship between heat-unit accumulation and crop readiness for defoliation at each site-year is shown in Table 4. As expected, boll opening increased and nodes above cracked boll (NACB) decreased as heat-units accumulated in all site-years. By the time of control treatment application, boll opening ranged from 12% at El Maton, TX, in 1998 to 73% in Tifton, GA, in 1998. Nodes above cracked boll ranged from 7.3 in Tifton in 1999, to 2.0 in Vanderbilt, TX, in 1998. Results suggest that crop readiness for defoliation varied widely across site-years at ~472 DD15 after NAWF=5. Snipes and Baskin (1994) indicated that defoliants should not be applied prior to 60% open bolls to safeguard against yield loss. Kerby et al. (1992) suggested that cotton is generally safe to defoliate when NACB is less than or equal to four. Few site-years in this study met both of these criteria by the time of control treatment. In 11 of 16 site-years, fewer than 60% of bolls were open, and in 6 of 14 site-years, NACB were greater than four at ~472 DD15 after NAWF=5.

Observed significance levels in *F*-tests of timing effects on lint yield, micronaire, fiber length, and strength are shown in Table 5. Lint yields were significantly ($P \leq 0.05$) affected by defoliation timing in 13 of 16 site-years. Defoliation timing also had significant ($P \leq 0.05$) effects on micronaire in 9 site-years, on fiber strength in 4 site-years, and on fiber length in just 1 site-year. Results suggest that defoliation timing had greater, or more frequent influence on yield than on fiber properties.

Table 3. Average monthly air temperatures and precipitation totals, and their departures from normal (DFN) during months of flowering and boll maturation in the four states in 1998, 1999, and 2000

Location	Month	1998				1999				2000			
		Temp. (°C)	DFN (°C)	Precip. (mm)	DFN (mm)	Temp. (°C)	DFN (°C)	Precip. (mm)	DFN (mm)	Temp. (°C)	DFN (°C)	Precip. (mm)	DFN (mm)
Tifton, Georgia	Jul.	28	1	121	2	27	0	118	0	26	-1	128	10
	Aug.	27	0	52	-71	28	1	40	-83	27	0	61	-62
	Sep.	25	1	237	160	24	0	52	-25	23	-1	300	223
	Oct.	21	2	1	-54	20	1	19	-36	18	-1	28	-27
St. Joseph, Louisiana	Jul.	30	2	156	56	29	1	35	-66	29	1	45	-56
	Aug.	29	2	44	-40	29	2	116	32	30	2	55	-29
	Sep.	28	3	80	7	24	0	73	0	26	1	66	-7
	Oct.	22	3	27	-61	19	1	45	-43	20	1		
Jackson, Tennessee	Jul.	27	1	261	153	28	2	104	-4	26	0	63	-45
	Aug.	26	1	115	41	26	1	14	-60	27	2	74	0
	Sep.	25	3	26	-73	23	1	12	-87	22	0	83	-16
	Oct.	18	2	64	-19	16	0	104	21	18	2	22	-61
Palacios, Texas[z]	May	26	1	0	-112	25	1	54	-57	26	2	139	27
	Jun.	29	2	56	-66	28	1	65	-57	28	1	58	-64
	Jul.	30	1	20	-89	28	-1	194	85	29	1	12	-97
	Aug.	29	0	218	134	29	1	21	-64	29	1	22	-62

[z] **Weather station representing test sites at Wharton, El Maton, Vanderbilt, El Campo, and Palacios, Texas. Source: NOAA, 2004.**

Table 4. Degree-day accumulation, percentage of open bolls and nodes above cracked boll (NACB) at time of harvest aid application in the four states in 1998, 1999, and 2000

Location [y]	1998			1999			2000		
	Cumul. DD15.6[z]	Open bolls (%)	NACB	Cumul. DD15.6	Open bolls (%)	NACB	Cumul. DD15.6	Open bolls (%)	NACB
Tifton, Georgia	196	6	6.7	329	17	11.8	264	9	9.8
	279	42	4.3	388	31	10.3	354	31	5.9
	357	68	2.5	*463*	*55*	*7.3*	*459*	*57*	*4.0*
	451	*73*	*3.6*	536	64	4.5	498	58	3.7
	523	92	1.0	562	60	4.2	526	76	1.3
	581	100	0.0	612	83	2.1	584	80	0.9
	654	100	0.0	643	79	1.3	619	88	1.0
St. Joseph, Louisiana	364	14	--	365	8	--	367	24	3.9
	437	24	--	425	28	--	413	47	5.5
	484	*31*	--	436	40	--	*457*	*47*	*4.6*
	549	42	--	*487*	*51*	--	513	57	3.6
	596	63	--	532	70	--	589	80	1.4
	645	71	--	586	94	--	639	88	1.1
	721	95	--	636	93	--	--		
	809	98	--	700	97	--	--		
Jackson, Tennessee	361	5	7.6	361	13	7.0	367	1	6.2
	412	17	6.2	430	34	4.1	423	9	6.7
	475	*32*	*4.9*	*472*	*41*	*2.8*	*473*	*18*	*4.3*
	527	69	1.3	532	55	2.6	522	49	2.4
Wharton, Texas	357	0		361	1	10.1	--	--	--
	412	3	4.0	422	9	7.7	--	--	--
	469	*36*	*2.3*	*474*	*21*	*5.6*	--	--	--
	513	64	0.8	524	30	4.5	--	--	--
	570	75	0.6	566	50	2.6	--	--	--
El Maton, Texas	367	0		359	0		--	--	--
	432	2	4.5	419	18	9.0	--	--	--
	472	*12*	*2.7*	*468*	*34*	*5.6*	--	--	--
	526	36	1.1	533	60	2.7	--	--	--
	569	63	0.3	582	60	2.5	--	--	--
Three Loc's, Texas	375	0		359	21	5.9	361	29	5.7
	416	9	4.0	412	34	5.7	427	59	3.5
	471	*35*	*2.0*	*470*	*59*	*4.0*	*476*	*63*	*3.3*
	514	68	0.9	532	75	2.2	522	69	2.3
	571	92	0.2	583	89	1.0	568	91	1.1

[y] At Wharton, Texas, the location was the Beard farm in 1998; Fairgrounds in 1999. At Three Loc's, Texas, the location was Vanderbilt, Texas in 1998; Palacios, Texas in 1999; and El Campo, Texas in 2000.

[z] Cumulative degree-days, base 15.6 C, from NAWF=5 until treatment. *Italics* indicate control treatment.

Table 5. Observed significance levels of *F*-tests of timing effects on lint yield, micronaire, fiber length and strength by location and year

Location [z]	Year	*P*-value			
		Lint yield	Micronaire	Fiber length	Fiber strength
Tifton, Georgia	1998	0.1076	0.0027	0.2034	<0.0001
	1999	<0.0001	0.3228	0.9494	0.9370
	2000	<0.0001	<0.0001	0.2866	0.0004
St. Joseph, Louisiana	1998	<0.0001	0.3995	0.4926	0.6062
	1999	0.0174	0.0002	0.3145	0.0006
	2000	0.0026	0.0852	0.5504	0.0645
Jackson, Tennessee	1998	<0.0001	<0.0001	0.4363	0.3407
	1999	0.0290	0.5445	0.0813	0.6332
	2000	0.0019	0.0078	0.0721	0.2105
Wharton, Texas	1998	0.1721	<0.0001	0.2184	0.0012
	1999	0.0024	0.0068	0.0970	0.5810
El Maton, Texas	1998	0.0154	<0.0001	0.3901	0.6112
	1999	0.0220	0.2749	0.0796	0.2779
Three Loc's, Texas	1998	0.1786	0.0089	0.4976	0.1377
	1999	<0.0001	0.8100	0.0068	0.2124
	2000	<0.0001	0.7417	0.8034	0.9117

[z] At Wharton, Texas, the location was the Beard farm in 1998; Fairgrounds in 1999. At Three Loc's, Texas, the location was Vanderbilt, Texas in 1998; Palacios, Texas in 1999; and El Campo, Texas in 2000.

Lint yield. Table 6 presents lint yield responses to defoliation timing by cumulative degree-days after NAWF=5. Among the 13 site-years where defoliation timing significantly affected yield, there were nine instances in which defoliation at or near 472 DD15 produced yields that were statistically equivalent to the highest yields at those site-years. In 4 of these 9 site-years, maximum yield was achieved by defoliating earlier than 472 DD15. These "early" sites were at St. Joseph in 1999, Jackson in 1999, and El Maton in 1998 and 1999, where loss of time to harvest averaged about 4 d between the earliest defoliation that provided maximum yield and the control. Rainfall deficits during flowering may have contributed to early cutout at Jackson in 1999 and El Maton in 1998 and 1999. Despite irrigation at the Jackson 1999 site, crop water demand still greatly exceeded supply. Temperatures were also above average in the Texas upper coast in 1998 (Table 3).

Maximum yield was achieved by defoliating later than 472 DD15 at Tifton in 1999 and 2000, and St. Joseph in 1998 and 2000. Yield losses from defoliating at 472 DD15 in these instances averaged 291 kg ha^{-1}, or –18.5%, relative to the earliest defoliation that was statistically equivalent to the highest yield. On average, a 6-d delay in defoliation/harvest was required to recover this difference in yield. Relatively high yields at Tifton and St. Joseph were associated with later optimum defoliation dates than in lower yielding environments. Moderate temperatures during flowering and boll filling may have prolonged the fruiting period at Tifton in 2000 (Table 3).

At site-years where defoliation timing significantly influenced yield, heat-unit accumulation corresponding to the earliest date to reach the highest yielding group of treatments ranged from 419 to 596 DD15 (Table 6). Lint yields resulting from these treatments ranged from 759 to 1867 kg ha^{-1}. There was a significant ($P = 0.0007$) positive linear relationship between lint yield and heat-unit accumulation to earliest maximum yield (Fig. 1). The coefficient of determination suggests that about 66% of the variation in heat-units required to reach maximum yield was associated with yield level. Across

Table 6. Effects of defoliation timing on lint yield of cotton in the regional defoliation timing study conducted in four states in 1998, 1999, and 2000

Location [x]	1998		1999		2000	
	Cumul. DD15.6 [y]	Lint yield (kg ha^{-1}) [z]	Cumul. DD15.6	Lint yield (kg ha^{-1})	Cumul. DD15.6	Lint yield (kg ha^{-1})
Tifton, Georgia	196	1247	329	886 d	264	782 c
	279	1419	388	1007 d	354	941 b
	357	1410	*463*	*1198 c*	*459*	*1018 b*
	451	*1447*	536	1480 ab	498	1280 a
	523	1475	562	1622 a	526	1214 a
	581	1524	612	1600 a	584	1219 a
	654	1472	643	1399 b	619	1259 a
St. Joseph, Louisiana	364	842 d	365	1198 b	367	1119 c
	437	1417 c	425	1373 a	413	1337 bc
	484	*1554 bc*	436	1368 a	*457*	*1404 bc*
	549	1679 b	*487*	*1456 a*	513	1709 a
	596	1867 a	532	1478 a	589	1580 ab
	645	1657 b	586	1389 a	639	1800 a
	721	1626 b	636	1374 a	--	
	809	1671 b	700	1350 a	--	
Jackson, Tennessee	361	758 c	361	733 b	367	968 c
	412	1051 b	430	879 a	423	1037 bc
	475	*1131 ab*	*472*	*847 ab*	*473*	*1096 ab*
	527	1168 a	532	935 a	522	1178 a
Wharton, Texas	357	532	361	368 c	--	
	412	558	422	646 bc	--	
	469	*648*	*474*	*953 ab*	--	
	513	595	524	1226 a	--	
	570	607	566	1223 a	--	
El Maton, Texas	367	639 b	359	671 b	--	
	432	759 a	419	895 a	--	
	472	*793 a*	*468*	*937 a*	--	
	526	838 a	533	994 a	--	
	569	840 a	582	1002 a	--	
Three Loc's, Texas	375	898	359	743 c	361	573 c
	416	970	412	964 b	427	803 b
	471	*995*	*470*	*1091 a*	*476*	*1019 a*
	514	1037	532	1138 a	522	1095 a
	571	905	583	1198 a	568	1108 a

[x] Vanderbilt, Texas in 1998; Palacios, Texas in 1999; and El Campo, Texas in 2000.

[y] Cumulative degree-days, base 15.6 C, from NAWF=5 until treatment. *Italics* indicate control treatment.

[z] Within a location, means followed by the same letter are not significantly different at $P = 0.05$ in all possible pairwise t-tests. Absence of letters signifies a non-significant treatment F-test ($P > 0.05$).

environments, each increment of 100 kg lint ha^{-1} was associated with 12 more DD15 from NAWF=5 to defoliation. To the extent that higher yield level reflects more bolls per plant or larger bolls, this result supports the hypothesis that more competition for available nutrients within and between bolls may slow the overall rate of boll maturation relative to heat-unit accumulation. In Acala cotton, boll maturation required from 565 to 575 DD15 for larger bolls developed during the first three weeks of bloom, but decreased to 553 and 501 DD15 for smaller bolls developing during the fourth and fifth week of bloom, respectively (Kerby et al., 1987).

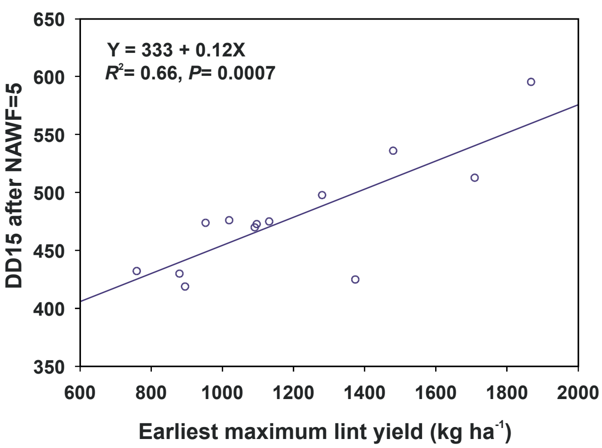

Fig. 1. Linear relationship between lint yield and degree-days, base 15.6 C (DD15), accumulated after five nodes above white flower (NAWF=5) corresponding to the earliest maximum yield at 13 site-years.

Fiber quality. Table 7 presents micronaire responses to defoliation timing in the regional study. In the nine site-years where defoliation timing significantly influenced micronaire, only three had treatments that produced micronaire values in the high or low discount range (USDA, 2001). At St. Joseph in 1999, defoliation at ~472 DD15 after NAWF=5 produced a high-discount micronaire of 5.3. In this instance, defoliation at 365 DD15 would have decreased the micronaire into the base range, albeit with significant loss of yield (Table 6). At Jackson in 2000, defoliation at ~472 DD15 produced a low-discount micronaire of 3.3. In this instance, delaying defoliation to 522 DD15 would have increased the micronaire into the base range with no loss of yield. At El Maton in 1998, defoliation at 472 DD15 avoided a low-discount micronaire that would have resulted from defoliation at 367 DD15 after NAWF=5. Overall results suggest that, while defoliation timing frequently influenced micronaire, defoliation at ~472 DD15 did not always result in avoiding extreme values that lead to price discounts.

Table 8 presents defoliation timing effects on fiber strength in the regional study. In only 4 site-years did defoliation timing significantly influence fiber strength. In 3 site years (Tifton in 1998 and 2000; Wharton in 1998) the effect of later defoliation was gradual deterioration in fiber strength, as described by Bednarz et al. (2002). Results from Louisiana in 1999 ran counter to this trend.

CONCLUSIONS

Results of this study show that defoliation at 472 DD15 after NAWF=5 resulted in yield that did not differ significantly from maximum yield in a wide range of cultivars and environments. This timing resulted in the earliest maximum yield in five of 13 environments. When exceptions to this result occurred, either time or yield was sacrificed. In four environments where defoliation at 472 DD15 was too early, yield loss averaged 18.5%. In four other environments where defoliation at 472 DD15 was too late, time loss averaged four days to harvest. Across environments, the heat-units required to reach the earliest maximum yield was associated with yield level, as each increment of 100 kg lint ha^{-1} was associated with 12 more DD15. This finding suggests that the existing heat-unit model may be improved for use in more diverse environments by incorporating a yield predictor, such as bolls plant per plant at NAWF=5. Most fiber properties were less sensitive than yield to defoliation timing based on heat-unit accumulation.

To achieve consistent results, the heat-unit approach is suitable for use but only in conjunction with other traditional methods of defoliation timing. In most cases where the 472 DD treatment did not optimize yields or quality in this study, use of traditional indicators of crop maturity, such as percentage open bolls or nodes above cracked boll, would have allowed a producer to fine-tune the actual defoliation date. Tracking heat-units during boll maturation remains a useful tool for general planning of crop termination and harvest operations.

Table 7. Effects of defoliation timing on micronaire of cotton in the four states in 1998, 1999, and 2000

Location [x]	1998		1999		2000	
	Cumul. DD15.6 [y]	Micronaire [z]	Cumul. DD15.6	Micronaire	Cumul. DD15.6	Micronaire
Tifton, Georgia	196	4.3 c	329	4.8	264	3.5 c
	279	4.5 bc	388	4.9	354	3.7 b
	357	4.4 c	*463*	*4.9*	*459*	*4.2 a*
	451	*4.7 ab*	536	5.1	498	4.3 a
	523	4.8 a	562	4.9	526	4.2 a
	581	4.7 ab	612	5.0	584	4.3 a
	654	4.7 ab	643	5.0	619	4.3 a
St. Joseph, Louisiana	364	4.7	365	4.9 c	367	5.1
	437	4.8	425	5.3 b	413	4.7
	484	*4.7*	436	5.4 ab	*457*	*4.9*
	549	4.9	*487*	*5.3 b*	513	5.4
	596	4.9	532	5.4 ab	589	5.0
	645	4.8	586	5.4 ab	639	5.3
	721	4.7	636	5.4 ab	--	
	809	5.1	700	5.6 a	--	
Jackson, Tennessee	361	3.5 c	361	4.9	367	3.4 b
	412	3.5 c	430	5.1	423	3.3 b
	475	*3.9 b*	*472*	*5.0*	*473*	*3.3 b*
	527	4.2 a	532	5.1	522	3.6 a
Wharton, Texas	357	3.1 c	361	3.5 c	--	--
	412	3.6 b	422	3.6 bc	--	--
	469	*3.9 a*	*474*	*3.7 bc*	--	--
	513	4.0 a	524	3.8 b	--	--
	570	4.0 a	566	4.1 a	--	--
El Maton, Texas	367	3.4 c	359	4.1	--	--
	432	4.1 b	419	3.9	--	--
	472	*4.2 b*	*468*	*3.9*	--	--
	526	4.4 ab	533	3.9	--	--
	569	4.6 a	582	4.1	--	--
Three Loc's, Texas	*375*	4.2 b	359	5.2	361	3.7
	416	4.5 ab	412	5.4	427	3.8
	471	*4.8 a*	*470*	*5.3*	*476*	*3.6*
	514	4.8 a	532	5.3	522	3.6
	571	4.9 a	583	5.3	568	3.8

[x] Vanderbilt, Texas in 1998; Palacios, Texas in 1999; and El Campo, Texas in 2000.

[y] Cumulative degree-days, base 15.6 C, from NAWF=5 until treatment. *Italics* indicate control treatment.

[z] Within a location, means followed by the same letter are not significantly different at $P = 0.05$ in all possible pairwise *t*-tests. Absence of letters signifies a non-significant treatment *F*-test ($P > 0.05$).

Table 8. Effects of defoliation timing on fiber strength of cotton in the four states in 1998, 1999, and 2000

Location [x]	1998		1999		2000	
	Cumul. DD15.6 [y]	Fiber strength (g tex^{-1}) [z]	Cumul. DD15.6	Fiber strength (g tex^{-1})	Cumul. DD15.6	Fiber strength (g tex^{-1})
Tifton, Georgia	196	35.3 a	329	28.9	264	26.8 a
	279	34.0 b	388	29.3	354	26.4 ab
	357	32.9 c	*463*	*28.9*	*459*	*25.8 bc*
	451	*33.1 bc*	536	28.8	498	25.6 cd
	523	32.5 c	562	28.7	526	25.6 cd
	581	32.1 c	612	28.6	584	25.0 d
	654	32.1 c	643	28.6	619	24.9 d
St. Joseph, Louisiana	364	27.2	365	29.6 c	367	30.7
	437	27.4	425	29.6 c	413	29.3
	484	*27.8*	436	29.3 cd	*457*	*29.6*
	549	27.0	*487*	*29.9 bc*	513	28.6
	596	27.6	532	30.0 bc	589	29.1
	645	26.7	586	30.6 ab	639	29.6
	721	27.2	636	31.1 a	--	
	809	26.3	700	28.6 d	--	
Jackson, Tennessee	361	28.3	361	29.3	367	28.6
	412	28.7	430	29.9	423	28.0
	475	*28.0*	*472*	*29.4*	*473*	*27.9*
	527	28.2	532	29.0	522	27.3
Wharton, Texas	357	31.6 a	361	30.7	--	--
	412	30.5 ab	422	31.1	--	--
	469	*29.7 bc*	*474*	*31.1*	--	--
	513	29.0 c	524	30.8	--	--
	570	29.1 c	566	29.9	--	--
El Maton, Texas	367	29.8	359	28.4	--	--
	432	30.4	419	28.1	--	--
	472	*29.3*	*468*	*27.9*	--	--
	526	30.4	533	28.1	--	--
	569	29.0	582	26.8	--	--
Three Loc's, Texas	375	29.4	359	28.7	361	27.9
	416	28.4	412	27.2	427	27.3
	471	*28.4*	*470*	*27.7*	*476*	*27.6*
	514	28.3	532	29.1	522	27.9
	571	28.1	583	28.0	568	27.2

[x] Vanderbilt, Texas in 1998; Palacios, Texas in 1999; and El Campo, Texas in 2000.

[y] Cumulative degree-days, base 15.6 C, from NAWF=5 until treatment. *Italics* indicate control treatment.

[z] Within a location, means followed by the same letter are not significantly different at $P = 0.05$ in all possible pairwise t-tests. Absence of letters signifies a non-significant treatment F-test ($P > 0.05$).

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