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Effect of an Upper Temperature Threshold on Heat Unit Calculations, Defoliation Timing, Lint Yield, and Fiber Quality in Cotton

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ABSTRACT

In cotton production, delaying defoliation exposes open bolls to rainfall, reducing lint yield and fiber quality. However, premature defoliation has detrimental effects on both yield and quality. Currently, one management strategy for defoliation is based on heat-unit (HU) accumulation after physiological cutout or five nodes above white flower (NAWF = 5). Results have been inconsistent across environments when utilizing HU accumulation; therefore, adoption of this method has been limited. Studies were conducted in the Brazos River bottom and upper Texas Gulf Coast to identify an upper temperature threshold (UTT) for calculating degree days for defoliation timing. Experimental design was a split-plot with main plots of temperature thresholds (32°C, 35°C, and no upper limit) and subplots of HU timings (361, 417, 472, 528, and 583) accumulated from cutout. Utilizing an UTT to calculate daily HU failed to explain differences in the optimum time to defoliate based on accumulated HU; however, accumulated HU had an impact on defoliation timing. Comparison of locations showed that maximum lint yield was obtained at 472 HU and 52% open boll in Wharton County versus a maximum of 528 HU and 62% open boll for Burleson County. Employing the NACB = 4 method to time defoliation at both locations would have resulted in premature application of harvest aids and reduced lint yields. There were no differences in adjusted gross income values at Wharton County among the 417, 472, 528, and 583 HU treatments. For Burleson County, adjusted gross income peaked in value at 528 HU.

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Cotton (*Gossypium hirsutum* L.) grows as a perennial shrub and is sensitive to temperature at all stages of development (Fryxell, 1986). Cooler temperatures that are less than optimum for growth occur both at the beginning and at the end of the growing season and warmer than optimum temperatures are known to occur during flowering (Reddy et al., 1999). As temperature increases, net carbon gain in C3 plants is affected partly due to the relationship between photorespiration and photosynthesis. Increased temperatures reduce the affinity of ribulose-1,5-bisphosphate carboxylase/oxygenase (rubisco) for CO_2 and enhance the affinity for O_2 (Cothren, 1999). At 22°C and 40°C, photorespiration in cotton was less than 15% and approximately 50% of net photosynthesis, respectively (Perry et al., 1983). Gross photosynthesis has a temperature optimum of 32° to 34°C. Net photosynthesis declines almost linearly from 25 to 37°C (Perry et al., 1983). Also light activation of rubisco was progressively inhibited as temperature became greater than 32°C. This decrease in activity is caused by a reduction in activity of rubisco activase, the enzyme that activates rubisco (Feller et al., 1998).

The growth and development of cotton plants can be characterized by the number of days between observable events, such as seedling emergence and first square; however, the number of days between events might be misleading because growth rates vary with temperatures. The measurement of events can be improved by expressing development units based on accumulated degree days per unit time above a lower temperature representing a threshold for growth (Fry, 1983). Growing degree days are obtained currently by adding the daily maximum and daily minimum temperature (°C), dividing this value by two, and then subtracting a base temperature (15.6°C for cotton) for the particular crop in question (Witten and Cothren, 2002). However, the current method does not take an upper threshold into consideration. Extreme high temperatures to which plants are sometimes subjected have negative effects on their rate of development and the growth curve becomes sigmoidal and not linear (Wang, 1960).

Substantial errors in calculation of day degrees can occur when lower and upper threshold temperatures are not determined correctly (Fry, 1983). The use of heat-unit cotton growth models without upper temperature thresholds results in an overestimation of the favorableness of the growing season and the time required to complete various physiological events (Kerby, 1985). Gilmore and Rodgers (1958) stated that above an upper threshold or optimum temperature, the rate of plant growth might be constant or might even decrease. During the boll maturation period, an upper temperature threshold of 30 to 35°C should be utilized when calculating degree days (Kerby, 1985). A warmer or longer growing season (more accumulated degree days) does not necessarily mean that the crop yield will be higher because excessive high daily temperatures can result in crop stress and affect plant-water status (Sevacharian and El-Zik, 1983). An upper limit threshold of 31 to 32°C is the limit for reproductive growth of cotton and high temperature injury probably is influenced by both extreme temperature and length of exposure to the high temperatures (Reddy et al., 1995). The rate of degree day accumulation and the crop growth rate increases with increasing temperature up to an optimum temperature value or range of values. Above the temperature value or plateau, the rate of degree day accumulation and the crop response decrease with further increases in temperature until no further accumulation occurs and crop development ceases (Hodges, 1991). Due to the extreme maxima and minima temperatures in the western Cotton Belt, a 30/13°C threshold is used to increase the precision of growth monitoring and management (Unruh and Silvertooth, 1997).

After approximately 431 to 472 degree days, or approximately 60 to 70 d after planting, cotton begins to produce flowers (Oosterhuis et al., 1992). A well-managed cotton plant should have at least eight sympodia when the first flower appears on the plant (Bourland et al., 1992). Monitoring nodes above white flower (NAWF) not only enhances the precision and confidence in end-of-the-season management decisions (Bourland et al., 1992), but monitoring NAWF values during the bloom period also gives an insightful measurement of the growth status of the crop (Oosterhuis, et al., 1992). More importantly, using NAWF allows us to adjust for different maturities (and different amounts of required heat units to maturity) between cultivars.

As the season progresses, white flowers located in the first position on sympodia grow progressively closer to the plant apex (Oosterhuis et al., 1992). A white flower in the plant apex is indicative of the termination of square and flower production and is precluded by termination of nodal extension; this stage of growth is commonly referred to as cutout (Guinn, 1979). The term "cutout" is used extensively throughout the U.S. Cotton Belt and it is defined in many ways. When cotton producers observe white flowers in the tops of the cotton plants this is the first signal of cutout or crop maturity (Waddle, 1982). Cutout can be defined as the time when a marked decrease in growth, flowering, and boll retention occurs (Patterson et al., 1978). The point at which demand for photosynthate exceeds the crop's ability to meet this supply for the vegetative and reproductive demands is likewise known as cutout (Guinn, 1984). In the lower southeastern portion of the Cotton Belt, late season weather patterns and insect pressure are not as troublesome as in some locations and flowering can proceed to NAWF = 3 (Bednarz and Nichols, 2005). Kerby (1996) defined the effective fruiting period as the time required to set 95% of all harvestable bolls. The last effective flower or boll population was defined as those that have a high probability of retention and capacity to reach an adequate size (Oosterhuis et al., 1996). Based on Arkansas research, Bourland et al. (1992) determined that a critical value of five nodes above the highest first position white flower (NAWF = 5) was the last effective boll population to contribute to economic yield, whereas at NAWF values less than five, boll size and boll retention were reduced significantly. As NAWF approaches five, the economic value of flowers that were produced at higher nodal positions decreased (Bourland et al., 1992).

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 operations in advance (Gwathmey et al., 2004).

Research has shown that cotton defoliation and harvest can be scheduled on the basis of heat-unit accumulation after physiological cutout (NAWF = 5). The COTMAN Expert System Computer Program (Cochran et al., 1998) uses degree-day accumulation after cutout as a criterion to schedule cotton fields for defoliation. This system can help producers plan crop termination and harvest operations as early as mid-season (Larson et al., 2002). Bourland et al. (1997) suggested that 472 degree-day units, based on 15.6°C (472 DD15), should be accumulated after the last effective flowering date prior to defoliation. The COTMAN defoliation timing rules (472 DD15 after NAWF = 5) have been validated repeatedly 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 the Brazos River Valley region of 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 (Witten and Cothren, 2002). In the coastal region of 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 at 14 d after treatment (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. In Texas, loan value was reduced by defoliation earlier than 583 DD15 after NAWF = 5 due to fiber quality discounts (Witten and Cothren, 2002). Micronaire was also reduced by defoliation at 417 DD15 after NAWF = 5 or earlier, relative to later defoliation timing in Texas (Fromme, 1999). Micronaire values increased with DD15 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).

Crop managers need to determine the most profitable time to defoliate cotton in a high rainfall environment such as the coastal region of Texas. In cotton production, delaying defoliation exposes open bolls to a higher probability of rainfall, which can reduce lint yield and fiber quality. However, premature defoliation has detrimental effects on lint yield and fiber quality and can result in the need for additional defoliation applications. Therefore, defoliation timing is a production practice that is critical to the economic returns of cotton producers.

A recent method to determine defoliation is based on heat-unit (HU or DD15) accumulation after physiological cutout or five nodes above white flower (NAWF = 5). This is the only method that provides early prediction of crop maturity for crop managers to plan defoliation and schedule harvest operations in advance. Beginning at cutout, daily HUs are calculated by subtracting a base temperature of 15.6°C from the average daily temperature. This method recommends initiating defoliation once 472 HUs have accumulated from date of cutout. However, results have been inconsistent across a wide range of field environments when utilizing HU accumulation past cutout. Many regions of the Cotton Belt have maximum daytime temperatures during the growing season that are above the optimum for maximum growth. The rate of HU accumulation and crop growth or development rate increases with increasing temperature up to an optimum temperature value; however, temperatures above an optimum value or range will cause crop growth development rate to decrease or to even cease. In these environments, crop managers might be overestimating daily HUs without the use of an upper temperature threshold.

The primary objective of this research was to identify an upper temperature threshold for calculating degree days for defoliation timing. Identification of an upper temperature threshold might help explain the inconsistent results that have been observed when utilizing degree days to schedule defoliation timing across a wide range of field environments. More importantly, a clear delineation of the proper upper limit threshold should improve scheduling defoliation timing based on heat unit accumulation and result in wider adoption of this practice throughout the U.S. Cotton Belt.

MATERIALS AND METHODS

Field studies were conducted for three consecutive growing seasons (2003-2005) at the Texas Agricultural Experiment Station (TAES) Research Farm located in Burleson County near College Station, TX, and Emshoff Farms located in Wharton County near Wharton, TX. Soil types are a Weswood silt loam (fine-silty, mixed, superactive, thermic, Udifluventic Haplustepts) and a Lake Charles clay (fine, smectitic, hyperthermic Typic Hapluderts) at the College Station and Wharton sites, respectively.

Cotton cultivars utilized in this study were Delta and Pine Land 20B (2003 and 2004) and Delta and Pine Land 444BG/RR (2005) (Delta and Pine Land Company; Scott, MS). Cultivars were seeded at 123, 500 plants ha^{-1} with a John Deere 1700 MaxEmerge Plus Vacuum planter (John Deere Company; Moline, IL). Planting dates for the Wharton sites in 2003, 2004, and 2005 were March 22, March 29, and April 2, respectively, whereas the planting dates for the Burleson sites for 2003, 2004, and 2005 were May 12, April 8, and April 12, respectively. Planting was delayed in 2003 at Burleson due to dry soil moisture conditions in the spring. Furrow irrigation was provided to alleviate water deficit stress throughout the growing seasons. Irrigation amounts for the Wharton County location were 248, 231, and 257 mm, whereas for the Burleson County location the amounts were 236, 269, and 221 mm for 2003, 2004, and 2005, respectively. Management decisions pertaining to fertility, weed control, insect scouting, and control measures were based on Texas Cooperative Extension guidelines (Sansone et al., 2002).

All trials were conducted in a randomized complete block design using a split-plot arrangement of treatments with four replications. The main plots consisted of three upper temperature thresholds (32°C, 35°C, and no upper limit) and the subplots were five HU timings (361, 417, 472, 528, and 583) accumulated from date of cutout (defined as NAWF = 5). Each plot was four rows (1.01-m spacing) wide and 9.7 m long (College Station) and four rows (1.01-m spacing) and 15.2 m long (Wharton). Because monitoring and recording of plant growth and development data was obtained from rows one and four from each of the plots and resulted in plants being damaged, rows two and three were utilized at harvest to determine lint yield.

Beginning at cutout and continuing through the day that defoliation was initiated, ambient daily high and low temperatures were recorded for the calculation of daily HU from weather stations located within 8 km of test locations. Calculation of HUs was obtained by the following equation: [(daily high °C + daily low °C/2)] – 15.6°C (Ritchie et al., 2004). When ambient daily high temperatures exceeded either the 32°C or 35°C upper temperature thresholds, the daily high for the HU equation was fixed at 32°C and 35°C, respectively.

A harvest aid application consisting of thidiazuron at 0.11 kg ha^{-1} (Dropp®) (Bayer Crop Science; Research Triangle Park, NC), tribufos at 0.44 L ha^{-1} (Def®/Folex®) (Bayer Crop Science; Research Triangle Park, NC/AMVAC Chemical Corp; Los Angeles, CA), and ethephon at 1.56 L ha^{-1} (Prep™) (Bayer Crop Science; Research Triangle Park, NC) was applied to each plot at the designated accumulated degree days. Harvest aids were applied using a compressed air small plot sprayer delivering 93.5 L ha^{-1} of water using Tee Jet® (Spraying Systems Inc.; Wheaton, IL) TX-VS 10 hollow cone nozzles with 50.8-cm nozzle spacing.

During the bloom period, biweekly NAWF counts were recorded for each of the plots until date of cutout. NAWF counts were determined by selecting 10 representative plants per plot. Prior to harvest aid application, these 10 plants were removed and plant mapped to determine percent open boll. Prior to harvest, this procedure was repeated.

Plots were harvested 10 and 14 d after harvest aid application for the Wharton and Burleson County sites, respectively. Seed cotton yields were determined by harvesting the middle two rows of each plot. A subsample consisting of 150 g of seed cotton were collected from each plot for ginning to determine percent ginout and lint yield. Each sample was ginned using a 10-saw, hand-fed portable gin. After ginning, a 50-g fiber sample from each plot was subjected to High Volume Instrument (HVI) testing at the International Textile Center in Lubbock, Texas. Results from HVI classing were utilized to calculate the Commodity Credit Corporation (CCC) loan value for each treatment. For all 3 yrs of the study, loan value calculations were based on the 2006 loan rate schedule for upland cotton. HVI color and leaf grades were not considered reliable as the seed cotton was not ginned with lint cleaners. Therefore, all treatments were assigned a 41-4 value for color and leaf grades. Adjusted gross income values for each treatment were calculated by multiplying the yield by the base loan value price plus the total fiber premiums and discounts.

An analysis of variance (ANOVA) appropriate for split-plot design (McIntosh, 1983) was conducted using PROC Mixed of SAS, ver. 9.1.3 (SAS, 2004). Main plots, subplots, and locations were treated as fixed effects. Years, blocks, and interactions involving these terms were considered random. Years were combined at each location for analysis and a combined analysis across locations and years was calculated. When a significant interaction existed for location x treatment for a specific parameter, those means were presented separately by location. The ANOVA was used to test the main effects and their interactions on nodes above cracked boll, percent open boll, lint yield, turnout, micronaire, strength, length, uniformity, loan value, and adjusted gross income. Mean separations for main plots and subplots were conducted using LSD tests at the 5% probability levels (Steel et al., 1997). The probability difference (PDIFF) option within the LSMEANS statement was used to report p-values for all possible pairwise comparisons among the three upper temperature thresholds and five HUs. LSD values were computed by utilizing the highest standard error value of all the combinations from the differences of least square means and multiplying that value by the t-value obtained from t-distribution table. The correct degrees of freedom were obtained from the highest standard error value. Finally, PROC REG of SAS was utilized to measure the relationship between percent open boll at defoliation and average daily high temperature from cutout to defoliation.

RESULTS AND DISCUSSION

For Wharton County, date of harvest aid application in 2003 for the 32°C upper temperature threshold (UTT) was applied 1, 2, 3, 4, and 1 day later than the 35°C UTT and no upper limit thresholds for the 361, 417, 472, and 528 HU timings, respectively. In 2004, date of harvest aid application for the 32°C UTT was applied 3, 4, 4, 3, and 3 days later than the 35°C UTT and no upper limit thresholds for the 361, 417, 472, and 528 HU timings, respectively. For the 2005 study, date of harvest aid application for the 32°C UTT was applied 2, 1, 2, 3, and 3 days later than the 35°C UTT and no upper limit thresholds for the 361, 417, 472, and 528 HU timings, respectively. For all three years of the study, date of harvest aid application for the 35°C UTT and no upper limit threshold were the same for all five HU timings.

In 2003 at Burleson County, date of harvest aid application utilizing the 32°C UTT for the 361, 417, 472, 528, and 583 harvest aid timings was 3, 3, 3, 4, and 6 days later, respectively when compared to the 35°C UTT and 4, 4, 5, 6, and 7 days later, respectively when compared to the no upper limit threshold. For the 2004 study, date of harvest aid application utilizing the 32°C UTT for the 361, 417, 472, 528, and 583 harvest aid timings was 2, 2, 2, 3, and 3 days later, respectively when compared to the 35°C UTT and 2, 2, 3, 4, and 4 days later, respectively when compared to the no upper limit threshold. In 2005 at Burleson County, date of harvest aid application utilizing the 32°C UTT for the 361, 417, 472, 528, and 583 harvest aid timings was 3, 3, 4, 3, and 3 days later, respectively when compared to the 35°C UTT and 4, 4, 5, 5, and 5 days later, respectively when compared to the no upper limit threshold.

When both locations were combined and defoliation, harvest, and fiber quality parameters were analyzed, there was significant interaction for either location x HU, location x upper temperature threshold, or location x upper temperature threshold x HU for percent open boll at defoliation and harvest, lint yield, turnout, strength, length, uniformity, and adjusted gross income (Tables 1 and 2). Due to these interactions, each location was analyzed separately (Tables 3 and 4).

Nodes Above Cracked Boll. At defoliation, nodes above cracked boll (NACB) were calculated as the node position difference between the uppermost harvestable boll and that of the uppermost first position cracked boll. UTT treatments at both locations had no effect on NACB (Table 3). However, NACB values were significantly affected by HU treatments (Table 3). As expected, NACB value decreased as accumulated HUs increased. NACB value at the Wharton County decreased linearly from 5.51 for 361 HUs to 0.92 for 583 HUs (Table 5). Similar findings were recorded in Burleson County; NACB values decreased from 6.56 for 361 HUs to 2.06 for 583 HUs (Table 6). Kerby et al. (1992) stated that harvest aid materials should be applied at NACB = 4. When comparing the two locations, Wharton County and Burleson County reached NACB = 4 at 417 and 472 HUs, respectively. For each of the locations, there were no significant lint yield interaction effects between UTT and HU timings.

Percent Open Boll. The percent of open bolls (POB) was obtained by plant mapping on the day of harvest aid application followed by a subsequent plant mapping at harvest. UTT treatments had no effect on POB at defoliation for Wharton County; however, POB was significantly affected at Burleson County (Table 3).

Percent open boll for Burleson County was significantly higher at 54.52% for the 32°C threshold compared to 48.08% for the no upper limit threshold (Table 7). Accumulated HUs significantly affected POB at both study locations (Table 3). Percent open bolls at Wharton County reached 52 and 67% at the 472 and 528 HU treatments, respectively. The POB value for the 583 HU treatment was significantly higher compared to all other HU treatments with the exception of the 528 HU treatment (Table 5). At Burleson County, HU treatment means exhibited full separation, with 361 HUs having the lowest POB and 583 HUs having the highest. Percent open boll values at Burleson County, reached 50.38 and 62.40% at 472 and 528 HU treatments, respectively (Table 7). McCarty et al. (2000) stated that it is acceptable to defoliate when 50 to 60 % of the bolls are open and the youngest boll you expect to harvest is mature. Although UTT and HU significantly affected POB at Burleson County, the UTT x HU interaction was significant. This interaction was explained by the following observation: Percent open boll for the 35°C and no upper limit thresholds was numerically greater than the 32°C threshold at 417 HUs. Also, the 35°C threshold was numerically greater than the 32°C threshold at 583 HUs (Table 7). The numerically greater percent open bolls did not contribute significantly to yield.

Table 1. Variance components for defoliation and harvest parameters; combined across three years (2003-2005) and two locations, Wharton and Burleson counties.

Main effects[z]	Defoliation		Harvest		
	Nodes above cracked boll	Open bolls	Lint yield	Turnout	Open bolls
	no.	%	kg ha^{-1}	%	%
UTT	NS[y]	NS	NS	NS	NS
HU	***[x]	***	***	NS	*
UTT x HU	NS	NS	NS	NS	*
L	NS	NS	NS	***	NS
L x UTT	NS	NS	NS	NS	**
L x HU	NS	***	***	*	NS
L x UTT x HU	NS	NS	NS	NS	NS

[z] UTT, HU, and L represent upper temperature threshold, heat units, and location, respectively.

[y] NS, no significant differences at $p \leq 0.05$.

[x] *, **, *** Significant at the 0.05, 0.01, and 0.0001 probability levels, respectively.

Table 2. Variance components for fiber quality parameters, loan value and adjusted gross income; combined across three years (2003-2005) and two locations, Wharton and Burleson counties.

Main effects[z]	High volume instrument testing				Loan value ¢	Adjusted gross income $
	Micronaire	Strength	Length	Uniformity		
	value	kN m kg^{-1}	cm	%	kg^{-1}	ha^{-1}
UTT	NS[y]	NS	NS	NS	NS	NS
HU	*[x]	***	NS	NS	NS	**
UTT x HU	NS	NS	NS	NS	NS	NS
L	NS	NS	NS	NS	NS	NS
L x UTT	NS	NS	NS	NS	NS	NS
L x HU	NS	*	***	NS	NS	***
L x UTT x HU	NS	NS	NS	***	NS	NS

[z] UTT, HU, and L represent upper temperature threshold, heat units, and location, respectively.

[y] NS, no significant differences at $p \leq 0.05$.

[x] *, **, *** Significant at the 0.05, 0.01, and 0.0001 probability levels, respectively.

Table 3. Variance components for defoliation and harvest parameters; combined across three years (2003-2005) for each location, Wharton and Burleson counties.

Main Effects[z]	Defoliation		Harvest		
	Nodes above cracked boll no.	Open bolls %	Lint yield kg ha^{-1}	Turnout %	Open bolls %
Wharton					
UTT	NS[y]	NS	NS	NS	NS
HU	**[x]	***	***	NS	***
UTT x HU	NS	NS	NS	NS	NS
Burleson					
UTT	NS	*	NS	NS	*
HU	***	***	**	NS	NS
UTT x HU	NS	*	NS	NS	***

[z] UTT and HU represent upper temperature threshold and heat units, respectively.

[y] NS, no significant differences at $p \leq 0.05$.

[x]*, **, *** Significant at the 0.05, 0.01, and 0.0001 probability levels, respectively.

Table 4. Variance components for fiber quality parameters, loan value, and adjusted gross income; combined across three years (2003-2005) for each location, Wharton and Burleson counties.

Main effects[Z]	High volume instrument testing				Loan value ¢ kg^{-1}	Adjusted gross income \$ ha^{-1}
	Micronaire value	Strength kN m kg^{-1}	Length cm	Uniformity %		
Wharton						
UTT	NS[y]	NS	NS	NS	NS	NS
HU	NS	***[x]	***	NS	*	**
UTT x HU	NS	NS	NS	NS	NS	NS
Burleson						
UTT	NS	NS	NS	NS	NS	NS
HU	**	NS	NS	NS	NS	**
UTT x HU	NS	NS	NS	***	NS	NS

[z] UTT and HU represent upper temperature threshold and heat units, respectively.

[y] NS, no significant differences at $p \leq 0.05$.

[x]*, **, *** Significant at the 0.05, 0.01, and 0.0001 probability levels, respectively.

Table 5. Overall study means for defoliation and harvest parameters, combined across three years (2003-2005), Wharton County

HU[z]	Defoliation		Harvest		
	Nodes above cracked boll no.	Open bolls %	Lint yield kg ha^{-1}	Turnout %	Open bolls %
361	5.51a[y]	25.05d	862c	38.46a	73.37d
417	3.79 ab	41.57cd	1144b	39.21a	81.54c
472	2.67bc	52.07bc	1205ab	38.92a	87.45bc
528	1.73c	67.07ab	1221a	38.81a	91.33ab
583	0.92c	78.58a	1241a	38.81a	95.76 a
Pr > f[x]	0.0028	0.0003	0.0002	0.6076	0.0008
LSD	1.92	16.54	92.17	NS	7.32
UTT[w]					
32°C	2.60a	56.15a	1154a	39.02a	88.14a
35°C	2.98a	51.24a	1105a	38.71a	84.55a
No upper limit	3.19a	51.23a	1144a	38.79a	84.99a
Pr > f	0.0586	0.2350	0.4191	0.4500	0.2589
LSD	NS[v]	NS	NS	NS	NS

[z] HU = Heat units.

[y] HU and UTT values within a single column followed by the same letter are not different at a 0.05 probability level.

[x] Probability of the ANOVA.

[w]UTT = Upper temperature threshold.

[v] NS = Not significant.

Table 6. Overall study means for defoliation and harvest parameters, combined across three years (2003-2005), Burleson County.

HU[z]	Defoliation	Harvest	
	Nodes above cracked boll no.	Lint yield $kg\ ha^{-1}$	Turnout %
361	6.56a[y]	997d	38.63a
417	5.11b	1095cd	39.00a
472	3.73c	1176bc	38.60a
528	2.59cd	1391a	38.68a
583	2.06d	1266ab	39.07a
Pr > f[x]	0.0002	0.0064	0.4304
LSD	1.25	156.98	NS
UTT[w]			
32°C	3.67a	1201a	38.55a
35°C	4.16a	1176a	39.12a
No upper limit	4.20a	1177a	38.72a
Pr > f	0.3286	0.8821	0.0574
LSD	NS[v]	NS	NS

[z] HU = heat units.

[y] HU and UTT values within a single column followed by the same letter are not different at a 0.05 probability level.

[x] Probability of the ANOVA.

[w] UTT = upper temperature threshold.

[v] NS = not significant.

Table 7. Upper temperature threshold x heat unit interaction for percent open boll at defoliation, combined across three years (2003-2005), Burleson County.

UTT x HU = .0241[z] Heat units (HU)	Upper temperature threshold (UTT)			Pr > f = <.0001
	32°C	35°C	No upper limit	
361	39.19	30.97	27.20	32.45e[y,x]
417	40.16	43.68	40.44	41.43d
472	55.03	50.29	45.81	50.38c
528	65.70	64.92	56.97	62.40b
583	72.53	73.46	69.97	71.98a
Pr>f= .0394	54.52a	52.59ab	48.08b	

[z] Probability of the ANOVA.

[y] HU and UTT values within a single column followed by the same letter are not different at a 0.05 probability level.

[x] To compare means in a column, LSD = 5.72; and in a row, LSD = 4.57.

Percent open boll at defoliation was strongly correlated to average daily high temperatures from cutout to 472 HUs and no upper limit threshold. As temperatures increased, the rate of boll opening decreased (Fig. 1). In a study conducted in Greece, when day temperature exceeded a maximum of 30.5 to 32°C, boll maturation was not hastened (Yfoulis and Fasoulis, 1978). Upper temperature threshold treatments at Wharton County had no effect on POB at harvest; however, POB at Burleson County was significantly affected (Table 3). Percent open boll for the 32°C threshold at Burleson County was significantly higher compared to the 35°C and no upper limit thresholds (Table 8). Accumulated HU significantly affected POB at Wharton County; however, there was no on POB at Burleson County

(Table 3). Percent open bolls at Wharton County increased significantly, ranging from 73.37% for 361 accumulated HUs to 95.76% for 583 HUs (Table 5). At Burleson County, numerical values for POB increased as accumulated HU treatments increased from date of cutout (Table 8). Significant differences in POB were not found due to variability among the three years.

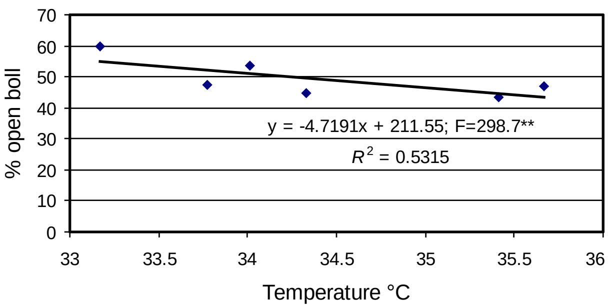

Figure 1. Linear relationship of percent open boll (POB) at defoliation to average daily high temperature from cutout to 472 accumulated heat units (HU) and no upper limit threshold.

Although UTT significantly affected POB at Burleson County, the UTT x HU interaction was significant. An explanation of the interaction is summarized from the following observation: Percent open boll for the 35°C threshold was numerically higher than the 32°C threshold at 472 and 528 HUs (Table 8).

Lint Yield. Upper temperature thresholds at both locations had no effect on lint yield; however, accumulated HUs significantly affected lint yield (Table 3). Maximum lint yield for Wharton County was reached at 472 HUs (Table 5). There were no significant differences in lint yield among the 472, 528, and 583 HU treatments at this location. For Burleson County, maximum lint yield was reached at 528 HUs. Lint yield for the 528 HU treatment was significantly higher than all other treatments with the exception of the 583 HUs (Table 6). Possible explanations for the differences in the optimum time to defoliate between the two locations as reflected in yield might be attributed to: contribution of lint yield above NAWF = 5, light intensity, or the utilization of a UTT lower than 32°C. In a study conducted in Arkansas, bolls produced after NAWF = 5 did not contribute to economic yield (Bourland et al., 1992). However, research in Georgia found that 15% of total lint was contributed after NAWF = 5 (Bednarz and Nichols, 2005). Leffler (1976) reported that bolls did not gain mass during a period of overcast skies. This period of low light intensity (199 ly/d) occurred during secondary wall deposition at 31 to 39 days post anthesis. Studies by Reddy et al. (1991; 1992a,b) indicated that daytime temperatures of 30°C were optimum for total biomass and a higher percentage was partitioned to bolls and squares (Reddy et al., 1991); also, this was the temperature at which the maximum number of bolls and squares were retained (Reddy et al.,1992a,b). In another study, when day temperature exceeded a maximum of 30.5°C, boll maturation was not hastened and became adverse in some genotypes (Yfoulis and Fasoulis, 1978). Therefore, utilizing 30°C as the UTT to calculate HUs is an option that should be considered when attempting to explain differences between the two locations. For each of the locations in our study, no significant lint yield interaction effects were found between UTT and HU timings.

Table 8. Upper temperature threshold x heat unit interaction for percent open boll at harvest, combined across three years (2003-2005), Burleson County.

UTT x HU = <.0001[z] Heat units (HU)	Upper temperature threshold (UTT)			Pr > f = .1494
	32°C	35°C	No upper limit	
361	86.27	84.47	72.10	80.95a[y]
417	89.67	89.47	82.54	87.23a
472	92.07	92.79	90.68	91.85a
528	97.14	98.08	96.57	97.26a
583	100.00	100.00	99.94	99.98a
Pr>f = .0128	93.03a[x]	92.96b	88.37b	

[z] Probability of the ANOVA.

[y] HU and UTT values within a single column followed by the same letter are not different at a 0.05 probability level.

[x] To compare means in a column, LSD = not significant; and in a row, LSD = 2.65.

Turnout. Turnout represents the percent of lint obtained or produced from a known amount of seed cotton. For both of the locations, UTT and HUs had no effect on turnout (Table 3). Numerical values for turnout at Wharton County ranged from 38.46 to 39.21% (Table 5). For Burleson County, numerical values for turnout ranged from 38.60 to 39.07% (Table 6).

Fiber Quality. Micronaire values at both locations were not affected by the UTT treatments (Table 4). Accumulated HU significantly affected micronaire values at Burleson County; however, there was no affect on micronaire values at Wharton County (Table 4). Micronaire tended to increase numerically at Wharton County as defoliation was delayed (Table 9). At Burleson County, micronaire increased from 4.28 at 361 HU to 4.42 at 583 HU (Table 10). Both of these values were within the acceptable range for micronaire (USDA-AMS, 2001).

Increases in micronaire with later defoliation timing support the hypothesis that delayed defoliation allows for more carbon assimilation and/or partitioning of photoassimilates to developing cotton bolls. For both of the locations, there were no significant micronaire interaction effects between UTT and HU timings.

Fiber strength at both locations was not affected by the UTT treatments (Table 4). Accumulated HU at Burleson County did not affect strength; however, at Wharton County there was a significant effect on strength (Table 4). When comparing the accumulated HU treatments at Wharton County, fiber strength value decreased from 30.06 at 361 HUs to 28.68 at 583 HUs, or as defoliation was delayed (Table 9). Fiber strength tended to decrease at Burleson County as defoliation was delayed, but again these values were not significant (Table 10). These findings suggest that with delays in defoliation, weathering was instrumental in reducing fiber strength. For both locations, no significant strength interaction effects between UTT and HU timings were observed.

UTT treatments at both locations had no affect on fiber length (Table 4). Length at Burleson County was not affected by the accumulated HU treatments; however, length at Wharton County was significantly affected by the accumulated HU treatments (Table 4). When comparing the accumulated HU treatments, length values at Wharton County decreased from 2.9 at 361 HUs to 2.84 at 583 HUs as defoliation was delayed (Table 9). The reduction in fiber length as defoliation was delayed cannot be explained. Fiber length values at Burleson County remained at 2.84 among all five accumulated HU treatments (Table 10). For both of the locations, no significant length interaction effects between UTT and HU timings were observed.

Fiber length uniformity at both locations was not affected by UTT or accumulated HU treatments (Table 4). However, at Burleson County there was significant UTT x HU interaction detected for uniformity. Uniformity responded at different rates and not necessarily in the same direction for any of the three UTT or five HU levels (Table 11). At Wharton County, uniformity values decreased numerically from 361 to 583 HUs or as defoliation timing was delayed (Table 9).

Loan Value. Upper temperature thresholds at both locations did not affect loan values (Table 4). Accumulated HUs had no effect on loan value at Burleson County; however, there was a significant decrease in loan value at Wharton County as accumulated HUs increased (Table 4). Loan values at Wharton County decreased from 120.31 ¢ kg^{-1} at 361 HUs to 119.04 ¢ kg^{-1} at 583 HUs (Table 9). When comparisons were made, loan values for 361 and 417 HU treatments were significantly higher than all other treatments with the exception of the 472 HU treatment. For both of the locations, no significant loan value interaction effects between UTT and HU timings were observed.

Adjusted Gross Income. Adjusted gross income at both locations was not affected by UTT (Table 4). However, adjusted gross income at both locations was significantly affected by accumulated HU treatments (Table 4). For Wharton County, adjusted gross income increased as accumulated HUs increased. Values ranged from $926.17/ha at 361 HUs to $1,320.21/ha at 583 HUs (Table 9). However, there were no significant differences in adjusted gross income between the 417, 472, 528, and 583 HU treatments. The 361 HU was significantly lower compared to all other treatments (Table 9). Adjusted gross income at Burleson County peaked in value at 528 HUs. With the exception of the 583 HU treatment, the 528 HU treatment was significantly higher than all other HU treatments (Table 10). For both of the locations, no significant adjusted gross income effects between UTT and HU timings were observed.

Table 9. Overall study means for fiber quality parameters, loan value, and adjusted gross income, combined across three years (2003-2005), Wharton County.

HU[z]	High volume instrument testing				Loan value ¢ kg^{-1}	Adjusted gross income $ ha^{-1}
	Micronaire value	Strength kN m kg^{-1}	Length cm	Uniformity %		
361	4.16a[y]	294.89a	2.90a	84.04a	120.31a	926.17b
417	4.20a	291.26ab	2.87a	84.03a	119.92a	1,223.34a
472	4.19a	287.53bc	2.87a	83.88a	119.86ab	1,289.75a
528	4.21a	285.18cd	2.84b	83.72a	119.12bc	1,298.63a
583	4.23a	281.35d	2.84b	83.54a	119.04c	1,320.21a
Pr > f[x]	0.7335	<.0001	<.0001	0.3080	0.0230	0.0002
LSD	NS[w]	4.12	0.01	NS	0.79	114.44
UTT[v]						
32°C	4.23a	288.22a	2.87a	83.84a	119.76a	1,233.60a
35°C	4.19a	287.62a	2.84a	83.88a	119.72a	1,181.97a
No upper limit	4.17a	288.32a	2.87a	83.81a	119.46a	1,219.29a
Pr > f	0.6643	0.9319	0.7366	0.8866	0.5491	0.4072
LSD	NS	NS	NS	NS	NS	NS

[z] HU = heat units.

[y] HU and UTT values within a single column followed by the same letter are not different at a 0.05 probability level.

[x] Probability of the ANOVA.

[w] NS = not significant.

[v] UTT = upper temperature threshold.

Table 10. Overall study means for fiber quality parameters, loan value, and adjusted gross income, combined across three years (2003-2005), Burleson County.

HU[z]	High volume instrument testing			Loan value ¢ kg^{-1}	Adjusted gross income $ ha^{-1}
	Micronaire value	Strength kN m kg^{-1}	Length cm		
361	4.28c[y]	289.00a	2.84a	118.69a	1,058.73c
417	4.24c	288.61a	2.82a	117.96a	1,160.07bc
472	4.29bc	289.49a	2.84a	118.06a	1,244.82b
528	4.40ab	288.22a	2.84a	117.59a	1,465.27a
583	4.42a	285.67a	2.84a	117.76a	1,388.19ab
Pr > f[x]	0.0054	0.7426	0.6923	0.5846	0.0094
LSD	0.11	NS[w]	NS	NS	192.14
UTT[v]					
32°C	4.30a	289.00a	2.82a	118.04a	1,271.49a
35°C	4.31a	287.92a	2.82a	117.92a	1,242.25a
No upper limit	4.37a	287.73a	2.84a	118.08a	1,246.50a
Pr > f	0.2264	0.8709	0.1112	0.9184	0.8744
LSD	NS	NS	NS	NS	NS

[z] HU = heat units.

[y] HU and UTT values within a single column followed by the same letter are not different at a 0.05 probability level.

[x] Probability of the ANOVA.

[w] NS = not significant.

[v] UTT = upper temperature threshold.

Table 11. Upper temperature threshold x heat unit interaction for uniformity, combined across three years (2003-2005), Burleson County.

UTT x HU = <.0001[z] Heat units (HU)	Upper temperature threshold (UTT)			Pr >f = .1166
	32°C	35°C	No upper limit	
361	83.08	83.49	83.70	83.43a[y]
417	83.28	83.03	83.05	83.12a
472	82.72	82.73	83.78	83.08a
528	83.33	82.67	82.98	82.99a
583	82.82	83.81	82.79	83.14a
Pr>f = .2624[x]	83.05a	83.15a	83.26a	

[z] Probability of the ANOVA.

[y] HU and UTT values within a single column followed by the same letter are not different at a 0.05 probability level.

[x] To compare means in a column, LSD = not significant; and in a row, LSD = not significant.

CONCLUSIONS

Utilizing the designated UTTs for our study to calculate daily HUs failed to explain differences in the optimum time to defoliate based on accumulated HU from cutout. Accumulated HUs had a greater impact on defoliation timing. In comparison of the two locations, maximum lint yield was obtained at 472 HUs and 52% open boll at Wharton County versus 528 HUs and 62% open boll at Burleson County. In a typical year, the difference between 472 and 528 HUs in the two production regions means delaying defoliation by 4 to 5 d. Additional research that might contribute to the explanation of location differences should include contribution of lint yield above NAWF = 5, differences in light intensity, and the utilization of a lower UTT.

Utilizing the NACB = 4 method to time defoliation would have resulted in premature application of harvest aids and reduced lint yields. The NACB benchmark was reached at 417 HU at Wharton County and 472 HU at Burleson County or approximately 4 d too early for optimum lint yield.

At Wharton County, the effect of delaying defoliation resulted in a gradual reduction or weathering of fiber strength when defoliation was initiated at 472 HU or later. Length was reduced when defoliation was initiated at 528 HU or later. The findings of this phenomenon cannot be explained. Micronaire and uniformity were not affected by the defoliation timings. As defoliation was delayed at Burleson County, micronaire values were increased. Micronaire values were increased when defoliation was delayed until 528 HU. However, other fiber characteristics were not affected by defoliation timings.

Loan values at Wharton County decreased when defoliation timings were delayed until 528 and 583 HU. For Burleson County, HU timings had no impact on loan values. Differences in adjusted gross income values at Wharton County were not affected once 417 HU was reached. Burleson County adjusted gross income peaked in value at 528 HU.

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DISCLAIMER

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