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Seasonal Canopy Temperatures for Normal and Okra Leaf Cotton under Variable Irrigation in the Field

James R. Mahan *, Paxton R. Payton and Haydee E. Laza

Cropping Systems Research Laboratory, 3810 4th St Lubbock, TX 79415, USA;
paxton.payton@ars.usda.gov (P.R.P.); haydee.laza@ars.usda.gov (H.E.L.)
* Correspondence: james.mahan@ars.usda.gov; Tel.: +1-806-723-5221

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Abstract: Temperature affects a number of physiological factors in plants and is related to water use, yield and quality in many crop species. Seasonal canopy temperature, measured with infrared thermometers, is often used in conjunction with environmental factors (e.g., air temperature, humidity, solar radiation) to assess crop stress and management actions in cotton. Normal and okra leaf shapes in cotton have been associated with differences in water use and canopy temperature. The okra leaf shape in cotton is generally expected to result in lower water use and lower canopy temperatures, relative to normal leaf, under water deficits. In this study canopy temperatures were monitored in okra and normal leaf varieties for a growing season at four irrigation levels. Differences in canopy temperature (<2 °C) were measured between the two leaf shapes. As irrigation levels increased, canopy temperature differences between the leaf shapes declined. At the lowest irrigation level, when differences in sensible energy exchanges due to the okra leaf shape would be enhanced, the canopy temperature of the okra leaf was warmer than the normal leaf. This suggests that varietal differences that are not related to leaf shape may have more than compensated for leaf shape differences in the canopy temperature.

Keywords: cotton; canopy temperature; okra leaf; normal leaf; leaf shape; water deficits

1. Introduction

Temperature has a pervasive effect on the growth and development of plants and, since it is continuously variable, its influence can be difficult to understand on a mechanistic level, and even more difficult to manage in an agricultural context. Environmental factors, primarily solar radiation, air temperature, humidity, and soil water continuously affect the temperature of plants. The temperature of a plant as measured with non-contact infrared thermometers is commonly referred to as "canopy temperature". Canopy temperature is generally related to the water status of the crop and has been the object of numerous studies over many years [1,2]. In general, the shape of plant leaves is a well-established effector of leaf and canopy temperature primarily through its effects on sensible energy exchanges between the leaf and the surrounding air [3–8].

Two common types of leaf shape are present in cotton (*Gossypium hirsutum* L.), normal and okra, with a gradient of various degrees of the okra characteristic [9]. While the effects of these leaf shapes on cotton yield, quality, disease susceptibility, canopy temperature and water use have been the subject of numerous research efforts, the results have sometimes been contradictory and the value of okra-shaped leaves in production is not universally recognized [10–13]. Heitholt et al. [12] summarized a number of possibly desirable characteristics of okra-leaf type cottons. Included in their list are earlier maturity, yields similar to normal-leaf varieties, reduced boll rot, reduced leaf area index, higher single-leaf photosynthesis per unit leaf area, moderate pink bollworm resistance, and growth characteristics, such as fewer branches, fewer nodes, greater production of flower buds, and flowers, when compared with normal-leaf types.

With respect to canopy temperature, it has been proposed that the varieties with the okra leaf shape have an advantage over normal leaf varieties with respect to a number of factors, including light capture in the canopy and the leaf energy balance, that affect canopy temperature and water use [10,14]. The more open canopy associated with the okra leaf shape generally allows radiation to penetrate deeper into the canopy. This has the potential advantage of allowing higher photosynthesis rates in the leaves that are at the fruiting sites and, thus, providing more metabolites for fiber mass and enhanced quality. The okra leaf shape alters the boundary layer between the leaf and the surrounding air which has the capacity to increase leaf-to-air energy exchanges which can alter canopy temperature under certain conditions. Thus, okra leaf varieties are often predicted to be more efficient in sensible energy exchanges and, thus, possibly less susceptible to harmfully elevated canopy temperature. The ability to maintain more favorable (cooler) canopy temperatures may prove to be beneficial in terms of maintaining metabolic activity under hot and dry conditions, in contrast to normal leaf varieties that would be more adversely affected by the same conditions.

The goal of this study was relatively simple: to monitor canopy temperatures in normal and okra leaf cotton varieties in the field over the course of a growing season. Four irrigation levels were included to induce a range of canopy temperatures in each variety and to allow comparisons between varieties under differing production conditions. Our goal is to compare the patterns of canopy temperature between the two leaf shapes across a growing season under different irrigation scenarios.

Hypothesis

It is hypothesized that the okra leaf variety will experience lower canopy temperatures under water deficit conditions when sensible energy exchanges predominate and, as irrigation increases the canopy temperatures of the normal and okra leaf varieties, will become more similar.

Thus, at the extremes of the water deficits, we anticipate that the okra leaf canopy will be cooler than the normal leaf canopy under low water conditions and, at the high irrigation levels, the normal leaf will be cooler.

2. Materials and Methods

Okra leaf and normal leaf cotton (*Gossypium hirsutum* L.) varieties were grown in the field during the summer of 2014 in Lubbock, TX under four water levels: rainfed and 3 rates of irrigation. The rainfed plots received only rain and the irrigation rates were 1.5 mm/day, 3 mm/day and 6 mm/day with the 6 mm/day rate being representative of a well-irrigated commercial cotton crop for the region.

2.1. Varieties

Cotton was planted on 15 May 2014 (Day of year (DOY) 135). The normal leaf variety was Fibermax 9180B2RF (Bayer Crop Science, Lubbock, TX, USA) and the okra leaf variety was AllTex OL220 (AllTex Seed Inc., Levelland, TX, USA). Plots consisted of eight rows (1 m spacing), 20 m in length, with ~12 plants per meter. In-season management followed typical production practices of the region. Weed control was by surface cultivation.

2.2. Irrigation

Each irrigation treatment consisted of eight rows with irrigation applied by a sub-surface drip system at a depth of 30 cm under each row. Irrigation was applied once per day (at night) for all of the treatments. Irrigation treatments began on DOY 177 and were terminated on DOY 231. The crop matured by DOY 295.

2.3. Environmental (Weather) Monitoring

Environmental conditions were monitored continuously by an on-site weather station [15] that was 250 m from the experimental plots. Air temperature, dew point temperature, and solar radiation were collected as 15-min averages of five-minute measurements.

2.4. Canopy Temperature Monitoring

Canopy temperature was monitored at a 15-min interval using a Smartcrop infrared thermometry system (Smartfield Inc., Lubbock, TX, USA). One IRT (infrared thermometer) sensor was installed in each plot at the time of seedling emergence (DOY 140). The sensors were installed approximately 0.3 m above the canopy, at an angle of ~45° from vertical. The height of the sensors was adjusted weekly to maintain the 0.3 m height. The sensors have a 1:1 field of view resulting in a sensor view of approximately 0.3 m diameter. The system measured canopy temperature once per minute and reported data as 15-min averages.

2.5. Seasonal Analysis

The dataset consisted of canopy temperatures for the period from DOY 184 (3 July) to DOY 304 (31 October) covering the interval from 50 DAP to 170 DAP, referred to as "Full Season". The dataset was divided into three sections of 40-days each: 50–90 DAP (early Season), 90–130 DAP (mid-Season) and 130–170 DAP (late Season). Within each period, the canopy temperatures were filtered on the basis of radiation (>0 for day) to produce 24-h, day, and night subsets of canopy temperature.

2.6. Canopy Temperature Differences

The difference in canopy temperature between the two varieties was calculated as the difference between the normal and okra leaf canopies (normal–okra). Positive differences indicate that the normal leaf is warmer than the okra; negative differences indicate that okra is the warmer of the two.

2.7. Statistics

Two-way analysis of variance (ANOVA) was used to determine the effect of leaf type, water supply, and their interaction on canopy temperature. The differences between mean treatments were identified using the Tukey honest significant difference (HSD) test at $p > 0.05$, $p > 0.01$, and $p > 0.001$. Prior to the analysis the data was tested for the parametric assumptions. To study the relationship between each factor we used regression analysis. All the statistical tests were done using the R software program (R version 3.2.3, Foundation for Statistical Computing, Vienna, Austria).

3. Results

The data set consists of ~92,000 measurements of cotton canopy temperature collected over a 120-day period from July through September, with ~11,000 measurements per variety in each of four treatments. Thus, while the measurements are not replicated, the magnitude of the dataset allows for a detailed analysis of canopy temperatures over a production season.

3.1. Environment During Experiment

Air temperature, dewpoint temperature, rain, and radiation over the course of the study are shown in Figure 1. The weather for 2014 was typical for the location. The decline in air temperatures after DOY 250 (7 September) indicates the beginning of the season's end and such abrupt end-of-season temperature transitions are not unusual. Dew point temperatures varied diurnally and seasonally over the study period. Solar radiation over the season was typical with a gradual decline over the study period.

The pattern of rain events is shown in Figure 1. Total in-season rain of 406 mm fell in 24 events with 18 events <12.5 mm and 6 events of ≥12.5 mm. The irrigated plots received 54 irrigation events resulting in the following irrigation amounts: 0 mm @ no irrigation, 81 mm @ 1.5 mm, 162 mm @ 3 mm and 324 mm @ 6 mm. Total water on the crop (rain + irrigation) varied from 407 mm to 729 mm. The yield varied across the irrigation treatments (402 to 2832 kg/ha), indicating that water deficits were present.

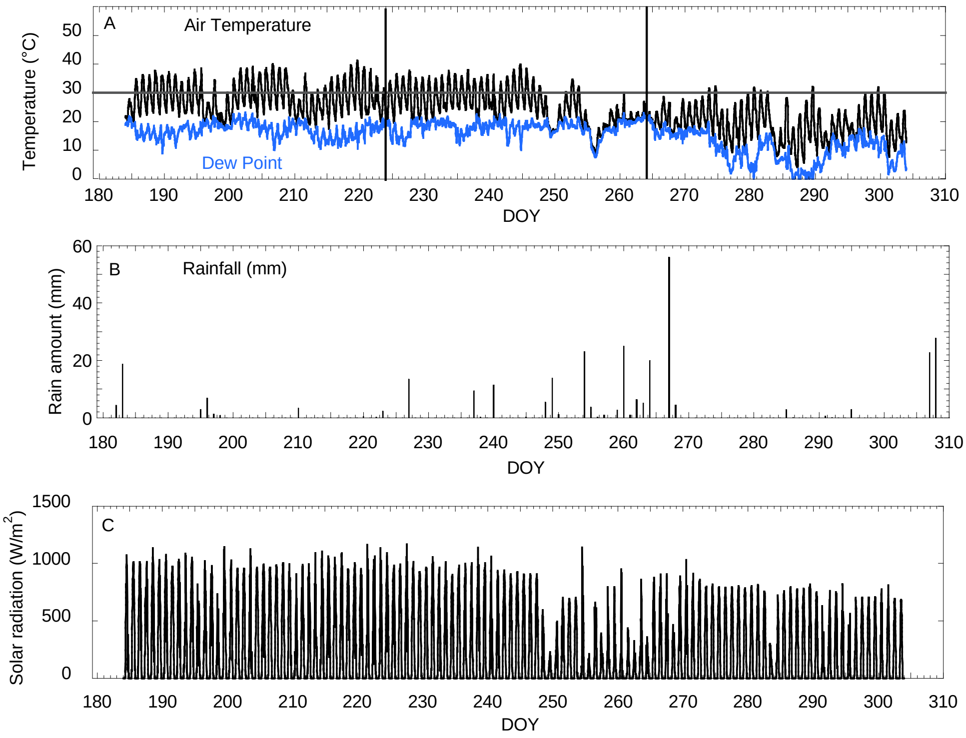

Figure 1. Air temperature and dewpoint (15 min) (**A**), rain (daily) (**B**), and solar radiation (15 min) (**C**) over the 120-day study interval collected by a weather station at the field site.

3.2. Seasonal Canopy Temperatures

It was expected that canopy temperatures of the two leaf shapes would differ under certain conditions and would be more similar under others. In an effort to accentuate differences, different water regimes were implemented and the season was divided into several periods. As the season progressed and the water demand of the crop increased, the water deficits in the rainfed, 1.5 mm, and 3.0 mm irrigation regimes increased in intensity. The effect of water on temperature differences over the season should be minimal in the 6 mm treatment. From a seasonal perspective, in addition to the 120-day period (full-season period), the experimental period was divided into three sequential 40-day periods for analysis in an effort to detect canopy-relates developmental differences in the canopy temperature patterns. To understand diurnal influences, the canopy temperature data was also divided into 24-h, day, and night periods on the basis of solar radiation.

Figure 2 shows the canopy temperatures over the 120-day measurement period beginning 50 DAP. The effect of irrigation on the canopy temperatures is clearly evident with temperatures above 28 °C more common as irrigation level declines. The horizontal line on the figure indicates 28 °C which represents the optimal temperature for cotton [16]. Around DOY 250 (7 September) the temperatures declined in response to end-of-season changes in the weather as evidenced in the air temperatures.

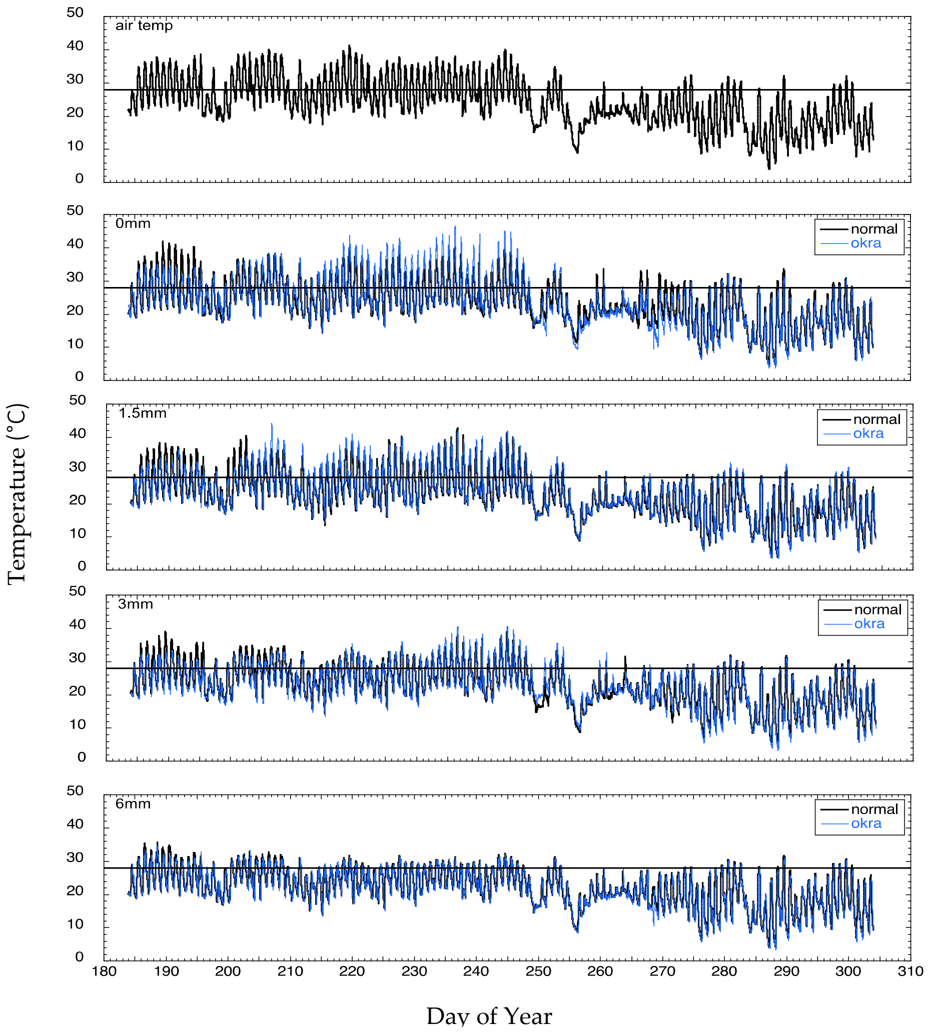

Figure 2. Pattern of air and canopy temperatures measured in the field for 120 days for okra and normal leaf varieties. The horizontal line indicates the 28 °C, the putative optimal cotton canopy temperature.

Figure 3 compares the canopy temperature of the normal and okra leaf over the 120-day Full-season period. As the irrigation level increased the canopy temperatures of the two varieties became more similar. In the 1.5 mm, 3 mm, and 6 mm irrigation treatments the y-intercepts are <0.55 °C which is near the resolution limit of the IRTs, while it is higher, at 2.3 °C, in the 0 mm condition. The R^2 value is lowest for the 0 mm (0.94) and >0.95 for the 1.5 mm, 3 mm, and 6 mm treatments. Thus, for the entire study period there are differences in canopy temperature between the varieties but they are generally small.

Table 1 shows the air and canopy temperatures over the study period. In the "full", "early", and "mid" periods of the study, there was a trend of lower average canopy temperatures as irrigation amount increased. The maximum temperature followed a similar pattern, as well. These trends were not as pronounced in the "late" period measurements, perhaps indicating that at season's end the water deficits were diminished. The trends in canopy temperature were similar for both leaf shapes. Canopy temperatures for day and night periods over several multi-day periods of the season were analyzed using a two-factor ANOVA. Over the full-season period, the canopy temperatures were significantly different ($p < 0.05$) during the night period while differences were not significant ($p > 0.05$) during the day period. Over the full-season period, the effect of irrigation was significant ($p < 0.001$) for both varieties for both the night and day periods. Over the full-season period, the interaction between variety and irrigation was significant ($p < 0.01$) for both the night and day periods. The full-season period was divided into three 40-day periods for analysis that were not analyzed in terms of night and day periods. During the early-season period the canopy temperatures were significantly different ($p < 0.01$) for varieties and irrigation. The interaction between variety and irrigation was significant ($p < 0.001$). During the mid-season period, the canopy temperatures were not significantly different ($p < 0.01$) for variety. Both the effect of irrigation and the interaction between variety and irrigation was significant ($p < 0.01$). During the late-season period, the canopy temperatures were significantly different ($p < 0.05$) for variety and irrigation with a significant ($p < 0.001$) interaction between variety and irrigation. While instances of significant differences between the varieties were detected in all of the periods, irrigation treatments, and times of day, they were generally small (<1 °C) and their relevance in an agricultural context is questionable.

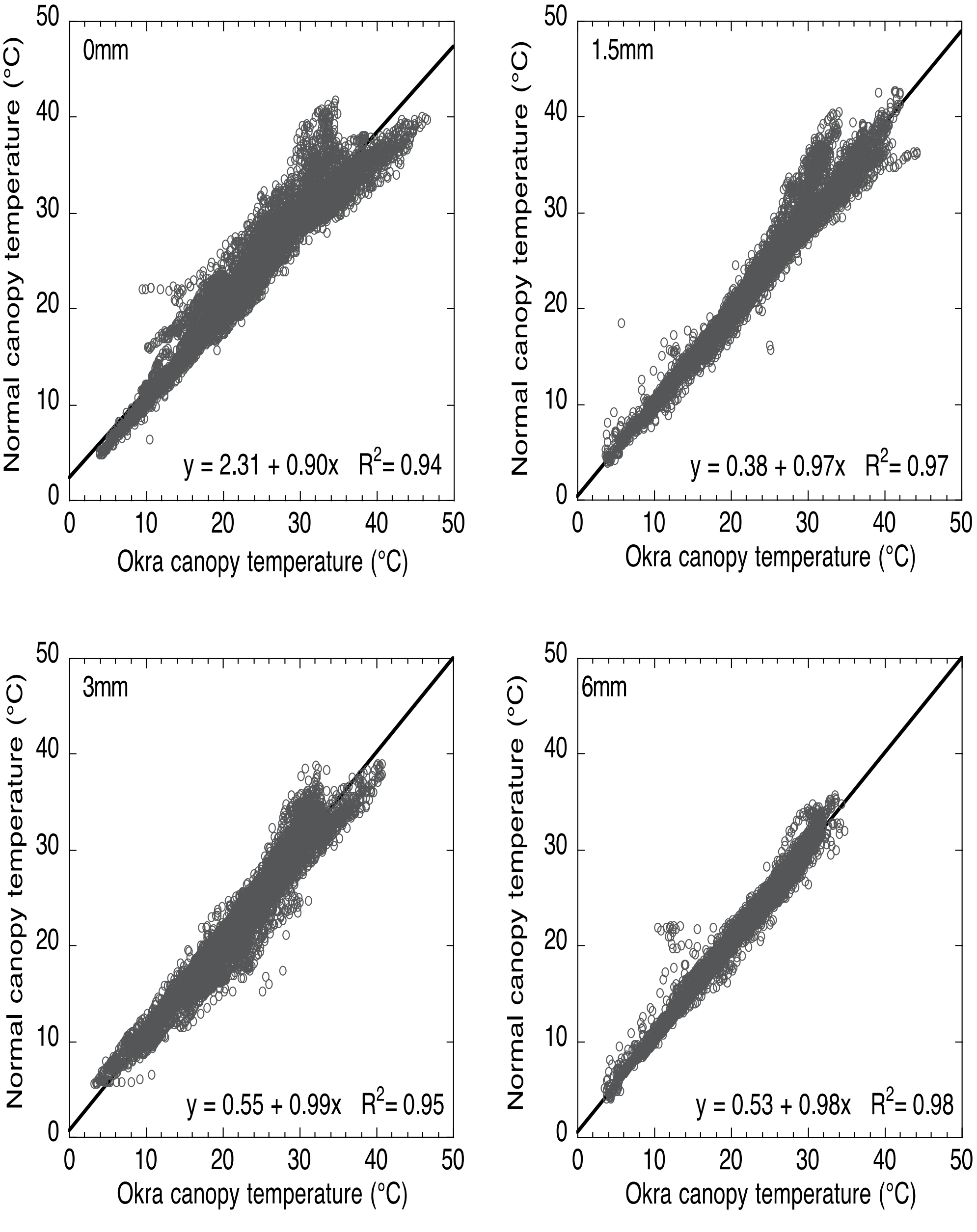

Figure 3. Comparison of canopy temperature at four irrigation treatments; 0 mm, 1.5 mm, 3 mm, and 6 mm for okra and normal leaf varieties over the 120-day study period.

Table 1. Canopy temperature statistics for okra and normal leaf varieties across seasonal periods at four irrigation treatments.

		Air Temp (°C)	**Canopy Temperature by Leaf Type (°C)**							
			Normal				**Okra**			
			Irrigation Level (mm/day)							
			0	**1.5**	**3**	**6**	**0**	**1.5**	**3**	**6**
Season	Mean	24.2	23.5	23.1	22.6	21.7	23.5	22.8	22.9	22
	Min	4	3.9	3.6	3.2	3.5	4.8	3.9	5.7	4
	Max	41.3	46.5	44.1	40.7	34.8	41.8	42.8	39	35.7
	St Dev	6.9	7.2	6.9	6.2	5.7	6.8	6.8	6.3	5.7
	Variance	47.8	52.5	47.9	38.2	32.3	45.7	46.7	39.2	32.2
Early	Mean	28.1	27	26.4	25.2	24.7	27	26.4	26.2	25.1
	Min	17.4	14.5	14.1	13.5	13.4	14.3	13.5	14.3	13.8
	Max	41.3	43.7	44.1	35.4	34.8	41.8	40.5	38.9	35.7
	St Dev	5.3	5.2	5.1	4.1	3.8	5.5	5.3	4.6	4.1
	Variance	27.6	26.5	26.4	16.7	14.6	30	27.6	21	16.5
Mid	Mean	25.5	25.4	24.8	24.5	22.8	24.8	24.3	24.2	22.9
	Min	8.9	9.4	9.1	9.6	8.4	11.4	8.9	8.7	8.8
	Max	39.9	46.5	42	40.7	32	40	42.8	39	32.3
	St Dev	6.2	7.1	6.5	5.6	4.6	5.6	6.2	5.6	4.6
	Variance	37.9	50.4	42.1	31.1	20.9	31.4	38.9	31.2	21
Late	Mean	18.9	18	18	18.1	17.6	18.7	17.7	18.3	18.1
	Min	4	3.9	3.6	3.2	3.5	4.8	3.9	5.7	4
	Max	32.2	32.1	32.5	31.4	31	33.6	31.1	31.8	31.6
	St Dev	5.7	5.9	6	6	5.8	6.2	5.7	5.7	5.8
	Variance	32.7	34.8	36.1	36.2	33.9	38.8	33	32.2	33.2

Min, minimum; Max, maximum; St Dev, standard deviation; Temp, temperature.

The normal leaf and okra leaf canopy temperature pairs at each point in time were compared using a paired *t*-test. The results of these comparisons are shown in Table 2 with significant differences ($p < 0.001$), denoted with ***. With the exception of four instances in the 0 mm treatment and one instance in the 1.5 mm, the canopy temperatures were significantly different between the okra and normal leaf types. The differences are generally quite small and close to the resolution of the IRTs and, thus, their importance could be questioned from an agronomic perspective.

Figure 4 shows the mean canopy temperature for the normal and okra leaf cottons across the water levels when sorted into 24-h, day, and night groupings. The effect of irrigation on the canopy temperature is apparent and most pronounced in the daytime canopy temperatures. The mean canopy temperatures, with the exception of the night period are highly correlated ($R^2 > 0.9$) with irrigation treatment. The canopy temperatures at the 0 mm irrigation level are most similar. Canopy temperatures in the okra variety were higher than the normal variety at the 1.5 mm irrigation, and the okra was lower than the normal variety at the 3 mm and 6 mm levels. The trend is consistent across the 24 h, day, and night intervals.

Table 2. Results of paired *t*-tests of canopy temperatures for okra and normal leaf varieties across seasonal periods at four irrigation treatments.

	Full Season			**Early Season**			**Mid Season**			**Late Season**		
Irr level	**24 h**	**Day**	**Night**	**24 h**	**Day**	**Night**	**24 h**	**Day**	**Night**	**24 h**	**Day**	**Night**
0 mm	−0.02 ns	0.01 ns	−0.06 ***	−0.02 ns	−0.21 ***	0.27 ***	0.62 ***	1.12 ***	−0.01 ns	−0.67 ***	−0.97	−0.37 ***
1.5 mm	0.26 ***	0.25 ***	0.28 ***	0.01 ns	−0.21 ***	0.35 ***	0.48 ***	0.61 ***	0.32 ***	0.30 ***	0.42	0.19 ***
3 mm	−0.03 ***	−0.13 ***	−0.52 ***	−1.03 ***	−1.20 ***	−0.76 ***	0.37 ***	0.71 ***	−0.08 ns	−0.24 ***	0.22	−0.71 ***
6 mm	−0.03 ***	−0.33 ***	−0.28 ***	−0.31 ***	−0.36 ***	−0.23 ***	−0.14 ***	−0.12 ***	−0.16 ***	−0.49 ***	−0.54	−0.43 ***

“ns”, not significant, ***, significant at $p < 0.001$. Number indicates the difference between normal and okra leaf varieties.

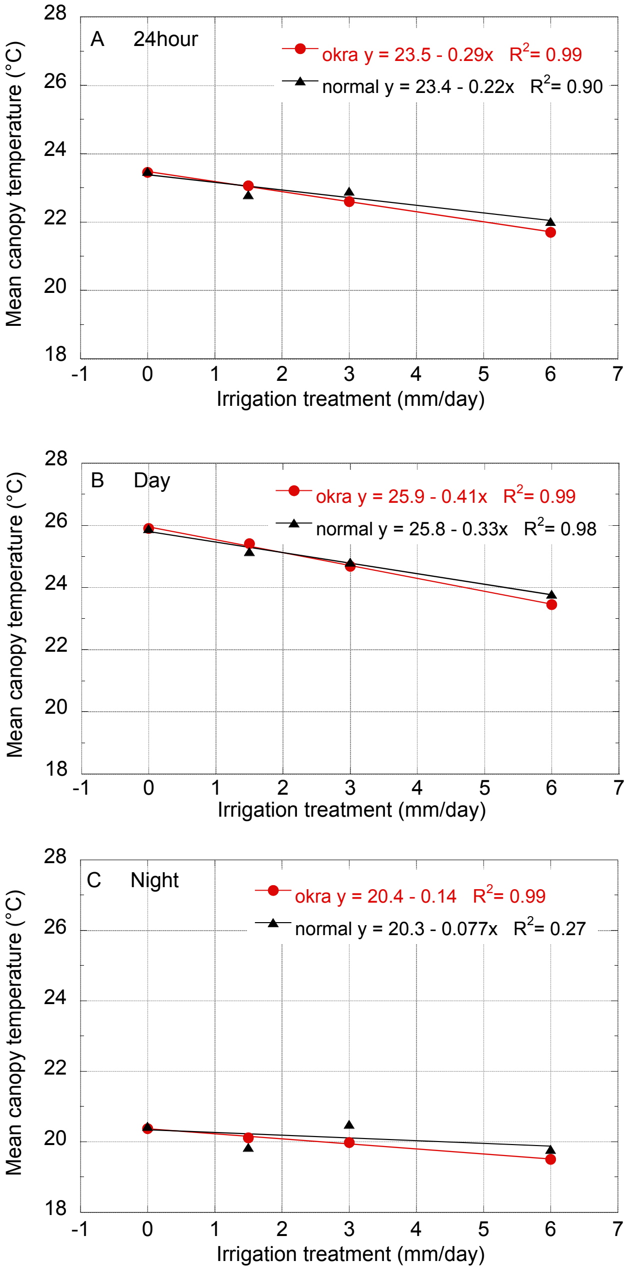

Figure 4. Comparison of mean canopy temperature of the okra and normal leaf varieties over the 120-day study period at four irrigation levels. Three periods of the day are shown; (**A**) 24 h, (**B**) day, and (**C**) night.

Figure 5 shows the seasonal mean of differences between the normal and okra for the 120-day measurement period as a function of irrigation treatment and time of day. Positive values indicate normal leaves are warmer and negative values indicate okra leaves are warmer. At the 0 mm irrigation level, the canopy temperatures of the two leaf types are very similar while in the 1.5 mm irrigation treatment the okra leaves were warmer than the normal leaves. At the 3 mm and 6 mm irrigation levels the normal leaves are warmer than the okra leaves. The pattern is consistent between the night and day periods.

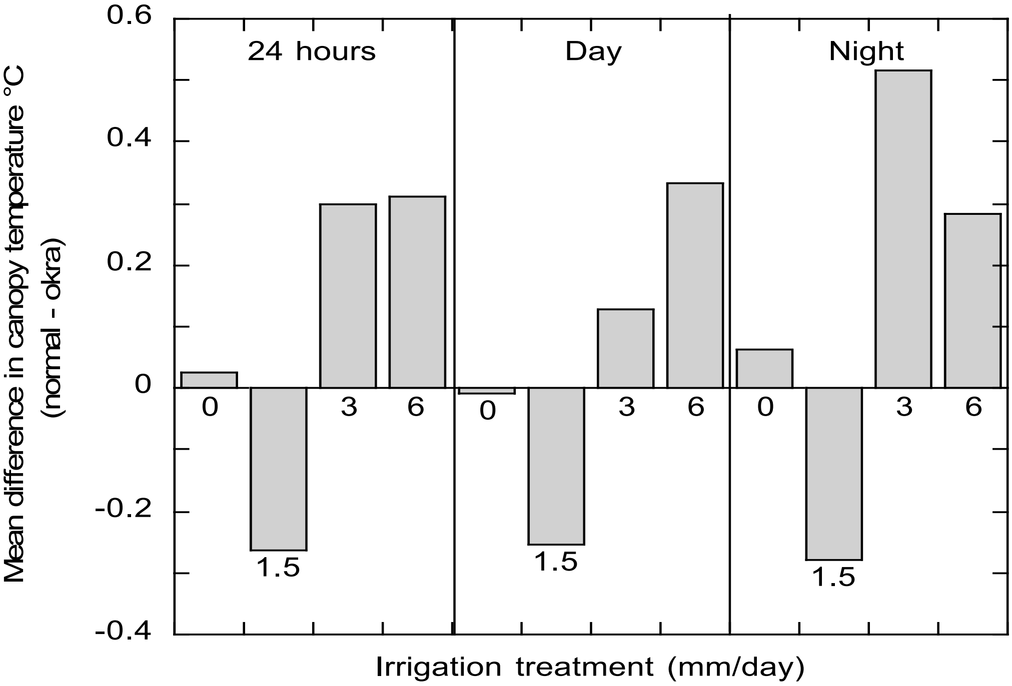

Figure 5. Mean difference in canopy temperature for okra and normal leaf varieties (normal–okra) as a function of irrigation treatment over the 120-day study period. Three periods of the day are shown; 24 h, day, and night.

The analysis of canopy temperatures across several multi-day periods of the season underscores the well-established effect of irrigation on canopy temperature [1,2]. While differences in canopy temperature between the two varieties are evident and often significant, they are generally small in magnitude. Viewing the canopy temperatures on a daily basis as a time series may provide additional insight into differences between the varieties.

Figure 6 shows the difference in canopy temperature (normal leaf–okra leaf) over the 120-day Full-season period. The effect of irrigation on the differences is evident with the 6 mm irrigation treatment consistently showing the smallest differences, and the rainfed treatment showing the largest differences between the two leaf shapes. The two intermediate irrigation regimes showed temperature differences between the irrigation extremes. The patterns of differences over the season were generally consistent in the 6 mm irrigation while the three other irrigation treatments all showed a seasonal pattern with the normal leaf warmer (difference values positive) early in the season. The rainfed treatment showed the largest differences between the two leaf types with the normal leaf warmer in the early period, cooler in the middle period and warmer later in the season.

The distribution of the differences over the full-season period helps to understand how the differences in seasonal means between the two varieties across water levels are relatively small (<0.5 °C) while, for any point in time, differences >5 °C are not uncommon. Irrigation consistently reduces the differences between the varieties as evidenced in the pattern of variance in Table 1.

Since the multi-day means reduce the variation apparent in seasonal differences, it might be instructive to look at the time series of canopy temperature data. While the effect of irrigation on canopy temperature is apparent, not all days of the season look the same (see Figure 6). Figure 7 shows the pattern of air and canopy temperature for two 24-h periods (DOY 191 and DOY 231) of the study period that were chosen to demonstrate some characteristics of canopy temperature in the two varieties at two water levels. Figure 7A shows the patterns of air and canopy temperature for DOY 191. At 6 a.m. the temperatures of the varieties are quite similar, the water effect is minimal and canopy temperatures are below air temperature. As radiation increases over time, both air and canopy temperatures increase. The canopy temperatures of both varieties in the 6 mm irrigation treatment are similar throughout the period. In the 0 mm treatment, the temperatures of the varieties begin to diverge by 8 a.m., with the normal leaf variety becoming warmer than the okra leaf and remaining higher until approximately 8 p.m. The temperature of the normal leaf variety remains lower than the okra over the 8 a.m. to 8 p.m. period. After 8 p.m. the temperatures of the varieties remain similar and below air temperature for the remainder of the 24-h period. On this day canopy temperatures for both varieties in the 6 mm treatment and the normal leaf in the 0 mm treatment remained below the air temperature over the period. Under such conditions, transpirational cooling largely influences the canopy temperatures, and leaf shape-related differences would be minimal. During DOY 191, any effect of leaf shape on canopy temperature would probably be relevant only for the normal leaf in the 0 mm treatment. Figure 7B shows air and canopy temperatures for DOY 231. At 6 a.m. the temperatures of the varieties are quite similar and the water effect is minimal. Canopy temperatures are below the air temperatures. As radiation increases over time, both air and canopy temperatures increase. In the 6 mm irrigation treatment, the temperatures of the varieties increase and remain very similar. In the 0 mm treatment, the temperatures of the varieties begin to diverge by 8 a.m., with the okra leaf variety becoming warmer than the normal leaf and remaining higher until approximately 8 p.m. The temperature of the normal leaf variety remains lower than the okra over the 8 a.m. to 8 p.m. period. After 8 p.m. the temperatures of the varieties remain similar and below the air temperature for the remainder of the 24-h period. On this day canopy temperatures for both varieties in the 6 mm treatment and the normal leaf in the 0 mm treatment remained below the air temperature over the period. Under such conditions, transpirational cooling largely influences canopy temperatures and leaf shape-related differences would be minimal. During DOY 231, any effect of leaf shape on canopy temperature would probably be relevant only for the okra leaf in the 0 mm treatment.

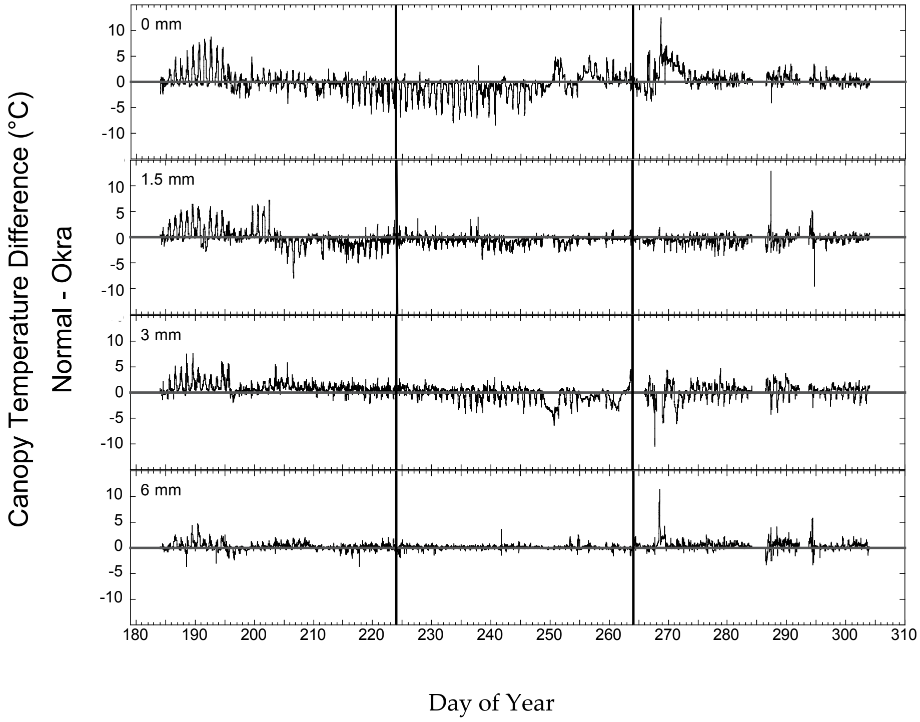

Figure 6. Difference in canopy temperature (15 min interval) for okra and normal leaf varieties (normal–okra) as a function of time (DOY) over 120-day study period for four irrigation treatments. Positive values indicate that normal leaves are warmer than okra leaves and negative values indicate okra leaves are warmer than normal leaves.

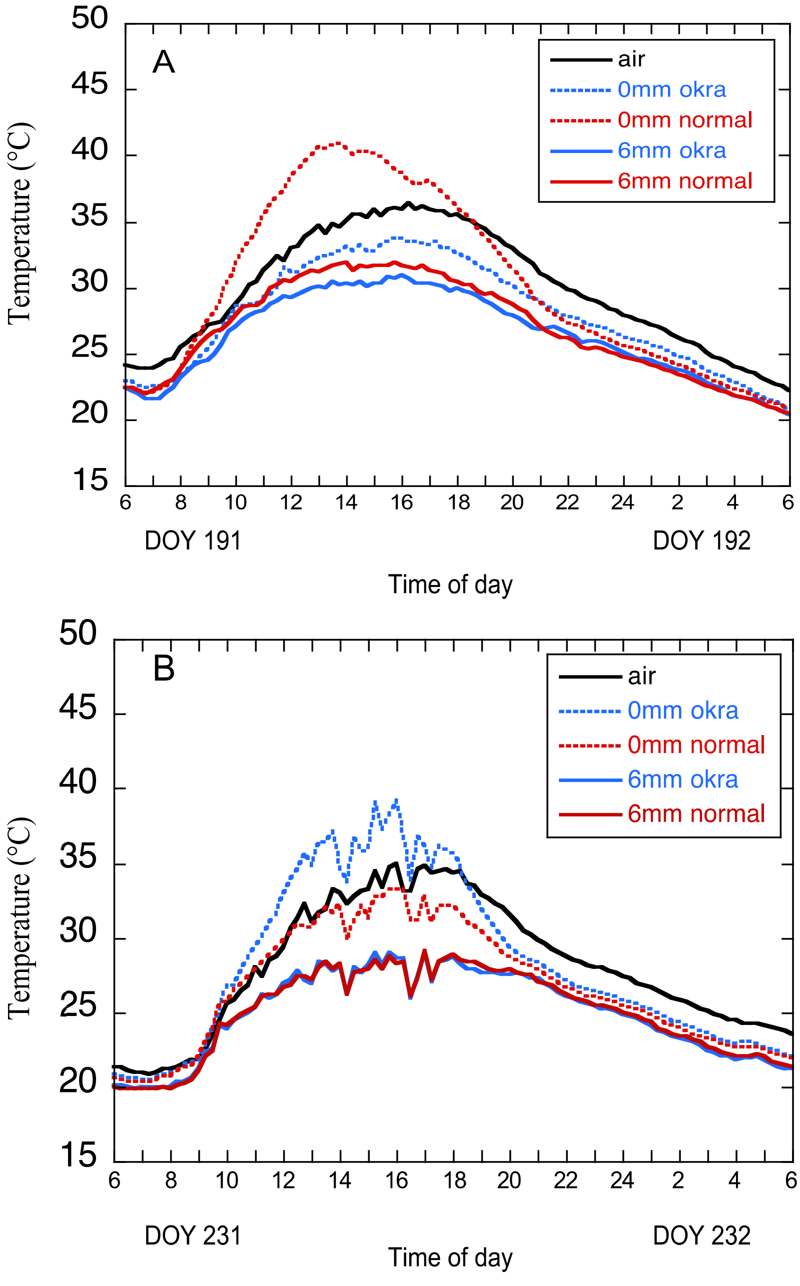

Figure 7. Diurnal pattern of air and canopy temperatures (15 min interval) of okra and normal leaf varieties as a function of time and day for a 24 h period (6 am to 6 am) in four irrigation treatments for DOY 191 (**A**) and DOY 231 (**B**).

The analysis of two days of temperature variation demonstrates that the canopy temperature differences between the two varieties change over time. In each of the single days subjected to analysis, the 6 mm irrigation level produced similar canopy temperatures patterns. At the 0 mm irrigation level, the temperatures of the varieties differed over the course of the day with the normal variety warmer than the okra variety on DOY 191, with the reverse being true on DOY 231.

Since the difference in canopy temperature between the two leaf shapes is variable over the season, the distribution of those differences over time might be instructive. Figure 8 shows the distribution of the difference between normal and okra leaf canopy temperatures over the study period. The distributions for the 3 mm and 6 mm treatments are symmetrical with a peak at 0 °C though the 3 mm distribution is slightly broader. The peak in the 1.5 mm distribution is at −1 °C indicating a shift toward the okra leaf being warmer. The distribution of the 0 mm is broader and generally shifted toward okra leaf being warmer. These data indicate that at high irrigation the differences between the okra and normal leaf varieties small and random while, at the lower irrigation levels, the differences are larger and skewed toward the okra leaf being slightly warmer than the normal leaf. These results suggest that the okra leaf canopy temperatures are not lower than the normal leaf temperatures based on the possibility of enhanced sensible energy exchanges associated with the okra leaf shape, particularly in the lower irrigation regimes.

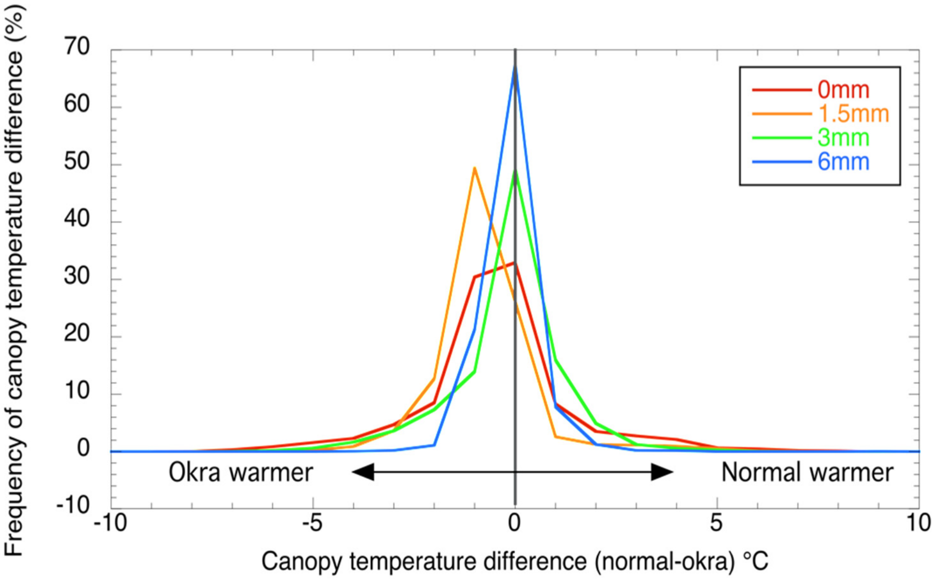

Figure 8. Frequency distribution (%) of the difference in canopy temperature for okra and normal leaf varieties (normal–okra) for four irrigation treatments.

The distribution of canopy temperature differences shown in Figure 8 suggests that canopy temperatures in the okra leaf are not cooler than those of the normal leaf under water deficits. To further investigate this finding, the canopy temperature data has been analyzed from the perspective of conditions that enhance or restrict sensible energy exchanges between the canopy and the environment. Leaf shape differences in sensible energy exchanges would be enhanced when canopy temperature is greater than air temperature, generally under low irrigation. The Figure 9 [1,2] compares the canopy temperatures of the okra leaf to the normal leaf as a function of the difference between the okra leaf and air temperatures. On the x-axis, as the difference between okra leaf canopy and air temperature increases, the ability of the canopy to cool by sensible energy exchanges increases (left to right). On the y-axis, positive values of the difference between the normal and okra leaf canopy temperatures indicate that the okra leaf is cooler than the normal leaf. Temperatures in the lower right quadrant indicate that the normal leaf is cooler than the okra. Enhanced energy exchange caused by the okra leaf shape would be indicated by canopy temperatures in the upper right quadrant of the figure. Under well-irrigated conditions (6 mm), it would be expected that latent energy exchanges would predominate and canopy temperatures would be similar between leaf shapes and largely independent of air temperatures. The data agree. Under water deficit conditions (0 mm), when latent energy exchanges are limited, enhanced sensible exchanges by the okra leaf would be indicated by temperature values in the upper right quadrant. The predominance of cooler normal leaf values in the lower right quadrant suggest better cooling of the normal compared to the okra under conditions where sensible energy exchanges should predominate. This evidence suggests that canopy temperature differences between the varieties are not a result of enhanced sensible energy exchanges in the okra leaf variety.

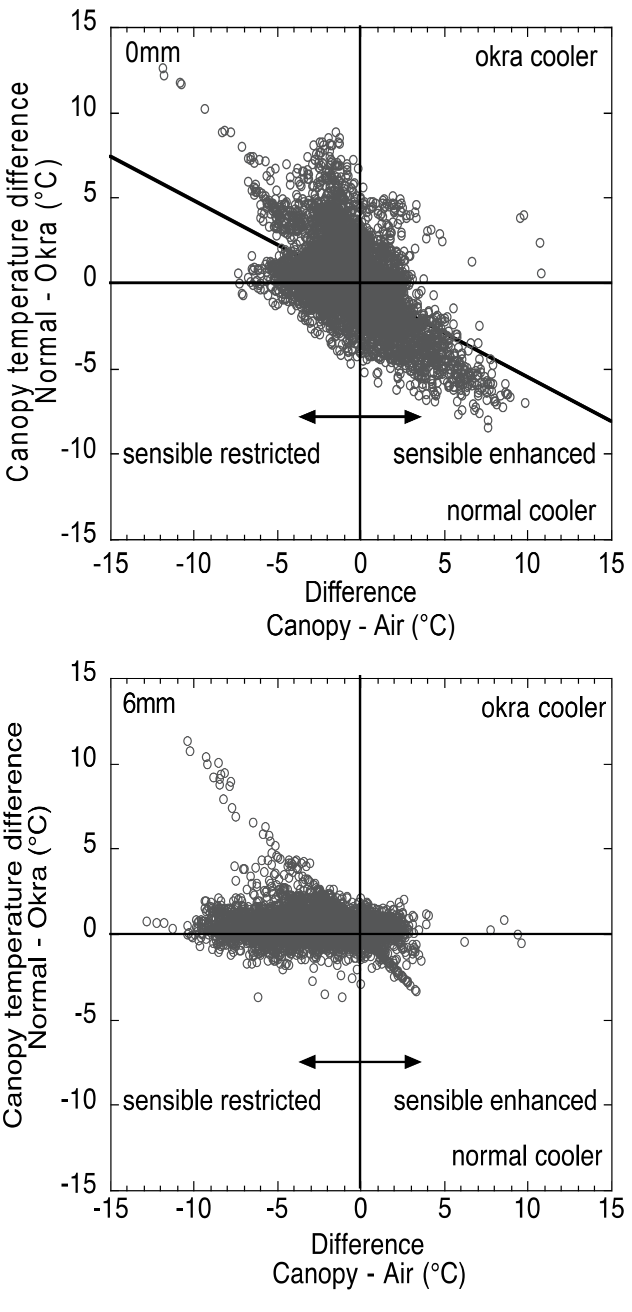

Figure 9. Difference in canopy temperature for okra and normal leaf varieties (normal–okra) as a function of the difference between the canopy temperature of the okra leaf variety and air temperature (okra leaf–air) for the 0 mm and 6 mm irrigation treatments. Positive values on the x-axis indicate increasing capacity for sensible cooling of okra leaf variety. Positive values on the y-axis indicate okra leaf variety cooler than normal leaf variety.

4. Discussion

The goal of this study was to compare canopy temperatures over the course of a growing season for two cotton varieties with different leaf shapes. A search of existing literature did not result in studies involving measured canopy temperatures in okra and normal leaf cotton. Since the plants in this study were grown in the same location, at the same time, in the same soil moisture, and developed within identical environments, the effects of environmental variability should be reduced and varietal differences enhanced. When considered over multi-day periods, canopy temperature differences between the varieties were detected, though they were generally small <1 °C. However, for any given point in time, differences between the varieties varied from 0 to 8 °C (Figure 6). Possible sources of variation including (1) canopy-related differences in soil background contribution to scene temperature; (2) differences in water use and water status; and (3) leaf shape-related differences in the leaf energy balance will be discussed in the following paragraphs.

4.1. Canopy-Related Differences in Soil Background Contribution to Scene Temperature

Perhaps the most significant challenge to the interpretation of plant canopy temperature in the field is the inability to exclude, or quantitatively account for, background soil temperature in the canopy scene. The soil background component of a canopy temperature measurement is generally related to the density of the canopy, with such factors as leaf area index, leaf shape, and leaf orientation all affecting the contribution of soil background to the scene.

Leaf shape-related differences in canopy temperature can be due to the generally more open canopy in the okra variety that results in the inclusion of more soil background (compared to the to normal leaf canopy). The okra leaf variety, given a similar number of leaves as a normal variety, would be expected to have a lower leaf area index and more soil background at a given point in development. This would result in higher canopy temperatures in the okra leaf until its leaf area index reached the value (~3) needed to fill the IRT field of view. This effect would be most pronounced early in the season before the canopy is fully developed and at the lower irrigation levels where water deficits result in smaller canopies.

Leaf orientation can affect canopy temperature measurements in a similar manner by increasing the contribution of soil background. Leaf wilting can increase the contribution of background soil to the canopy temperature in a manner that would generally lead to increased measured canopy temperature under water deficit conditions. In an effort to reduce background soil effects canopy temperature during the first 50 days of development was excluded from the analysis. By 50 days after planting leaf area indices of both varieties were >3, and though background soil was not fully excluded, the contribution to the canopy scene should be greatly reduced.

4.2. Varietal Differences in Water Use and Water Status

While leaf shape was the focus of the study, it is possible that the two varieties could also differ in terms of rooting patterns and, thus, might differ in their ability to access and extract soil water. Differential water extraction could result in differences in canopy temperature that are not associated with leaf shape. While no effort was made to document differences in water extraction between the varieties, it would be expected that such differences would be most apparent under water-limited conditions and less apparent at full irrigation. In the event that the okra leaf variety was more efficient at extracting soil moisture its canopy temperature would be expected to be lower than that of the normal variety under water-limiting conditions. The results show that under low water conditions the canopy of the okra leaf variety was warmer than the normal variety and perhaps indicate that even if the okra leaf had greater water extraction potential, it was not sufficient to result in canopy temperatures below the normal leaf variety. It is possible that the normal leaf variety was more effective in extracting soil moisture than the okra leaf since such behavior would result in lower canopy temperatures in the normal leaf variety under the water-limited conditions. Regardless, under low-water conditions the canopy of the okra leaf was generally warmer than that of the normal leaf.

4.3. Leaf Shape-Related Differences in the Leaf Energy Balance

Leaf shape can affect the ability of the leaf to exchange energy with the surrounding air [3–8]. Okra leaf shape in cotton is generally expected to enhance sensible energy exchanges relative to a normal leaf with the result of lower canopy temperatures in okra under some environmental conditions. This okra leaf-related reduction in canopy temperature would be expected to be most pronounced under water deficits and when the canopy temperature is greater than the air temperature. Under the lower irrigation regimes in this study, when the canopy temperature was greater than that of the air, the okra leaf canopies were found to be warmer than the normal leaf canopies. This suggests that, with respect to the enhanced energy exchange associated with leaf shape, the okra leaf shape did not result in enhanced leaf cooling under water deficit conditions.

In summary, (1) our prediction that canopy temperatures of the two varieties would be most similar under the highest irrigation treatment was correct. Irrigation treatment had a greater effect on canopy temperature under all irrigation regimes than the leaf shape of the varieties; (2) our prediction that the okra leaf variety would be cooler than the normal leaf under the lowest irrigation treatment was not correct; the normal leaf was cooler; (3) our prediction that the temperature differences would be greater under day conditions than night was correct; (4) our prediction that the ability to access and use water might be different between the varieties, while not addressed in the study, may be correct.

5. Conclusions

The hypothesis of the paper was that when transpirational leaf cooling was limited, the okra leaf shape would have greater sensible energy dissipation than the normal leaf. This would result in the canopy of the okra leaf being cooler than that of the normal leaf variety, primarily under water-limited conditions. In general, the canopy temperatures of both varieties were affected by irrigation level and, within an irrigation treatment, the canopies of the two varieties were generally similar. The canopy temperature differences in the study were generally small and probably not physiologically important.

With respect to canopy temperature differences associated with leaf shape, we found that the okra leaf was warmer than the normal leaf when the canopy and air temperature difference was conducive to sensible energy exchanges. This result did not fit our prediction based on leaf shape. It is possible that the normal leaf variety, even under rainfed conditions, was more effective at accessing soil moisture and its lower canopy temperatures under stress were an indication of its ability to maintain higher transpiration than the okra leaf variety under similar conditions. Thus, it is possible that there are varietal differences in the ability to access soil moisture that may have masked possible leaf shape-related differences. We chose to use commercial cotton varieties in this study based on discussions with producers who believed that the okra leaf shape would reduce heat stress under water deficits and the results suggest this is not the case. Varietal differences that were not related to leaf shape could not be resolved in this study. A study of canopy temperature differences in isolines that differ in leaf shape might provide additional insight.

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