CROP PHYSIOLOGY & METABOLISM

Use of Canopy Temperatures to Identify Water Conservation in Cotton Germplasm[1]

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ABSTRACT

Screening crop germplasm for water conserving traits is difficult under dryland environments because of the variability in soil-water use. Canopy temperatures have been related to crop water stress. This study was designed to evaluate whether cotton (*Gossypium hirsutum* L.) germplasm differs in canopy temperatures and whether these temperatures could be related to performance under deficit soil-water conditions. Cotton strains (both exotic and commercial) were grown in irrigated and dryland field plots on an Olton clay loam (fine, mixed, thermic Aridic Paleustolls). The dryland plots were grown under a rainout shelter to exclude any rainfall during the season while the irrigated plots received two irrigations during the measurement period. Canopy temperatures were measured daily between 1330 to 1430 h CST with a hand-held infrared thermometer. Consistent canopy temperature differences occurred among strains grown in the irrigated plots even though the environmental conditions varied. In the dryland plots, canopy temperatures showed significant strain-by-day interactions suggesting that some strains use their available soil water faster than other strains. Calculated nonstressed baselines showed that the strains had a constant slope of −2.00°C kPa⁻¹ and differed only in their intercept. Those strains, which had warmer canopies in the irrigated plots, had the larger biomass in the dryland plots. It is possible to separate cotton germplasm with infrared thermometry.

Additional index words: Canopy temperature, Stomatal resistance, Genetic populations, Canopy morphology, Water use, Energy balance, *Gossypium hirsutum* (L.)

W HEN IRRIGATION water is not available in semiarid climates, crop yields are dependent upon the amount and distribution of rainfall during the growing season. Yields could be improved if water use could be reduced early in the growing season, thereby making more stored soil water available at later stages of plant growth. This delayed consumption of soil water should increase the probability of rainfall occurring before crop yields are severely depressed.

Canopy temperatures have been used to quantify stress within a given species (Idso et al., 1981; Jackson et al., 1981). In cotton (*Gossypium hirsutum* L.), the observed relationships between canopy temperature, vapor pressure deficit, and stress have allowed the development of crop stress indices applicable to yield estimation and irrigation management (Hatfield et al., 1985; Howell et al., 1984; Pinter and Reginato, 1982). Several researchers (Hatfield et al., 1985; Howell et al., 1984; Idso, 1982; Wanjura et al., 1984) have shown that the unstressed baseline of cotton for the crop water stress index varies little from those initially defined by

Idso et al. (1981). The unstressed baseline is −2.0°C kPa⁻¹ for a range of locations. To date there has not been a large diversity in the germplasm used in these studies.

Blum et al. (1978) showed that differences in drought avoidance (delayed soil-water consumption) could be detected with infrared photography through a change in reflected near-infrared radiation among sorghum [*Sorghum bicolor* (L.) Moench] strains. Singh and Kanemasu (1983) found differences among pearl millet [*Pennisetum americanum* (L.) Leeke] strains for canopy temperatures under irrigated conditions and showed that these differences were related to variation in leaf diffusion resistances. They suggested the use of canopy temperatures as a screening tool for drought avoidance. Idso et al. (1984) found no significant differences among six wheat (*Triticum aestivum* L.) cultivars in their canopy temperatures, but a wide range among various types of water hyacinths [*Eichhornia Crassipes* (Mart.) Solms.]. They suggested that the differences in water hyacinth were the result of various leaf shapes.

The effects of canopy morphology, leaf shape, stomatal conductance, and albedo on temperature of a canopy can be evaluated through the manipulation of the energy balance, given as

$$
\begin{aligned}
(1 - \alpha)\, St &+ (1 - \epsilon)\, Ld \\
&= \epsilon \sigma T_c^4 + \rho Cp\, \frac{(T_c - T_a)}{r_a} + \frac{\rho Cp}{\gamma}\, \frac{(e_s(Tc) - e_a)}{r_a + r_s}
\end{aligned} \quad [1]
$$

Where α is the albedo, St the solar radiation (W m⁻²), Ld the incoming longwave radiation (W m⁻²), ϵ the longwave emissivity, σ the Stefan-Boltzman constant (5.67×10^{-8} J m⁻² s⁻¹ K⁻⁴), T_c the canopy temperature (K), ρCp the volumetric heat capacity of air (J m⁻³ K⁻¹), T_a the air temperature (K), r_a the aerodynamic resistance (s m⁻¹), γ the psychrometric constant (kPa °C⁻¹), $e_s(T_c)$ the saturation water vapor pressure at canopy temperature (kPa), e_a the actual water vapor pressure (kPa) and r_s the stomatal resistance (s m⁻¹). Changes in either r_a or r_s among germplasms would influence canopy temperature through an effect on either sensible or latent heat exchanges. Germplasm with warmer canopy temperature, given that all other conditions are equal, will have decreased evapotranspiration. These aspects have been discussed in detail by Hatfield et al. (1983) and Singh and Kanemasu (1983). O'Toole and Real (1986) have shown that the aerodynamic resistance and canopy resistance to water vapor transfer can be determined from the linear relationship of $T_c - T_a$ and vapor pressure deficit (VPD). They showed that canopies differ in aerodynamic and

canopy resistances and that measurements of T_c may be useful in evaluating these parameters in diverse canopies.

Quisenberry et al. (1981) found significant differences in the shoot dry weight among exotic strains of cotton and suggested that several possible traits could account for these differences including root morphology and root growth. They also found differences in water-use efficiency between these strains, which indicate possible differences in canopy temperatures. Quisenberry et al. (1985) compared physiological and agronomic performance of wilting and nonwilting strains of cotton. They concluded that much of the superior agronomic performance of the nonwilting strain was related to stomatal regulation of seasonal water flow. Roark and Quisenberry (1977) demonstrated that intraspecific differences in stomatal regulation were heritable and suggested that stomatal regulation would be a useful trait for temporary drought avoidance.

The objectives of this study were to determine (i) if canopy temperature measurements could be used to identify cotton strains that had relatively warm or cool temperatures under both irrigated and dryland environments, and (ii) if canopy temperatures could be related to plant characteristics expressed under soil-water deficit field conditions.

MATERIALS AND METHODS

In 1983, 50 photoperiodic (long-night) exotic cotton strains were grown under irrigated and dryland conditions on an Olton clay loam soil (fine mixed, thermic Aridic Paleustolls) at Lubbock, TX. In the dryland plots, each of the 50 strains was replicated twice and planted in single north-south rows 1 m in length with a row spacing of 0.5 m under a rainout shelter. Each row was bordered by a common row of the exotic strain T-25 (Quisenberry et al., 1985). These exotic strains were randomly selected from the world cotton collection maintained by USDA-ARS scientists at College Station, TX. The plots were irrigated before planting to completely recharge the 1.5-m soil profile to the upper limit of available soil water (150 mm). No additional water was received after plant emergence.

In the irrigated plots, the 50 strains were replicated two times and randomly planted in a field adjacent to the rainout shelter. Single east-west rows, each 2-m long, of each strain were planted without any common border at a 1-m row width with a plant population of six plants per meter of row. Irrigations of 80 and 130 mm were supplied at day of year (DOY) 188 and 207, respectively, with a 36-mm rain on DOY 196. Irrigation water was applied when tensiometers registered −0.05 MPa at the 0.46-m depth.

Biomass of plants from both soil-water treatments was measured at 23 and 80 days after planting. At this time, leaf area, number of leaves, plant height, and total dry biomass were determined on five plants from each treatment.

Canopy temperatures were measured daily between 1330 and 1430 h CST with a hand-held infrared thermometer equipped with a 10.5- to 12.5-μm filter and a 4° field of view (fov). The signal from this unit was automatically integrated and stored on a portable data acquisition system, Polycorder Model 516 (Omnidata International, Logan, UT).[3] On each strain, three measurements of canopy temperature were made

at a 45 to 50° angle from horizontal and parallel to the row. The infrared thermometer was positioned to have a target size of 0.03 to 0.04 m² of canopy area in the irrigated plants and 0.01 to 0.015 m² in the dryland plants. This target size was necessary to avoid contamination of the signal by the soil background. Preliminary measurements of the plots showed that this procedure alleviated any bias due to different row directions between the irrigated and dryland study. This number of samples allowed all 50 strains to be measured within a 1-h time period. Measurements of canopy temperature were made only under unobstructed direct solar beam conditions. The canopy temperature measurements began at 51 days after planting (DOY 187) and concluded at 79 days (DOY 215) after planting. During this period there was adequate canopy cover to allow an unbiased measure of canopy temperature without interference of the soil background. Observations of canopy temperature in this study occurred within a fully developed boundary layer allowing Eq. [1] to be valid in its assumptions. Hatfield et al. (1985) have shown that cotton fields on the Southern High Plains are aerodynamically very rough with a large amount of mixing. We assume that a genetic trial placed in a large field of cotton (2 ha) would be within a fully adjusted boundary layer.

Prior to and immediately after the measurements of canopy temperature, observations were made of dry- and wet-bulb temperature, windspeed, wind direction, cloud amount and types, and any obstruction of the direct solar beam. Temperatures were measured with an aspirated Assman Psychrometer (Science Associates, Princeton, NJ) suspended at 0.5 m above a cotton crop adjacent to the rainout shelter. For each of the strains in this study we calculated relationship between $(T_c - T_a)$ and VPD to determine the unstressed baseline as defined by Idso (1982). Howell et al. (1984) had shown that for adequate soil-water conditions the unstressed baseline could be determined across days as well as from diurnal measurements as originally used by Idso et al. (1981).

At 79 days after planting leaf conductance and water potential measurements were made on five, uppermost fully expanded leaves from each strain and replication of the soil-water treatments. These measurements were made between 1100 and 1400 h CST under clear sky conditions using a LI-COR model 1600 steady-state porometer (Lincoln, NE) to estimate conductance and Merrill thermocouple psychrometers (Wescor, Logan, UT) for leaf water potential (Quisenberry et al., 1985).

In 1985, a selected subset of both six commercial and 19 photoperiodic cottons was grown under irrigated and dryland conditions for the purpose of validating the 1983 observations. These lines were selected because of their range in observed water-use efficiencies from greenhouse experiments (Quisenberry, unpublished data) and their range in canopy temperatures from the 1983 study. The dryland plots were randomly planted in a rainout shelter in two replications of one-row plots each 1-m long. The same lines were planted in an irrigated plot in two 1-m-wide rows 3 m in length. Plant populations were five plants per meter. Irrigations of 75 mm each were applied on DOY 210 and 224 based on tensiometer readings at the 0.46-m depth.

Commencing on DOY 186, daily measurements of canopy temperature were made from 1330 to 1415 h CST on clear days with a 4° fov infrared thermometer with six measurements from an oblique angle over the row to view only foliage. Data were recorded on a portable data acquisition system, Polycorder model 516.[3] Prior to and immediately after determination of canopy temperatures, air dry and wet-bulb temperatures were recorded with an Assman aspirated psychrometer at a height of 0.5 m above the canopy. On

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[3] Mention of a specific tradename is for benefit of the reader and does not imply preferential treatment by the USDA-ARS.

DOY 228 a series of diurnal canopy temperature measurements were made every 30 min in the irrigated plots commencing at 0900 and ending at 1600 h CST.

In this study, irrigation treatments were not randomized, therefore, all ANOVA's were conducted within an irrigation treatment. Each irrigation treatment was set up as a randomized complete block and was analyzed as such since the objective was to evaluate differences within a genetic population for canopy temperatures. An a priori assumption was that observations of canopy temperature for a given strain had to be consistently separable over days to be useful for screening genetic populations. Prior to analysis the data were screened for any erroneous data points. Correlation analyses were conducted between observed plant data on DOY 215 and canopy temperature to assess any potential relationships.

RESULTS AND DISCUSSION

The continuous 28-day data set in 1983 was collected for both irrigated and dryland plots, however, there were eight strains removed because they segregated for plant morphological characteristics (okra shaped leaf). The final data set included 1344 mean observations on canopy temperature for each soil water treatment in 1983 and 598 in 1985.

In the irrigated treatment, significant differences were found between days and strains, however, the day × strain interaction was not significant (Table 1). Days were expected to be significantly different since the air temperature ranged from 26 to 36°C during the 28 days and the vapor pressure deficit ranged from 0.8 to 4.2 kPa. The irrigated canopy temperature means among the 42 strains in this study ranged from 27.5 to 30.5°C. The lack of a significant day × strain interaction demonstrated that the strains were consistent in their canopy temperatures when adequate soil water was available even though there was a wide range of environmental conditions.

Consistent canopy temperature differences within the irrigated plots were observed among strains. Four strains selected as representative of the extremes among strains between warm and cool canopies are shown in Fig. 1. Canopy temperatures for T227 were the warmest observed in this study while T1400 was the coolest. Although the air temperature ranged from 26.5 to 35.1°C and VPD's ranged from 0.79 to 4.24 kPa for this period from DOY 208 to 215 these canopies remained different. Data for T25 and T169 are shown because these strains have been previously shown by Quisenberry et al. (1985) to exhibit differences in their stomatal resistance-water potential relationships with T25 having a higher stomatal resistance at any given water potential. These consistent differences between the strains resulted in the lack of a significant interaction between days and strains (Table 1).

During the 28-day period in the dryland environment, the day and strain effects and the day × strain interaction were significant (Table 2). Both the day and the strains were expected to be different because of the results found in the irrigated study. The day × strain interaction suggest differential depletion of the available soil water. In the irrigated environment, the strains were consistently different; however, in the dryland environment some strains began to undergo stress (increased canopy temperatures) earlier than others. Can-

Table 1. Analysis of variance of canopy temperature for 42 exotic cotton strains grown under irrigated conditions for the period of DOY 187 to 215.

Source	df	Mean square	F
Rep (R)	1	65.24	25.89**
Strain (S)	41	6.73	2.67**
S × R	41	2.52	
Day of Year (D)	27	442.08	337.47**
D × S	1107	1.41	1.08 NS†
D × R	27	8.09	13.81**
D × R × S	1107	1.31	

** Significant at the 0.01 probability level. † NS—nonsignificant.

Table 2. Analysis of variance of canopy temperature for 42 exotic cotton strains grown under dryland conditions for the period of DOY 187 to 215.

Source	df	Mean square	F
Rep (R)	1	40.07	6.97**
Strain (S)	41	11.39	1.98*
R × S	41	5.75	
Day of Year (D)	27	742.58	424.33**
D × S	615	1.99	1.22**
D × R	27	21.08	12.04**
D × R × S	630	1.90	

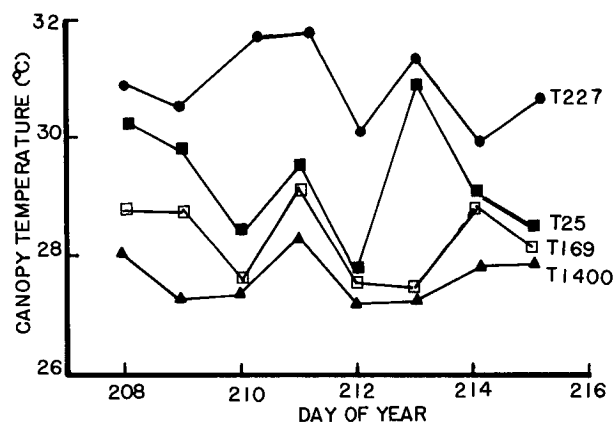*,** Significant at the 0.05 and 0.01 probability levels, respectively.

Fig. 1. Canopy temperatures at 1330 to 1430 h CST for the period DOY 208 to 215 for T25 and T169 cotton strains.

opy temperature of each strain must be dependent upon the amount of water remaining in the soil volume and is a function of the rate of water extraction. For example, a strain that extracted most of the available soil water early in the season (i.e., cooler) would become progressively warmer. A strain with a slower rate of water use early in season (i.e., warmer) would become relatively cooler as the season progressed. Thus, the canopies that were warmer at the beginning of the season with a reduced rate of soil-water use would be cooler at the end of the season because they would still have soil water available for transpirational cooling.

To be useful in screening, crop germplasm canopy temperature patterns must be consistent during defined intervals that can be controlled, i.e., observations after an irrigation. When the data from DOY 208 to 215, which followed an irrigation, were extracted, the same significant sources of variation were found and the ranking of the strains did not change. This period was chosen for further analysis because it represented a period just after a 120-mm irrigation in which soil-water availability and leaf area index were at their maximum.

Table 3. Adjusted intercepts computed from the relationship $(T_c - T_a) = a + b$ (VPD) with $b = -2.00\,°C\,kPa^{-1}$ for selected strains in 1983 and 1985.

Strain	Adjusted intercept (°C) 1983	1985
T25	2.70	3.50
T80	2.90	3.84
T169	2.20	2.70
T256	3.10	4.51
T283	1.90	2.73
T461	3.50	4.46
Lubbock Dwarf	--†	3.00
Pima S-5	--†	2.85

† Not grown in 1983.

Table 4. Simple correlation coefficients (r) for various plant parameters from cotton strains grown under irrigated conditions (n = 42).

Plant parameters	Leaf conductance	Leaf water potential	Leaf size	Height
	m s⁻¹	MPa	m²	m
Intercept†	−0.50**	−0.28	0.28	0.35*
Leaf conductance	1.00	0.39**	0.59**	−0.67**
Leaf water potential		1.00	−0.51**	−0.34*
Leaf size			1.00	0.44**

*,** Significant at the 0.05 and 0.01 probability levels, respectively.
† Adjusted intercept of the linear relationship $(T_c - T_a) = a + b$ (VPD) with $b = -2.00\,°C\,kPa^{-1}$.

The unstressed baselines for the 42 strains had slopes not significantly different from $-2.0\,°C\,kPa^{-1}$ with a mean slope of $-2.08\,°C\,kPa^{-1}$. The intercepts differed among strains and ranged from 1.2 to 4.0. Since there was no significant difference between the slopes for the different strains the mean slope was used to compute an adjusted intercept for each strain. The adjusted intercept values then ranged from 1.8 to 4.1°C and selected strains are shown in Fig. 2.

In the 1985 data set from DOY 228 or the period from DOY 226 to 236, the mean value of the slope was $-2.16\,°C\,kPa^{-1}$. The adjusted intercepts were larger than those found in 1983 and ranged from 2.73 to 4.69, however, the common strains in 1983 and 1985 did not change greatly in their ranking (Table 3). Commercial lines tended to have lower intercepts than most of the exotic strains, indicating that the commercial strains have less water conserving ability than the exotic germplasm. Those that were warmer in the 1983 study were warmer in the 1985 study.

Leaf conductances and plant height were significantly correlated with adjusted intercept values (Table 4). Conductances were positively correlated with leaf
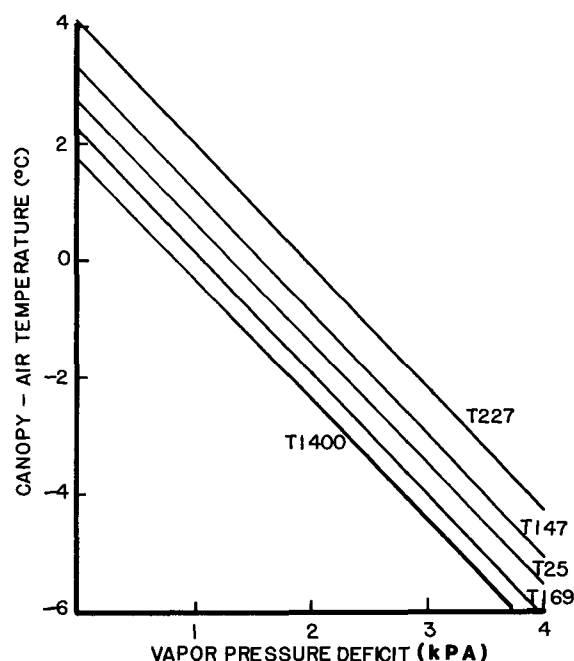
water potential, which indicates that leaf conductance differences among the strains were influenced by the leaf water status. The adjusted intercept was negatively correlated with conductance and positively correlated with plant height. These data indicate that factors causing increased canopy temperature and decreased leaf conductance have a positive effect on growth.

Canopies that were warmer (i.e., the adjusted intercept values were larger) had lower leaf conductances. This would result in reduced transpiration. In Eq. [1], r_s can be replaced with a canopy conductance term, r_c, to more closely represent the plant under field conditions. From Eq. [1], it is obvious that reduced transpiration results in a warmer canopy. For example, a 10% reduction in evapotranspiration induces a canopy with a temperature 1.5°C warmer than another. For the strains evaluated in this study, the temperature difference indicates a maximum potential difference in evapotranspiration rates of 13%. The reduced transpiration rate in the warmer should reduce the rate of water uptake from the profile and increase the period of water availability to the plant.

Twenty strains, 10 of the warmest and 10 of the coolest, were selected from the 42 strains. These strains were selected with this criteria because it was felt that to be useful in a selection program the technique would have to be related to some performance characteristic. The warmer strains in the irrigated plots had the largest biomass in the dryland plots (Fig. 3). Thus, the potential water savings due to reduced transpiration are beneficial in increasing biomass production. The

Fig. 2. Canopy-air temperatures for selected strains as a function of vapor pressure deficit with differing intercepts.
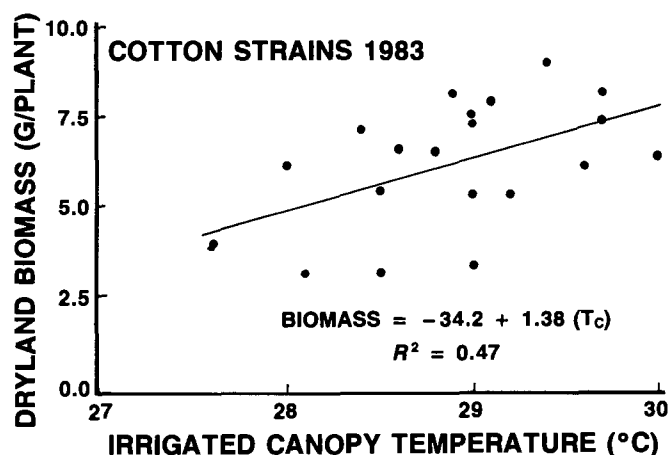

Fig. 3. Canopy temperatures from 20 selected strains in the irrigated plots compared to the dryland biomass production in 1983.

internal factors or morphological characteristic of these strains are not fully understood and are the focus for future studies.

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