ARIZONA COOPERATIVE EXTENSION

College of Agriculture and Life Sciences

THE UNIVERSITY OF ARIZONA. College of Agriculture and Life Sciences

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Cotton Heat Stress

Introduction

Upland cotton is vulnerable to heat stress during the summer monsoon season in the low desert production areas (<2,500′ elevation) of Arizona. The primary impact of heat stress is a reduction in fruit retention which can: 1) reduce overall lint yields, 2) delay crop maturity, and 3) reduce lint quality. This bulletin provides a general overview of cotton heat stress as it pertains to Arizona production systems. Among the topics covered in this bulletin are: 1) a brief summary of relevant research on cotton heat stress; 2) meteorological factors that contribute to heat stress; 3) typical plant responses to heat stress; 4) the Arizona model used to predict heat stress; 5) possible management options for minimizing the impact of heat stress; and 6) how to access on-line information on heat stress conditions.

Research Review

A number of recent studies have examined the impact of temperature on cotton reproductive development. Perhaps the most recognized work was a series of Mississippi studies completed by Reddy et al. (e.g., Reddy, 1992; Hodges, et al., 1993) where cotton was grown under natural sunlight conditions in temperature-regulated growth chambers. This work clearly revealed that fruit retention and yields reached optimal levels when the mean temperature in the chambers ranged from 77-82.4°F (25-28° C). Fruit retention in these same studies declined rapidly as mean temperatures climbed above 82.4°F (28°C) and was essentially zero when temperatures exceeded 91.4°F (33°C). While Reddy et al. (1992) reported some square loss at high temperatures, boll abscission 3-5 days after bloom was the major factor impacting fruit retention and overall reproductive performance.

Zeiher and Brown conducted a number of field, growth chamber and greenhouse studies between 1993 and 1998 and came to similar conclusions regarding temperature and cotton reproductive performance (Zeiher et al., 1994; Zeiher et al., 1995; Brown et al., 1995; Brown and Zeiher, 1997; Brown and Zeiher, 1998a; Brown, 2001). They found that fruit retention, seed number and boll size declined as mean temperatures increased above 82.4°F (Fig. 1); and very low rates of fruit retention once mean temperatures increased above 89.6°F (32°C) [Fig. 2]. Heat stress had little impact on square retention in the Arizona studies; abscission of 3-5 day old bolls was the cause of reduced fruit retention during heat stress. Brown and Zeiher (Brown and Zeiher, 1998a & 2008) also observed several flower abnormalities associated with heat stress, including smaller flowers that did not fully open, asynchronous development of male and female reproductive structures, failure of the anthers to release pollen and the presence of elongated stigmas in open flowers (Figs. 3 & 4). The elongated stigmas, upon closer examination, resulted not because the stigmas were longer than normal, but because the filaments supporting the anthers did not elongate properly. They found that the flower abnormalities developed ~15 days after exposure to severe heat stress (mean temperatures above 86°F), – a finding observed by Powell (1969) in earlier studies. They concluded that severe heat stress damages young

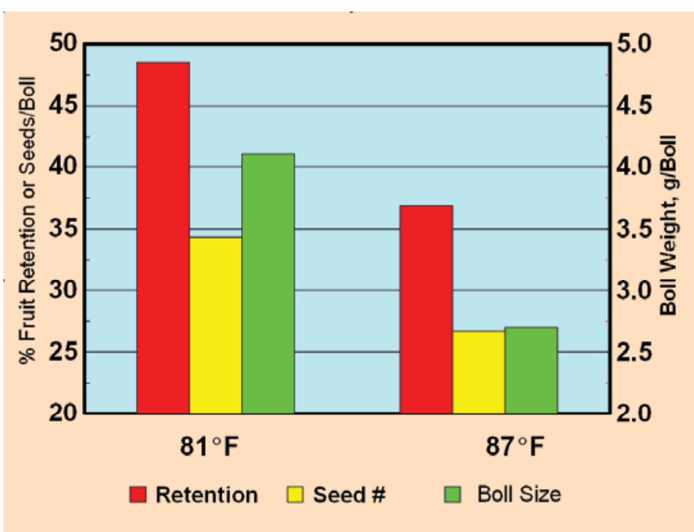

Fig. 1. Fruit retention, seed number/boll and boll size for variety DPL 5415 grown in two greenhouses where the mean temperature during the primary bloom cycle was maintained at 81°F and 87°F.

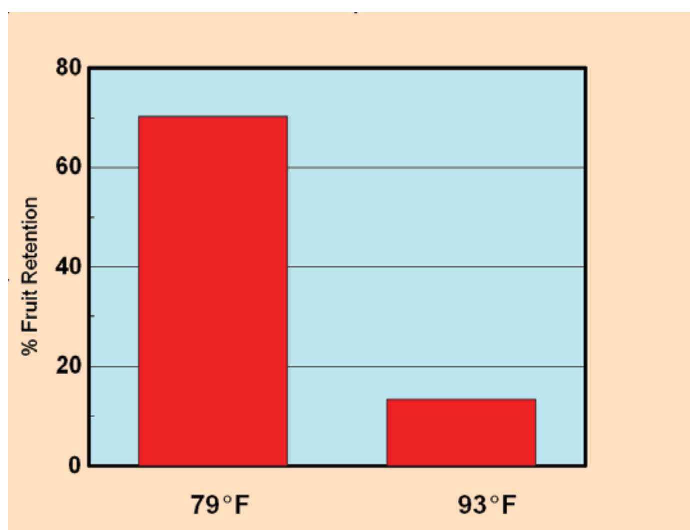

Fig. 2. Fruit retention for variety DPL 5415 grown in two greenhouses where the mean temperature during the primary bloom cycle was maintained at 79°F and 93°F.

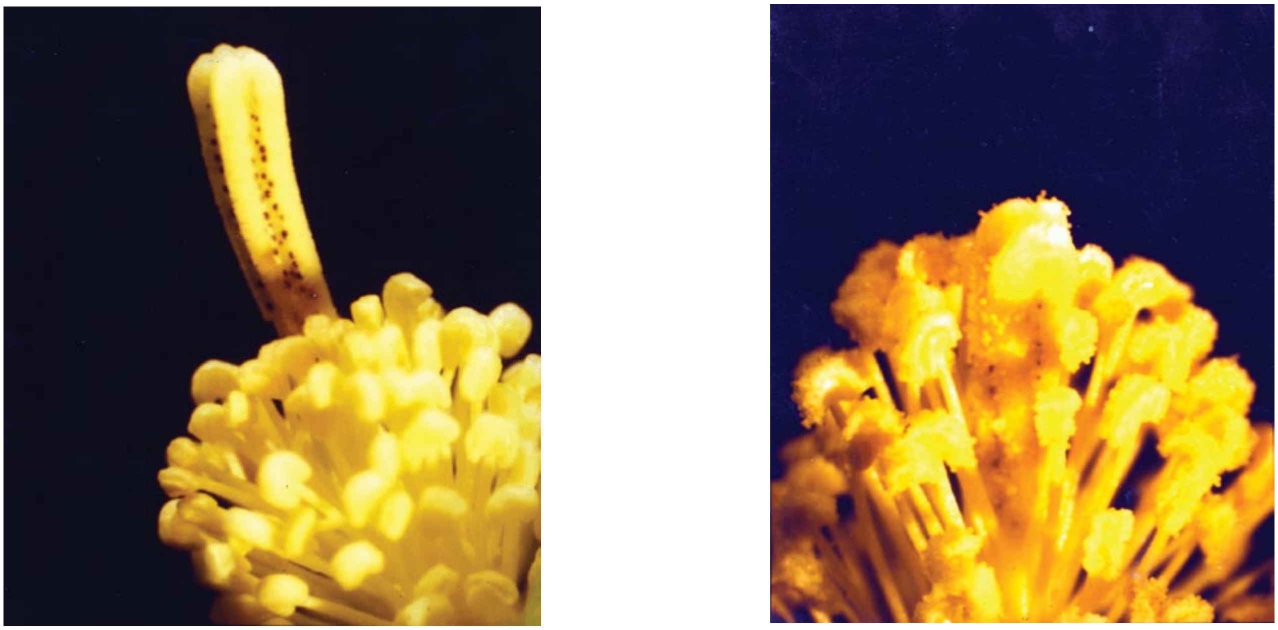

Fig. 3. Reproductive tissues of cotton flowers exposed to heat stress (left) and optimal thermal conditions (right). Heat stressed flowers commonly have short filaments which creates the illusion of an elongated stigma. The anthers of heat stress flowers often do not produce pollen.

Fig. 4. Heat stressed flower observed in the field approximately two weeks after a period of Level 2 heat stress (left). Heat stress flowers are usually smaller in size and often do not fully open (top right) relative to non-stressed flowers (lower right).

squares that are about 15 days from flowering. While these squares develop into flowers, they commonly exhibit the floral abnormalities mentioned above, and nearly all of the resulting bolls abort 3-5 days after bloom.

Recent in vitro studies examining the impact of temperature on pollen germination and pollen tube growth support the fact that temperatures above the 82.4-86.0°F (28-30°C) range negatively impact cotton reproductive performance. Burke et al. (2004) found that pollen germination peaked when temperatures were maintained at 82.4°F (28°C). Germination declined as temperatures increased above 82.4°F and declined precipitously at temperatures above 98.6°F (37°C). The length of the resulting pollen tubes also proved sensitive to temperature with maximum lengths resulting when temperatures were maintained between 82.4°F and 87.8°F (31°C). Tube lengths decreased significantly once temperatures reached 93.2°F (34°C) and approached zero at 109.4°F (43°C).

A number of researchers have suggested that warm night temperatures, alone, result in poor reproductive performance in cotton (e.g., Gipson and Joham, 1968; Powell, 1969; Zeiher et al., 1994; Zeiher et al., 1995; Brown and Zeiher, 1998a). This hypothesis has not been fully tested nor verified in Arizona. Zeiher et al. (1994 &1995) conducted a two-year study wherein they used reflective shelters to increase cotton canopy temperatures at night during the primary bloom period in Tucson, Arizona. Fruit retention and boll size were reduced in one year (1994) but

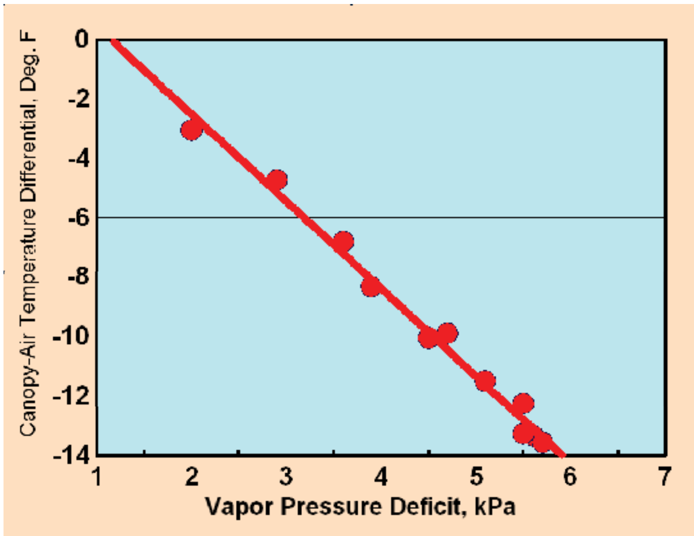

Fig. 5. Canopy-air temperature differential plotted as a function of atmospheric vapor pressure deficit for 12 June 1997 in Yuma Valley.

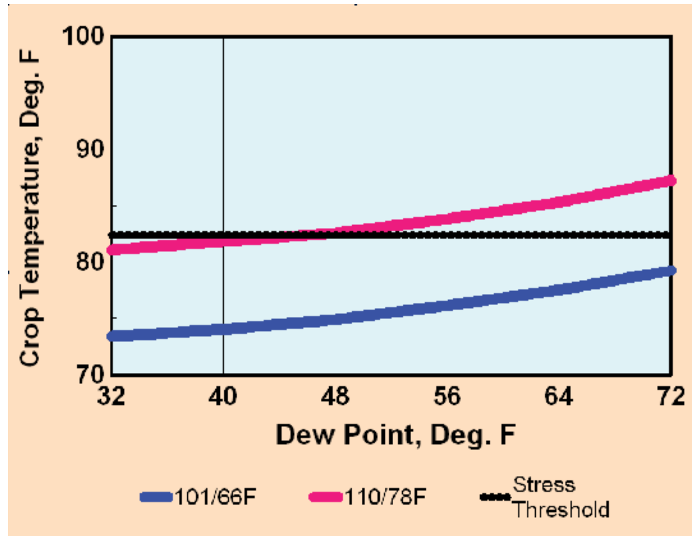

Fig. 6. Mean daily canopy temperature plotted as a function of dew point temperature for two hypothetical days with air temperature extremes of 101°F and 66°F, and 110°F and 78°F, respectively.
The black horizontal line identifies the approximate temperature threshold for cotton heat stress

not during the second year (1995). A weakness in this and most studies relating cotton reproductive performance to night temperatures is that the warm night treatments also increase overall mean temperatures. Brown and Zeiher (1998a) attempted to address the night temperature hypothesis in subsequent greenhouse and growth chamber studies, but could not isolate a night temperature effect. They concluded that the observed relationship between warm night temperatures and poor fruit retention in Arizona is actually the result of increasing humidity transported into the state during the summer monsoon season (Brown and Zeiher, 1997). This higher humidity inhibits radiative cooling at night which leads to higher nighttime canopy and air temperatures. However, humidity also lowers daytime transpiration rates (a cooling process) which results in higher daytime canopy temperatures as well (see discussion in next section).

Meteorological Factors Contributing to Heat Stress

Problems with heat stress develop when the temperature of the cotton canopy and/or floral parts average in excess of 82.4°-86.0°F (28-30°C) for the day. It is important here to distinguish between plant/canopy temperatures and air temperatures since they can be vastly different in Arizona. Research studies conducted in Arizona have consistently shown that cotton canopy temperatures run 7-14°F (~4-8°C) cooler than air temperatures during the daylight hours with the larger differences occurring when humidity is low (Idso et al., 1986; Brown and Zeiher, 1997; Brown and Zeiher, 1998b). Several investigators have found that the temperature difference between the air and crop canopy during the day varies in an inverse linear manner with a measure of atmospheric dryness known as the vapor pressure deficit (Fig. 5) [e.g., Idso et al., 1986; Brown and Zeiher, 1998b]. Zeiher et al. (1994 & 1995) conducted a series of field studies where they examined cotton canopy temperatures at night using infrared thermometers and found: 1) canopies are consistently cooler than air temperature, and 2) the air-canopy temperature differential varied inversely with a measure of atmospheric humidity known as vapor pressure.

Brown and Zeiher (1998b) used measurements of canopy temperature obtained by Zeiher et al. (1994 & 1995) to develop a simple meteorological model that predicts cotton canopy temperatures using air temperature and humidity data. The model was evaluated in a 1997 field study near Yuma where modeled canopy temperatures were found to be within +/-1°C of actual canopy temperatures on 80% of the days between 20 June and 10 August (Brown and Zeiher, 1998b). Fig. 6 presents some output from this model and shows how cotton canopy temperatures vary as a function of dew point temperature for two hypothetical air temperature regimes (High and low temperatures of 101°F/66°F [38.3°C/18.9°C] and 110°F/78°F [43.3°C/25.6°C]). Dew point is a measure of atmospheric humidity that is commonly reported by meteorological services including the National Weather Service and the Arizona Meteorological Network (AZMET). Dew point temperatures generally run between 32°F (0°C) and 40°F (4.4°C) in Arizona during the spring and early summer months. Under these humidity conditions, crop temperatures generally average below the threshold for heat stress (82.4°F (28°C); horizontal black line in Fig. 6). The monsoon develops in early July and imports considerable moisture into the low deserts of Arizona, causing dew points to increase above 55°F. Crop transpiration—an important cooling mechanism for plants—is reduced under these higher humidity conditions, causing canopy temperatures to rise. If air temperatures are sufficiently high (e.g., 110°F/78°F in Fig. 6), the increased humidity associated with the monsoon can cause canopy temperatures to rise to stressful levels (82.4°F and above). The monsoon and its associated humidity is therefore an important causal factor for cotton heat stress in Arizona.

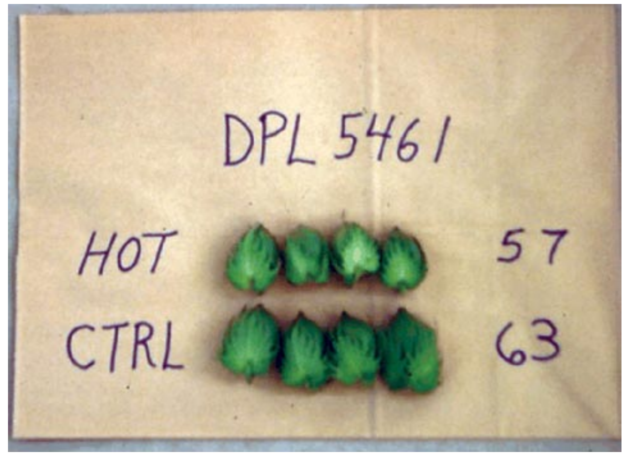

Fig. 7. Heat stress causes abortion of young, 3-5 day old bolls (left). Bolls retained during periods of heat stress (labeled HOT in right figure) are often smaller.

The second, cooler temperature condition presented in Fig. 6 shows that air temperature also plays a role in the development of heat stress. Note that canopy temperatures also increase with increasing humidity for a crop subjected to air temperature extremes of 101°F and 66°F. However, in this case the crop would not encounter heat stress because of the relatively cool air temperature regime. The cooler temperature regime in Fig. 6 is representative of a mid-summer day in the higher elevation production areas of Arizona (e.g., Safford) and explains why heat stress is rarely a problem in those locations.

Arizona Heat Stress Model

Research suggests there is a rather fine line between optimal cotton reproductive performance and serious reproductive failures due to heat stress. Optimal performance exists at temperatures below 82.4°F (28°C) while serious yield losses can result once temperatures exceed 86°F (30°C). Arizona has developed a heat stress model that integrates our present understanding of cotton heat stress with a crop temperature model that predicts mean daily canopy temperatures from air temperature and humidity data collected at local AZMET weather stations (Brown and Zeiher, 1998b). As indicated above, crop canopy temperatures generally run 7-14°F cooler than air temperature in Arizona, so air temperature alone can not reliably predict heat stress. The model generates three potential stress conditions based on mean daily canopy temperature: 1) a no-stress condition when canopy temperatures average less than 82.4°F; 2) a Level 1 heat stress condition when mean canopy temperature falls between 82.4°F and 86°F; and 3) a Level 2 heat stress condition when canopy temperatures exceed 86°F.

Heat stress is rarely a problem when the crop model generates a no-stress condition. Such conditions typically prevail during the hot months of May and June when humidity levels are low. These extended periods of no-stress conditions are typically periods when reproductive performance is optimal and fruit retention is high. No-stress conditions can also develop during breaks in the monsoon season when humidity levels decline toward early summer levels, or during the active monsoon season when temperatures are below normal. Often, fruit retention will improve significantly during these intermittent no-stress periods in late summer (see discussion below).

Level 1 heat stress typically develops during the monsoon season when both temperature and humidity levels are running near long-term normals. Level 1 stress produces light to moderate reductions in fruit retention, a reduction in boll size, and the increased presence of hooked or malformed bolls. The reduction in fruit retention is due to the abortion of young, 3-5 day old bolls. Growers often report considerable variation in crop response during Level 1 heat stress conditions. Potential explanations for this variation include varietal tolerance to heat stress, microclimate variation both within a canopy (sunlit vs shaded flowers) and within an area (cool vs. warm locations), and inaccuracies in the heat stress model.

Level 2 heat stress is the more serious stress condition and typically generates heavy fruit loss. Flowers subjected to Level 2 heat stress produce little or no pollen which leads to widespread abortion of young 3-5 day old bolls. Level 2 stress also damages young squares (~15 days pre-bloom) which leads to a period of low fruit retention ~15 days after the stress occurs, regardless of current conditions. These damaged squares do not abort, but rather develop into smaller flowers that do not fully open, produce sterile anthers, and exhibit what appears to be an elongated stigma (see Figs. 3 & 4). The appearance of the elongated stigma in these heat stressed flowers is actually an illusion and results because the filaments supporting anthers fail to grow and elongate properly.

The Arizona heat stress model presently generates two levels of heat stress. It is unclear from the present research whether the two stress levels are truly distinct or whether Level 1 stress represents a "transition thermal range" wherein less heat tolerant varieties, warmer field locations and/or more exposed flowers (less shaded) fall victim to heat stress. It is possible that once crop temperatures rise above 86°F, the bulk of the crop, regardless of genetics, field location or flower exposure is subjected to heat stress.

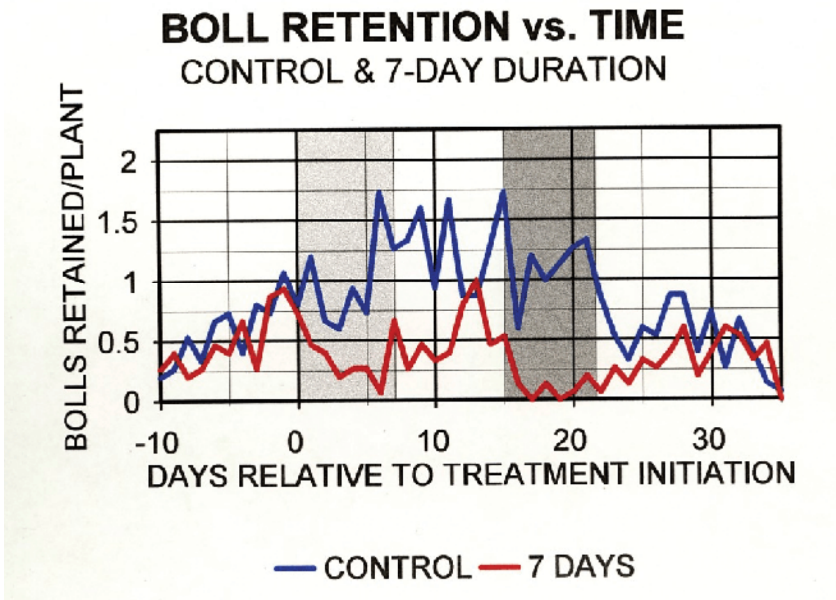

Fig. 8. Fruit retention of DPL 5415 subjected to a seven day period of Level 2 heat stress (red line) and an optimal thermal environment (blue line). Light grey area indicates period of Level 2 stress. Dark grey area delineates a 15-day lag for the period of stress. Note the decline in fruit retention both during the stress period and then 15 days later.

Justification for segregating the Level 2 from Level 1 stress is based largely on the magnitude of boll abortion and the presence of floral abnormalities.

Cotton responds rather quickly to both the development and termination of heat stress (Brown and Zeiher, 2008). It is not uncommon to see boll abortion within 2-3 days of the beginning of a stress event which suggests heat stress disrupts anthesis and/or fertilization rather quickly. Lack of pollen (failure of anthers to dehisce), sterile pollen, and failure of pollen tubes to reach the ovaries have been suggested as causes for this rapid response to heat stress. It is important to note that damage from heat stress is often short lived as fruit retention improves rather quickly once cooler and/or drier weather alleviates the stress, suggesting squares that are within a few days of blooming are the floral structures most vulnerable to heat stress. Young squares also are susceptible to the more intense, Level 2 heat stress conditions. Figure 8 shows fruit retention as a function of time for cotton subjected to a 7-day period of Level 2 heat stress. One sees two periods of low fruit retention – the first during the period of heat stress, and the second beginning ~15 days after the imposition of the stress. Fruit retention recovers significantly between these two periods (Days 8-15 in Fig. 8). Coincident with the second period of reduced fruit retention was the development of heat damaged flowers depicted in Fig. 4. It is important to note that this delayed reduction in fruit retention results from the abortion of 3-5 day old bolls and will occur even if the current weather conditions are optimal for fruit retention (no-stress condition) [Brown and Zeiher, 2008].

Vulnerability to Heat Stress in Arizona

Two meteorological factors determine the vulnerability of a given production area to heat stress – air temperature and humidity. Because air temperature in Arizona varies about 4°F for each 1000′ change in elevation, one sees a dramatic change in heat stress conditions as a function of elevation across the state. Figure 9 provides the mean number of days with heat stress for selected production areas in Arizona and clearly shows the impact of elevation. Heat stress generally occurs with a higher frequency in the hotter, lower elevation production areas in western Arizona. Production areas in central Arizona typically encounter problems with heat stress each summer, but both the intensity and duration of the stress are generally reduced relative to western Arizona. The number of heat stress days decreases dramatically with elevation (Fig. 9) and approaches zero at elevations above 2500′. Production areas near Marana, Safford and Willcox are rarely impacted by heat stress due to their higher elevations and cooler ambient temperatures.

While elevation can serve as a general proxy for determining the potential for heat stress in Arizona, the onset of heat stress in a given year is largely determined by the arrival of the monsoon. Table 1 provides the median date for the first Level 1 and Level 2 heat stress day for selected Arizona locations. The first Level 1 stress day typically occurs within +/- 3days of 1 July at locations ranging from Yuma to Marana. Likewise, the first Level 2 stress day typically develops within +/-2 days of 13 July at all locations except Marana which rarely encounters Level 2 stress due to its elevation.

Figure 10 presents the number of Level 1 and Level 2 heat stress days for Parker for the period 1987 through 2005 and provides further evidence that year-to-year variations in summer temperatures and humidity play an important role in the development and intensity of heat stress. Years with low numbers of stress days are years where the monsoon is sporadic and/or delayed. A delayed or sporadic monsoon produces more summer days with low humidity which helps keep canopies cool by enhancing evaporation during the day and radiational cooling at night.

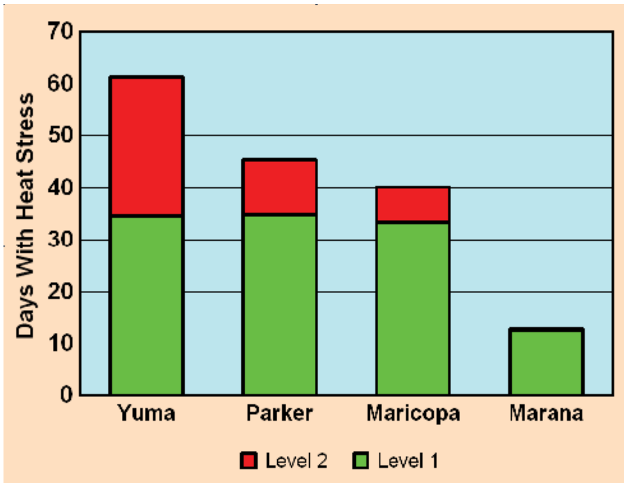

Fig. 9. Average number of days with heat stress from June through September for selected Arizona production areas.

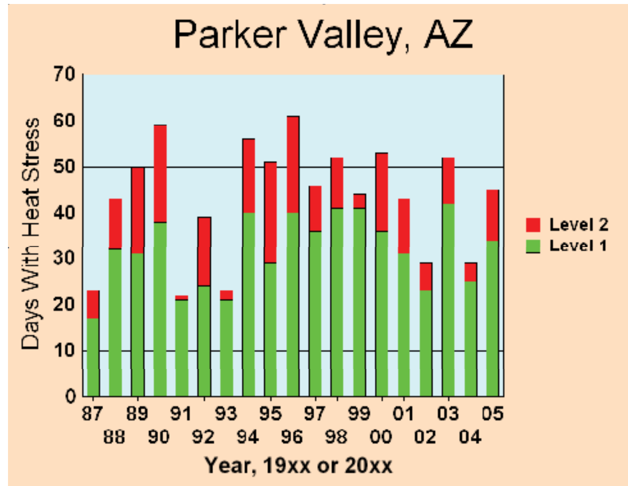

Fig. 10. Number of summer days with Level 1 and Level 2 heat stress in Parker Valley from 1987 through 2005.

Table 1. Median date for first summer days with Level 1 and Level 2 heat stress at selected Arizona locations.

Location	First Level 1 Stress Median Date	First Level 2 Stress Median Date
Yuma Valley	2 July	10 July
Parker Valley	2 July	15 July
Mohave Valley	28 June	12 July
Maricopa	1 July	13 July
Paloma	5 July	11 July
Queen Creek	27 June	13 July
Marana	5 July	N/A

Heat Stress & Yields

Heat stress represents just one of several factors that impact lint yields in Arizona. Other important factors include insect infestations (e.g., pink bollworm, whitefly, lygus), varieties, general crop management (varieties, fertility, irrigation) and date of crop termination. In general, the best relationships between lint yield and heat stress result when one relates yields to the accumulation of heat stress units (HSUs) during the primary bloom period. Many growers are familiar with heat units (HUs) which estimate the amount of heat that contributes to growth and development and thus have been used for years to predict the development of the cotton crop. HSUs work in a similar manner and examine how crop temperatures compare with the threshold temperature for heat-induced damage to cotton (82.4°F). To compute HSUs, we use the Arizona Heat Stress Model to estimate the mean canopy temperature (CT) for the day. We then subtract 82.4°F from CT to obtain HSUs with the proviso that all negative HSU values are set to 0 (no stress). Figure 11 shows the results of an analysis which compared lint yields for LaPaz County in years with below and above normal accumulations of HSUs during the first half of the primary bloom cycle (<2000 HU after planting). Lint yields averaged ~110 lb/a higher in years with reduced levels of heat stress. Similar analyses conducted across multiple counties have returned similar results. Brown (2001) divided years into low, intermediate and high heat stress years and compared the resulting yields in each category (Table 2). Lint yields in low heat stress years averaged 100-254 lb/a higher than yield in high heat stress years.

Management Options

Heat stress is a difficult problem to address through management since one can not control the weather. The primary management option is to minimize exposure to heat stress through planting date and variety selection. Early, optimal planting dates limit exposure to heat stress

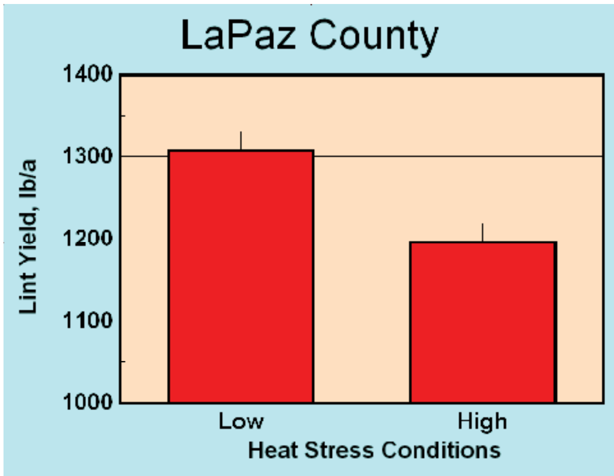

Fig. 11. Average lint yields for LaPaz County during years when the accumulation of heat stress units during the first half of the primary bloom period was below (Low) and above (High) normal.

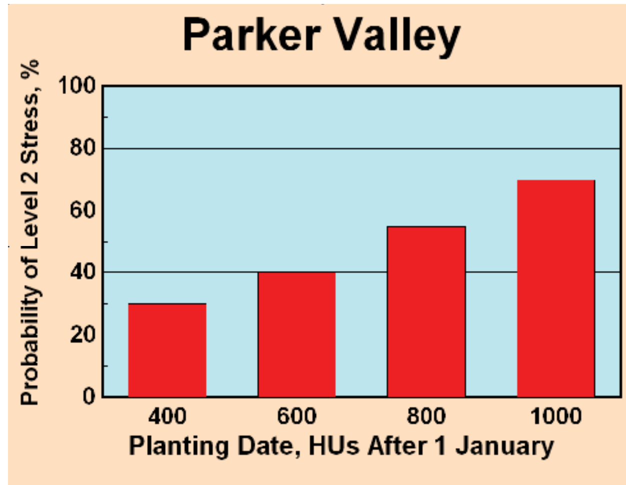

Fig. 12. Probability of encountering Level 2 heat stress prior to peak bloom for selected HU-based planting dates in Parker Valley. Calendar dates associated with 400, 600, 800 and 1000 HUs After 1 January are 14 March, 2 April, 17 April and 29 April, respectively.

Table 2. Average lint yields in lb/a for five Arizona counties when the accumulation of HSUs was low, intermediate and high during the primary bloom cycle.

Heat Stress Condition	Yuma	LaPaz	Mohave	Maricopa	Pinal
Low	1419a*	1310a	1360a	1314a	1308a
Intermediate	1278b	1320a	1301b	1186b	1225ab
High	1165b	1172b	1114c	1214b	1137b

*Means within a column labeled with different letters are significantly different at p<0.1

by allowing the crop to complete a higher fraction of the primary bloom period before the onset of heat stress (arrival of monsoon). The University of Arizona has recommended using heat unit accumulation after 1 January to identify the optimum planting dates for Upland cotton. The recommended planting windows open at 400 HUs after 1 January in most locations and close at 600, 800 and 1000 HUs after 1 January for full, medium and short season varieties, respectively. Cotton planted after the recommended HU window is more vulnerable to heat stress and generally yields less than cotton planted within the window. Figure 12 shows the probability of encountering Level 2 heat stress prior to peak bloom in Parker as a function of HU-based planting dates. The probability increases from 30% for cotton planted at 400 HU after 1 January to 70% for cotton planted at 1000 HU after 1 January. This pattern of increasing susceptibility to heat stress with delays in planting date is similar at all central and western Arizona locations.

Selection of short season and medium maturity varieties can also lessen exposure to heat stress. These varieties proceed through the primary bloom cycle at a faster pace and thus reach peak bloom several hundred HUs ahead of full season varieties. Planting medium season as opposed to full season varieties will reduce the probability of encountering Level 2 heat stress by 10-15% at most low desert locations.

Selection of heat tolerant varieties represents another possible management option. Seed companies do not have a standard rating system for heat tolerance, but sales representatives and local breeders should be able to provide insight on heat tolerance. Growers may also want to monitor local variety trials, especially in difficult heat stress years. Varieties that consistently perform well in high heat stress years likely have a higher level of overall heat tolerance. It is interesting to note that yields in most low desert production areas have been increasing in recent years. These improvements in yield are due in part to improvements in pest management (BT cotton, whitefly control), but may also reflect improvements in heat tolerance as heat stress conditions have not diminished during this period.

Good irrigation management may also minimize exposure to heat stress. Poor irrigation management can lead to water stress which causes the stomata (pores on leaves where water vapor escapes to atmosphere) to close. The foliage temperature of water stressed cotton increases rapidly with stomatal closure because evaporation is reduced. Proper water management avoids stress and keeps the canopies cool. Water stress also causes square abortion and thus should be avoided to ensure high levels of fruit retention.

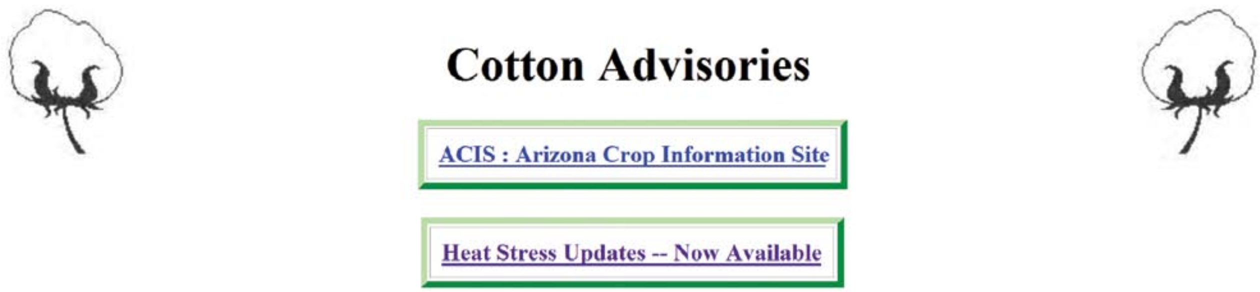

Fig. 13. AZMET's Internet Webpage provides access to heat stress updates via the Cotton Advisory page which is located at the following URL: http://cals.arizona.edu/azmet/cotton.htm

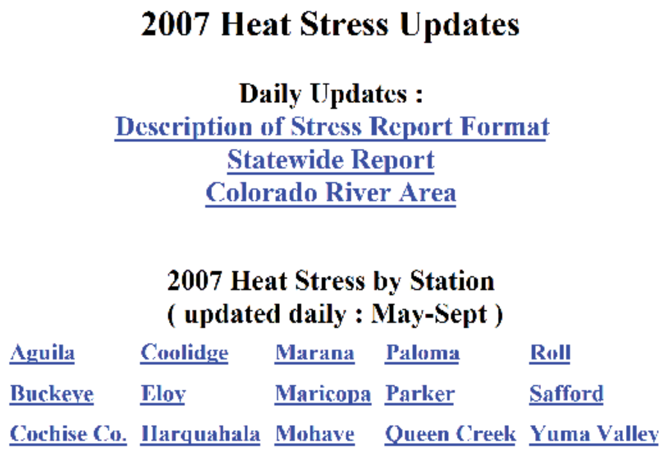

Fig. 14. Listing of various heat stress reports available from AZMET.

How To Obtain Heat Stress Information

Information on heat stress is available online via AZMET's website. Simply enter the following URL address to reach AZMET's Cotton Advisory webpage (Fig. 13):

http://cals.arizona.edu/azmet/cotton.htm

Next, click on the box labeled Heat Stress Updates to gain access to a listing of the various heat stress reports that are available (Fig. 14).

Then click on the report of interest. For example, clicking on the Statewide Report label brings the latest statewide summary of heat stress conditions to your screen (Fig. 15). Other reports provide similar information by region and location for time periods ranging from a week to the entire summer. Each report is updated daily so growers can monitor heat stress conditions throughout the summer.

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Cotton Stress Levels: Past 7 Days: 2006

	Aug 16	Aug 17	Aug 18	Aug 19	Aug 20	Aug 21	Aug 22
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Tucson	ns	ns	ns	ns	ns	ns	ns
Yuma Valley	ns	L1	ns	L1	L1	L1	L2
Yuma Mesa ..	ns	ns	ns	ns	ns	L1	L2
Safford	ns	ns	ns	ns	ns	ns	ns
Coolidge ...	ns	ns	ns	ns	L1	ns	ns
Maricopa ...	L1	ns	L1	ns	L1	L1	ns
Aguila	ns	ns	ns	ns	ns	ns	ns
Parker	ns	ns	ns	ns	ns	L1	L2
Bonita	ns	ns	ns	ns	ns	ns	ns
Citrus Farm	L1	L1	ns	ns	L1	L1	ns
Phx Greenway	L1	L1	ns	L1	L1	L1	ns
Marana	ns	ns	ns	ns	L1	ns	ns
Yuma N.Gila	ns	ns	ns	ns	ns	L1	L2
Phx Encanto	L1	L1	ns	ns	L1	L1	ns
Paloma	ns	ns	ns	ns	ns	ns	ns
Mohave	L1	ns	ns	ns	ns	ns	L2
Queen Creek	ns	ns	ns	ns	L1	L1	ns
Harquahala	ns	ns	ns	ns	ns	L1	L1
Roll	ns	ns	ns	ns	ns	L1	L1
Buckeye	L1	ns	ns	ns	L1	L1	ns
Desert Ridge	ns	ns	ns	ns	L1	L1	ns

ns = No Stress : Crop Temperature < 82.4F
L1 = Stress Level 1 : Crop Temperature: 82.4 to 86F
L2 = Stress Level 2 : Crop Temperature: > 86F

Fig. 15. The statewide heat stress advisory summarizes the stress levels by location for the past seven days. A subsequent section of this report provides the crop temperature estimates.

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