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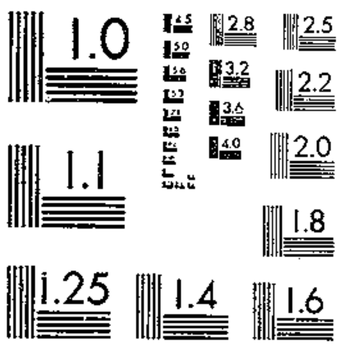

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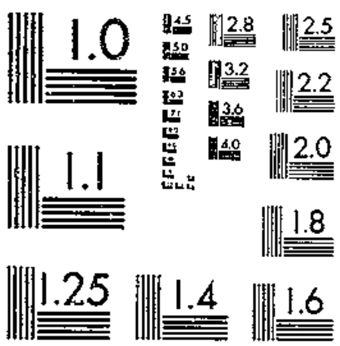

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LEAF TEMPERATURES OF COTTON AND THEIR RELATION TO TRANSPIRATION, VARIETAL DIFFERENCES, AND YIELDS

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INTRODUCTION

Exposures to very high temperature, intense light, and low humidity are common to many of the agricultural sections of the southwestern United States. Successful agriculture under such conditions involves considerations of plant fitness and adaptability which may be of only limited concern in more temperate climates.

The native plants which are found in any region differ among themselves in many respects, and though certain similarities exist, the balance between favorable and unfavorable characters, physiological or morphological, determines their success as competitors in the society of plants. The favorableness of a character is relative to environmental conditions which are somewhat different each year, and the area occupied by a species, though in frequent change, becomes the result of its comparative adaptability, not only during a single year, but over a period of years. Among agricultural plants the nature of the relationships is somewhat different, since economic considerations are involved, but competition nevertheless exists, and in this competition plant fitness is of prime importance. If an introduced variety gains favor it becomes a competitor in the community and may replace older varieties by averaging a trifle better over a period of years, during which time the area it occupies fluctuates, being increased after successful crops and diminished after

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partial failures. If the characteristics which fit or disqualify a plant for an environment are known, then it may be possible to shorten considerably the trial and error period by focusing attention not on yields alone but upon the conditions which prevailed during the years which were favorable or unfavorable and upon the probability of the future occurrence of such years.

It is well established that the rate of photosynthesis, which largely determines growth, is influenced by leaf temperature. In a region characterized by excessive temperatures, therefore, it seems logical that the temperatures of the leaves of crop plants should furnish a measure of a plant's relative ability to adjust itself to such an environment.

Although the rate of photosynthesis increases with temperature up to a certain point, it declines after the optimum is reached and becomes negligible at higher temperatures. Over a considerable range of temperatures below the optimum the rate of photosynthesis decreases as the period of exposure is lengthened. The wilting of leaves, independent of other factors, also results in reduced rates of photosynthesis. The cotton plant is particularly subject to wilting, and often to a very marked degree in the Southwestern States. By observation, as well as by measurements reported in the literature, wilting is known to be accompanied by increased leaf temperatures, and the subject naturally becomes pertinent to any leaf-temperature study.

As a part of the present investigation, conducted at the United States Field Station, Sacaton, Ariz., comparisons have been made between the leaf temperatures of the two most important cotton varieties of the Southwest, Pima Egyptian and Acala upland. These comparisons include hourly leaf-temperature measurements accompanied by measurements of the comparative hourly transpiration rates. Differences in the leaf temperatures of turgid and wilted Acala cotton leaves have been correlated with differences in the transpiration rates. The leaf temperatures of Acala cotton were measured on plants grown in a saline soil, on plants under a muslin shade, and on plants with whitewashed leaves. The method used in the measurement of leaf temperatures is described at some length, and a short section of this bulletin deals with the relation of leaf temperatures to yields.

The upland cotton plant in the Southwest may be relatively unproductive even though it makes a considerable or even a rank vegetative growth, the unsatisfactory yields frequently obtained being attributed to an excessive shedding of floral buds and young bolls. Although the present series of leaf-temperature measurements were undertaken as part of an investigation of factors associated with excessive shedding, the leaf-temperature data will be made the primary consideration in this bulletin since it is hoped that their tabulation and analysis may contribute to an understanding of the factors which influence the temperatures of leaves in general.

In view of Clum's (*8*)[2] historical sketch of earlier work on plant and leaf temperatures and the review of the literature by Ehlers (*15*), the results of previous investigations will be referred to only as they become pertinent in the discussions of the experiments.

[2] Italic numbers in parentheses refer to "Literature cited," p. 27.

METHODS AND APPARATUS

The leaf-temperature measurements were made by the thermoelectric method. For these measurements a wall galvanometer, permanently mounted on a large screened porch overlooking the experimental plants some 75 feet distant, was connected by flexible lighting cord to the thermocouples, which were conveniently inclosed, except for the junctions, in a piece of semiflexible composition tubing secured to a wooden handle. The measurements were made in terms of the departures of leaf temperatures from the temperature of the air surrounding an exposed junction, this junction being protected from the direct rays of the sun by two slightly separated slips of white paper. In taking leaf temperatures the leaf was folded upward with a pair of cork-tipped crucible tongs in such a manner that two portions of the upper leaf surface were brought firmly together over the second junction of the thermocouple. (Figs. 1 and 2.) The experimental plants were a part of a water-requirement series grown out of doors and freely exposed to the weather. A more detailed description of the experimental methods and apparatus follows.

FIG. 1.—Measuring leaf temperatures of cotton. (Photograph by H. F. Loomis)

MEASUREMENT OF LEAF TEMPERATURES

The wall galvanometer, provided with a telescope and scale, was formerly listed by Leeds & Northrup as No. 2200, type H. When purchased it had a coil resistance of 462 ohms, a sensitivity of the order of 2 microvolts per millimeter on the scale, and a period of 10 seconds. At the time of the present use the sensitivity of the galvanometer was such that with the double couple (used after August 3) of copper and constantan wire a deflection of 1 mm. on he scale indicated a difference in temperature at the junctions of the order of 0.125° C. The resistance of the extension cords and of the thermocouples was 34 ohms.

The thermocouples were of No. 36 copper and constantan wire with soldered junctions. The thermocouple wires were inclosed in a piece of semiflexible tubing which was bent into the form of a V and attached to a wooden handle. The junctions protruded about 1 inch from the ends of the tubing. The lead wires entered the wooden handle at the crotch, where they were connected with the extension cords.

The galvanometer and thermocouples were standardized by immersing the respective junctions in a series of water baths of different temperatures. Variations in the value of the factor and minor departures of the true zero from the scale zero resulted from changes in temperature and unequal heating of the galvanometer and the lead wires. These errors, though small, were minimized by frequent standardizations and by systematic comparisons of the true and the scale zeros. The zero was set in the early measurements by immersing the two junctions in a water bath. This method was abandoned, however, because of the difficulty of removing all of the moisture from the junctions. In the later work the scale zero was brought under the cross hairs, while the air junction was protected from the sun by its paper umbrella and the leaf junction by the shadow of the shallow tank.

FIG. 2.—Thermocouple mounting and the method of clasping a leaf preparatory to a leaf-temperature reading. The air junction is protected from direct sunlight by the paper umbrella. (Photograph by H. F. Loomis)

In making measurements the leaf junction was clasped between the leaf surfaces by one of the observers. The second observer seated at the galvanometer called back and recorded the reading when the galvanometer came to rest. The method permitted fairly rapid work. From 10 to 20 minutes were required to select and take the temperatures of a series of 48 leaves.

All leaf-temperature readings are expressed in degrees centigrade. The probable errors of the means have been calculated by the usual formula, but where the mean was based on 20 or fewer determinations Pearson's corrections for small numbers have been applied.

EXPERIMENTAL PLANTS AND SEED

The plants used for the leaf-temperature measurements were a part of the water-requirement series, grown in large galvanized-iron cans with a soil capacity of approximately 120 kilograms. The cultural methods and equipment were essentially those employed by

Briggs and Shantz (*3, 7*). At the beginning of the season the cans were filled with soil containing the moisture-equivalent percentage of moisture and weighed. The cans were weighed twice each week during the summer. On the basis of the average daily transpiration rates indicated by these weights, water was added, usually daily, to maintain the soil as nearly as possible at its original moisture content. The paper covers shown in the illustrations served to prevent overheating of the cans and soil by direct solar radiation. Cheesecloth was stretched along the south side of the cans in such a position that it did not shade the plants but protected them from high winds and shielded the cans from the direct rays of the sun during the middle of the day. All plants used for leaf-temperature measurements were from seeds planted March 31.

The seed was as follows: Pima, progeny 3–3–5–3, bulk of 1923 produced from continuous selections since 1919, Office of Alkali and Drought Resistant Crops. Acala, United States Experiment Date Garden, Indio, Calif., 1925, bulk increased from single plant P–12–19–1–3–9–1–4 in 1923. Okra-leaf Acala, bulk increase grown at Shafter, Calif., from select stock.

MEASUREMENT OF WILTING, WATER REQUIREMENT, TRANSPIRATION, AND CLIMATIC FACTORS

Wilting was graded on an arbitrary scale of 1 to 10. A grade of 1 was assigned before wilting was visible but when reduced transpiration was indicated by an increased leaf temperature sensible to the touch. A grade of 10 indicated the most severe wilting from which it was thought the plants could recover.

The term "water requirement" when employed in this bulletin indicates the ratio of the weight of water absorbed from the soil by the plant during its growth to the weight of the dry matter produced, exclusive of roots.

The hourly transpiration measurements were determined by weighing. Four large automatic self-recording platform scales were used in these measurements. These scales have been described by Briggs and Shantz (*5*).

In measuring evaporation, a shallow copper tank adapted from Briggs and Shantz (*7*) was used. The tank was 1 meter in diameter and 2.5 centimeters deep. This was mounted on a platform scale with agate bearings and having a capacity of 200 kilograms. The tank was screwed to a heavy flat wooden base which was supported on leveling legs about 3 feet above the scale platform. The inside of the tank was blackened with a mixture of lampblack and "bronzing liquid." The depth of the water in the tank was maintained at approximately 1 centimeter by means of a Mariotte apparatus supported from the scale platform and located on the north side of the tank so that its shadow did not fall on the tank.

The wind velocity was measured by an anemometer of the Weather Bureau pattern.

The air temperature was determined by mercurial thermometers exposed out of doors but protected by a shade from the direct rays of the sun.

Saturation deficit expressed in millimeters of mercury were calculated from wet-bulb depression values obtained with a sling psychrometer.

The solar radiation measurements were made automatically with a mechanical differential telethermograph developed by Briggs (*2*). After moving and setting up this instrument it is desirable that it be calibrated against an Abbott's silver disk pyrheliometer. Since the latter instrument was not available, the present readings can be looked upon only as relative for one day or one hour with respect to another.

DISCUSSION OF METHODS AND APPARATUS

In selecting a method for the measurement of leaf temperatures several requirements are to be met. It is very desirable that a leaf should remain uninjured. If a measurement is made while the leaf is freely exposed, any breaking of the epidermis or disturbance of the vascular bundles must change the transpiration rate and the leaf temperature. Shreve (*31*) has devised an application of the thermoelectric method whereby the leaf junction of the thermocouple is stretched over a clamp so provided with cross threads that a good contact with the leaf surface can be secured. Since the junction, by this method, was exposed to the light, it was found advisable at the moment of the reading to shade the leaf with an umbrella. Miller and Saunders (*29*) overcame the necessity for shading the leaf by the use of a clamp with cork tips. One of these tips supported the leaf from below while the second pressed the thermocouple junction against the leaf surface. It is obvious that readings so obtained, comparative or otherwise, would be influenced by the temperature of the cork which came into contact with the junction.

Clum (*8*) has more recently obtained leaf temperatures by an older method in which one of the wires of the couple is threaded through the mesophyll of the leaf until the junction is embedded in the leaf tissue. The method, aside from seriously injuring the leaf, which is undesirable, has the disadvantage of being very tedious, and it forbids the use of average values obtained from a large number of leaves selected for similar exposure to the sun at the time of the measurements. The importance of measuring the temperatures of a number of leaves in a short interval of time when comparative values are desired is indicated in the data of Miller and Saunders (*29*) and further illustrated in Table 3 of this bulletin. The angle which the leaf makes with the sun's rays, as Clum (*8*) points out, greatly influences the temperatures of the leaf.

Shreve's method refers the leaf temperatures to the temperature of the air within a stoppered thermos bottle. Miller and Saunders also kept one of their junctions at constant temperature and alternated between air-temperature readings and leaf-temperature readings, noting the departures of leaf temperatures from air temperatures.

The method improvised by the writers for the measurement of the temperatures of cotton leaves avoids many of the undesirable features of other methods and, seemingly, does not introduce new objections. By this method leaf injury is avoided, the junction comes into contact with leaf surface only, and changes in leaf temperature during the readings are negligible. The two portions of the leaf, after they are brought together between the rather large faces of the corks, can not dissipate energy by transpiration nor absorb heat from solar radiation, nor can the temperature of the leaf surfaces, compressed against the thermocouple junction, change appreciably by conduction of heat from the corks through the rather thick mesophyll of the leaf during the short period required for a reading. By the method used each reading is made directly in terms of the departures of the leaf temperature from air temperature at the moment of the measurement and does not require alternate air-temperature readings. The long extension cords permit comparisons of widely separated plants. The absence of the cumbersome constant-temperature bottles is also advantageous.

Averages are essential where leaf temperatures are to be compared either with air temperatures or with the leaf temperatures of other plants; and since the temperature of leaves may change rapidly, in response to changes in the climatic factors, which are never constant, it is important to obtain numerous readings in a very short interval of time. In bringing two portions of a leaf surface together an average of the temperatures of the two points in contact with the junction is obtained that automatically serves to reduce variability. Where the double thermocouple is used, four points of a leaf surface actually contribute to a single reading.

The air temperatures were obtained from a mercurial thermometer exposed to the wind in the shadow cast by the evaporation tank, in preference to values obtained from thermographs or thermometers inclosed in the standard instrument shelter. The desirability of this is shown by Table 1.

TABLE 1.—*Air temperature within a standard instrument shelter and air temperature in a shaded position freely exposed to the wind*

Items compared	Temperature (°C.) at hour shown											
	6 a. m.	7 a. m.	8 a. m.	9 a. m.	10 a. m.	11 a. m.	1 p. m.	2 p. m.	3 p. m.	4 p. m.	5 p. m.	6 p. m.
Outside, shaded	18.0	21.9	26.5	33.5	34.0	36.9	39.0	39.4	39.5	39.3	37.0	29.5
Inside shelter	18.7	21.0	22.5	31.8	33.8	36.4	39.4	39.0	39.5	39.7	38.5	33.4
Departure of inside from outside	+.7	−.9	−4.0	−1.7	−.2	−.5	+.4	−.4	0	+.4	+1.5	+3.9

The values shown in Table 1 were obtained with mercurial thermometers which had previously been compared and found to agree over the range of temperatures given in the table. The results confirm other comparisons made between a mercurial thermometer outside and the thermograph within the shelter. The departures of the temperature within the shelter from the air temperature outside are attributable to the absorption of heat by the walls of the shelter during the hours of rising temperatures and to the radiation of heat from the walls during the hours of falling temperatures. Other conditions being equal, the temperatures within the shelter and outside should be more nearly the same as the wind velocity increases and as air temperature becomes more constant.

Saturation deficits, expressed in millimeters of mercury (mm. Hg.), are used in this bulletin in preference to values for the wet-bulb depression or the relative humidity. The advantage in the use of this measure where leaf temperatures and transpiration rates are to be compared may be illustrated by assuming two cases, in one of which the temperature is 20° and in the other 40° C. and in both cases the relative humidity is 40 per cent. The respective wet-bulb depressions at the two temperatures would be 7.6° and 12.0° C. and the corresponding saturation deficits 10.3 and 32.8 mm. Hg, the latter indicating an evaporating power of the air more than three times as great at the higher temperature.

EXPERIMENTAL WORK

TEMPERATURE VARIABILITY OF LEAVES

VARIATIONS WITH SIMILAR EXPOSURE AND AGE

Variability of temperature is an inherent characteristic of leaves. The temperature of leaves may be affected by such a multitude of causes that it becomes difficult to isolate many of the factors which tend to produce variability. For a given plant or a group of similarly treated plants it may be possible to attach major importance to certain causes of variation and to select leaves which are at least somewhat alike in these respects. By measuring the temperatures of a number of such leaves one may arrive at an average value which can be looked upon as being representative of a plant or a group of plants at a particular time. If, however, the same leaves are measured again a little later, a different average will be obtained. It can be said that the temperatures of leaves are never constant.

Among the more stationary causes which produce variation in leaf temperatures may be mentioned age and exposure. If a series of leaves in positions approaching that of a plane normal to the rays of the sun and, within broad limits, of similar age and maturity is selected and their temperatures measured, it will be found that considerable variability exists in the values obtained. The mean departures and standard deviations of 14 such series of measurements taken at about hourly intervals, each on 48 leaves, are shown in Table 2.

TABLE 2.—*Mean departure from air temperature, standard deviation, and probable error of 48 turgid leaves of Acala cotton selected for similar age and exposure, August 20, 1926*

Items compared	Temperature data (°C.) at time of forenoon observations					
	6.30 to 6.43	7.34 to 7.47	8.24 to 8.36	9.30 to 9.47	10.27 to 10.40	11.25 to 11.39
Mean departure	+0.38	+2.08	+1.85	+0.20	+0.47	−0.68
Standard deviation	.301	.823	.986	.984	1.002	1.098
Probable error	±.020	±.080	±.094	±.096	±.106	±.107

Items compared	Temperature data (°C.) at time of afternoon observations							
	12.20 to 12.44	1.20 to 1.47	2.25 to 2.39	3.30 to 4.34	4.30 to 4.44	5.25 to 5.38	6.20 to 6.32	7.22 to 7.36
Mean departure	−0.24	−0.68	−2.93	−2.85	−3.81	−1.47	−2.28	−1.77
Standard deviation	.895	.843	.867	1.280	1.114	.903	.514	.484
Probable error	±.087	±.082	±.084	±.125	±.109	±.088	±.050	±.047

The variability of the leaf temperatures is found to be greater during the middle of the day than during the morning or evening hours. This doubtless was to have been expected, since differences in the exposure of the leaves during hours of high light intensity would be more important and the relative differences in the transpiration rates of different leaves would be comparatively more marked.

The hourly standard deviations ranged from 0.30° in the early morning to 1.28° C. at 3.30 p. m. The value at 3.30 is probably higher than should ordinarily be expected, since the measurements were interrupted by a broken thermocouple at a time when there was a downward trend in the readings. The next largest standard deviation is 1.11° at 4.30 p. m. The consecutive readings at 6.30 a. m. and at 4.30 p. m. are shown in Table 3.

TABLE 3.—*Variability in the temperature of Acala cotton leaves selected for similar age and exposure August 20, 1926*

Pot, plant, and order of reading		Departures from air temperature				Pot, plant, and order of reading		Departure from air temperature			
		Time a. m.	°C.	Time p. m.	°C.			Time a. m.	°C.	Time p. m.	°C.
Pot 24						*Pot 22*					
Plant 1:						Plant 1:					
Reading	1	6.30	+1.0	4.30	−4.2	Reading	25	6.37	+0.1	4.38	−3.0
	2		+ .4		−3.5		26		+ .3		−3.8
	3		+ .4		−6.4		27		+ .1		−4.0
	4		+1.0		−4.7		28		+1.0		−2.5
	5		+ .8		−4.9		29		+ .1		−1.4
	6		+ .4		−4.8		30		+ .1		−1.4
Plant 2:						Plant 2:					
Reading	7	6.32	+ .5	4.34	−5.3	Reading	31	6.38	+ .3	4.39	−4.9
	8		+ .5		−5.3		32		+ .1		−3.8
	9		+ .6		−4.5		33		+ .1		−3.9
	10		+ .1		−5.0		34		+ .1		−3.7
	11		+ .1		−4.5		35		+ .8		−3.8
	12		+ .1		−3.7		36		+ .4		−4.8
Pot 23						*Pot 21*					
Plant 1:						Plant 1:					
Reading	13	6.35	+ .6	4.35	−3.3	Reading	37	6.40	+ .3	4.40	−3.2
	14		+ .1		−2.9		38		+ .3		−3.9
	15		+ .1		−2.5		39		+ .8		−3.7
	16		+ .1		−1.9		40		+ .1		−3.5
	17		+ .3		−3.2		41		+ .0		−3.2
	18		+ .3		−1.0		42		+ .1		−3.4
Plant 2:						Plant 2:					
Reading	19	6.36	+1.0	4.36	−4.5	Reading	43	6.42	+ .4	4.42	−2.5
	20		+ .4		−3.9		44		+ .3		−3.7
	21		+1.0		−4.5		45		+ .5		−4.7
	22		+ .5		−4.8		46		+ .8		−4.9
	23		+ .1		−4.2		47		+ .4		−4.2
	24		+ .1		−3.4		48		+ .2		−3.4

VARIATIONS OF EXPOSURE TO SUN AT DIFFERENT ANGLES

It is generally recognized that the temperature of a leaf is influenced by the extent of its exposure to the direct rays of the sun. The positive phototropic responses common to many plants bring the leaves into positions approaching maximum light exposures. The Acala cotton plant (*28*) shows marked phototropic responses, whereas the responses of the Pima Egyptian cotton are very slight. Preliminary observations showed the importance of selecting leaves of as nearly full exposure as possible. Often there is a difference in temperature,

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sensible to the touch, between leaves normal to the sun and those departing from this position. The series of measurements shown in Table 4 illustrate such differences. Each value in the table is the average of 10 measurements, each from a different leaf. The differences between the paired series range from 1.4° to 3.2° C. All three differences are significant.

TABLE 4.—*Temperatures of leaves of Acala cotton growing in the field at different angles showing departures from air temperatures*

Day and hour	Departures of leaf temperatures from air temperatures (°C.)		
	Leaves normal to sun	Leaves at angle approaching 90° from normal	Difference: Normal−90°
September 10, 1926, 2.14 p. m.	+2.3±0.14	+0.9±0.20	1.4±0.24
October 4, 1926, 3.45 p. m.	−.5± .49	−2.6± .33	2.1± .59
October 4, 1926, 3.58 p. m.	+.8± .37	−2.4± .17	3.2± .41

YOUNG LEAVES COOLER THAN OLD LEAVES

Differences in the temperatures of old and young cotton leaves, like those resulting from differences in exposure, are frequently sensible to the touch. In Table 5 quantitative measurements are given which show a mean difference of 1.3° ± 0.25° C. in the temperatures of mature and immature leaves. The younger leaves were cooler than the older leaves in six of the seven comparisons. Each value shown in the table is the average of five readings, each on different leaves. At the time of these measurements the plants had made a second growth, which permitted of a comparatively easy differentiation in the age of the leaves. The young leaves selected were of good size, while the older were among the last to appear during the first growth. The comparison represents an age difference ranging from three to five weeks.

Balls (*1*), in comparing the temperatures of young and old leaves, writes:

> Young leaves which have not attained to a third of their ultimate length rarely exceed the shade temperature, but frequently fall below it, their extreme variation being about +0° to −6° [C]. Old leaves, on the other hand, rarely fall below air temperature, but frequently rise above it, varying from −3° to +10° [C].

TABLE 5.—*Temperatures of old and young leaves of Acala cotton, showing departures from air temperatures, August 20, 1926*

Pot	Time, p. m.	Departures from air temperatures (°C)		
		Old leaves	Young leaves	Difference
No. 88	1.57	−1.5±0.52	−3.5±0.55	−2.0±0.76
No. 89	2.16	−3.5± .30	−4.5± .54	−1.0± .66
Do	2.19	−3.1± .21	−4.4± .34	−1.3± .40
No. 88	2.49	−3.7± .67	−4.1± .54	−.4± .86
No. 89	2.51	−3.3± .38	−4.7± .34	−1.4± .51
No. 203	2.53	−.6± .33	−4.2± .31	−3.6± .46
No. 202	2.57	−4.9± .30	−4.3± .50	+.6± .58
Mean		−2.9± .20	−4.2± .15	−1.3± .25

TRANSPIRATION REDUCES LEAF TEMPERATURE

The cotton plant in the Southwest frequently shows considerable wilting on hot, dry days even though there is an abundant supply of moisture in the soil. Wilting becomes more severe and is in evidence earlier in the day as time elapses after irrigation or rain (*11*, *22*).

As soil moisture becomes limited the transpiration rate of cotton decreases. Series of daily weighings of plants grown in pots have shown that with the drying out of the soil the daily transpiration rate may fall below a quarter of the earlier rate or below a quarter of the rate of similar plants abundantly supplied with moisture. In the afternoon when wilting is very marked the hourly loss from

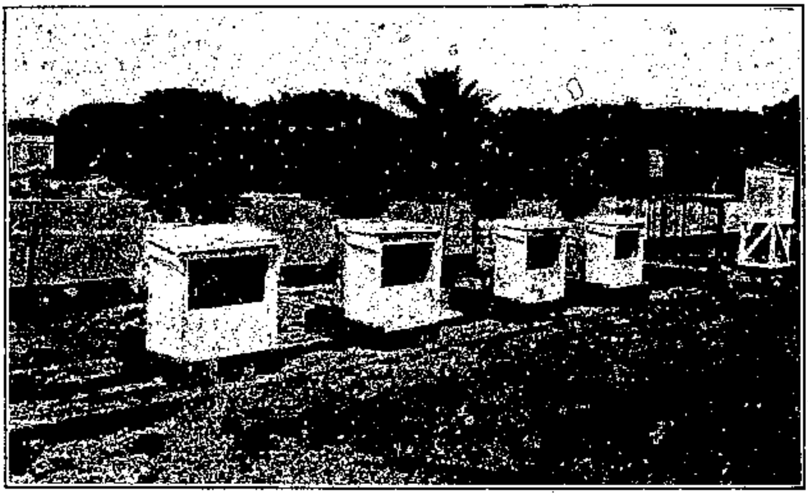

FIG. 3.—Automatic balances, the plants of August 3, 1926, the evaporation tank, and in the background a part of the water-requirement series. (Photograph by H. F. Loomis)

wilted plants may become almost insignificant as compared with the loss from turgid plants of the same size.

When cotton leaves wilt from a shortage of soil moisture,[3] the condition is accompanied by a very noticeable increase in leaf temperature. This increase may become perceptible to the touch several hours or even a day in advance of visible wilting. A grade 1 assignment at 3 p. m. as incipient wilting on the basis of leaf temperature alone has been repeatedly confirmed by visible wilting on the following afternoon.

Miller and Saunders (*29*) reported that the temperatures of wilted leaves of corn, sorghum, soy beans, and cowpeas were higher than turgid leaves of these plants by 1.85°, 1.55°, 2.80°, and 4.65° C., respectively. These relationships are in general keeping with the observations of Darwin (*12*), Smith (*32*), Kiesselbach (*21*), Loftfield (*25*), Balls (*1*), and Clum (*8*). Various methods of reducing transpiration rates were used by these investigators in their comparisons, and

[3] Temporary wilting of leaves and plants abundantly supplied with moisture has been noted which was not accompanied by increased leaf temperatures sensible to the touch. This has been most clearly noted after rainy weather or after the passing of a rather dense cloud.

the methods of measuring leaf temperatures were in many cases quite different. The magnitude of the differences found for the temperatures of leaves with high and low transpiration rates will be largely dependent upon local conditions, the plants used, their treatments, and upon the characteristics of the methods used for determining the leaf temperatures.

COMPARISON OF TURGID AND WILTED ACALA LEAVES

To obtain quantitative information on the relationships existing between the temperatures and transpiration rates of turgid and wilted

FIG. 4.—Turgid Acala cotton plants, August 3, 1926. (Photograph by H. F. Loomis)

cotton leaves, two series of comparisons were made with Acala plants. In the first series of measurements (August 3) the temperatures of the same leaves were taken each hour throughout the day. In the second series (August 25) leaves of similar exposures were selected at the time of the readings. Any personal factor involved in selecting leaves at the moment of a reading is avoided by the method used on August 3, but the variability of values is increased, since at any subsequent hour there are always a number of the previously selected leaves which are shaded or not fully exposed to the direct light.

Four pots of plants from the water-requirement experiments were placed on automatic balances for each series of hourly measurements. (Fig. 3.) Two plants were growing in each of the pots. Of the four pots, two were made ready for the observations of August 3 and August 25 by allowing the pot weight to be decreased by transpiration until the appearance of the plants indicated that the maximum wilting on the day of the temperature comparisons would be between 7 and 8 on the 1-to-10 scale, the plants in the other two pots being kept turgid by watering. (Figs. 4 and 5.)

The temperatures of six leaves were measured on each plant each hour, with the readings on turgid and wilted leaves alternating in

FIG. 5.—Wilted Acala cotton plants, August 3, 1926. The wilting at the time of photographing would have been graded as about 7 on the 1-to-10 scale. (Photograph by H. F. Loomis)

groups of 12. The August 3 comparisons lack data for the hourly transpiration rates because of the fact that the balances had not been sufficiently well adjusted to avoid uncertainties in the transpiration records for several of the hours.

The results of the August 3 comparisons are shown in Table 6 and graphically illustrated in Figure 6.

These data bring out marked differences in the temperature of wilted leaves on plants in dry soil and of turgid leaves on plants in moist soil. From 9 a. m. to 6 p. m. the turgid leaves maintained temperatures ranging from 1.7° to 4.9° C. below the temperatures of the wilted leaves. During this period of the day the highest evaporation rates were recorded and the greatest differences in the transpiration rates of the two sets of plants were noted.

Table 6.—*Temperatures of wilted and turgid leaves of Acala cotton showing departures from air temperatures and measurements of climatic factors, August 3 and 25, 1926*

Date and items compared		Hours of forenoon observations							Hours of afternoon observations							
		5.49 to 6.02	6.30 to 6.44	7.24 to 7.36	8.22 to 8.35	9.24 to 9.40	10.25 to 10.42	11.25 to 11.40	12.28 to 12.45	1.29 to 1.46	2.21 to 2.40	3.25 to 3.45	4.26 to 4.42	5.25 to 5.39	6.25 to 6.41	7.20 to 7.35
August 3, 1926																
Mean temperature departures, °C.:																
Wilted leaves		−0.6 ±.09	−0.3 ±.06	0.4 ±.11	1.6 ±.21	1.9 ±.22	1.9 ±.23	1.8 ±.23	4.0 ±.19	1.2 ±.26	1.6 ±.26	0.8 ±.14	0.9 ±.15	0.8 ±.14	−0.7 ±.03	−0.9 ±.05
Turgid leaves		−1.3 ±.01	−0.2 ±.08	0.5 ±.13	1.0 ±.18	−0.1 ±.22	0.2 ±.20	−1.2 ±.12	1.0 ±.14	−3.7 ±.20	−3.0 ±.23	−2.5 ±.13	−2.3 ±.13	−2.3 ±.12	−2.4 ±.05	−1.6 ±.04
Difference, wilted−turgid		0.7 ±.09	−0.1 ±.10	−0.1 ±.17	0.6 ±.28	2.0 ±.31	1.7 ±.31	3.0 ±.26	3.0 ±.23	4.9 ±.33	4.6 ±.35	3.3 ±.19	3.2 ±.20	3.1 ±.18	1.7 ±.06	0.7 ±.06
	Hour	*Hour 5.30*	*Hour 6.30*	*Hour 7.30*	*Hour 8.30*	*Hour 9.30*	*Hour 10.30*	*Hour 11.30*	*Hour 12.30*	*Hour 1.30*	*Hour 2.30*	*Hour 3.30*	*Hour 4.30*	*Hour 5.30*	*Hour 6.30*	*Hour 7.30*
Wilting of dry-soil plants, 1–10 scale		0	0	.5	2.8	3.4	4.3	5.5	6.0	6.8	7.3	7.3	7.5	7.5	7.0	6.3
	Hour	*Hour 5 to 6*	*Hour 6 to 7*	*Hour 7 to 8*	*Hour 8 to 9*	*Hour 9 to 10*	*Hour 10 to 11*	*Hour 11 to 12*	*Hour 12 to 1*	*Hour 1 to 2*	*Hour 2 to 3*	*Hour 3 to 4*	*Hour 4 to 5*	*Hour 5 to 6*	*Hour 6 to 7*	*Hour 7 to 8*
Evaporation, kilos per square meter		0	0	.13	.40	.67	.86	1.15	1.25	1.08	1.19	.99	.92	.67	.26	.28
	Hour 5	*Hour 6*	*Hour 7*	*Hour 8*	*Hour 9*	*Hour 10*	*Hour 11*	*Hour 12*	*Hour 1*	*Hour 2*	*Hour 3*	*Hour 4*	*Hour 5*	*Hour 6*	*Hour 7*	*Hour 8*
Air temperature, °C	22.5	24.4	25.9	29.3	31.4	34.0	35.0	35.0	36.7	38.1	38.9	39.1	38.5	35.6	33.4	33.3
Saturation deficit, mm. Hg	1.4	4.6	5.7	10.3	14.3	18.8	20.9	20.9	26.1	28.7	29.5	35.7	30.6	25.2	18.8	17.2
Sunshine differential, °C	0	.6	8.3	13.3	17.2	18.9	20.0	20.0	20.6	20.6	19.4	18.9	18.9	9.4	0	0
		5.38 to 5.51	6.32 to 6.40	7.28 to 7.45	8.30 to 8.45	9.30 to 9.45	10.26 to 10.45	11.20 to 11.36	12.29 to 12.43	1.30 to 1.46	2.24 to 2.35	3.27 to 3.43	4.26 to 4.45	5.19 to 5.34	6.24 to 6.37	7.25 to 7.41
August 25, 1926																
Mean temperature departures, °C.:																
Wilted leaves		−0.91 ±.033	−1.17 ±.092	−0.41 ±.153	−0.49 ±.175	0.63 ±.109	1.13 ±.121	0.63 ±.100	0.94 ±.153	1.13 ±.181	2.32 ±.198	1.63 ±.147	2.45 ±.095	0.84 ±.096	−0.53 ±.089	−1.58 ±.072
Turgid leaves		−1.33 ±.042	−1.42 ±.110	−1.22 ±.111	−2.44 ±.087	−2.32 ±.121	−2.49 ±.119	−3.59 ±.157	−2.99 ±.157	−3.73 ±.118	−3.24 ±.140	−3.51 ±.136	−3.35 ±.128	−3.75 ±.180	−3.24 ±.113	−1.76 ±.045

Difference, wilted—turgid		.42 ±.054	.25 ±.143	.81 ±.188	1.95 ±.196	2.95 ±.163	3.62 ±.170	4.13 ±.186	3.93 ±.218	4.86 ±.212	5.56 ±.242	5.14 ±.200	5.80 ±.161	4.57 ±.170	2.71 ±.141	.18 ±.08
		Hour 6	*Hour 7*	*Hour 8*	*Hour 9*	*Hour 10*	*Hour 11*	*Hour 12*	*Hour 1*	*Hour 2*	*Hour 3*	*Hour 4*	*Hour 5*	*Hour 6*	*Hour 7*	*Hour 8*
Wilting of dry-soil plants, 1–10 scale		0	0	1.5	2.8	3.3	4.0	4.5	5.5	6.3	7.3	7.8	7.8	7.0	6.3	5.5
Transpiration:																
Wilted plants, kilos per hour		.02	.04	.08	.22	.26	.16	.14	.12	.18	.14	.02	.02	.06	.06	.04
Turgid plants, kilos per hour		.02	.10	.26	.34	.46	.52	.58	.66	.70	.64	.58	.52	.44	.22	.08
Difference, turgid—wilted		.00	.06	.18	.12	.20	.36	.44	.54	.52	.50	.56	.50	.38	.16	.04
Evaporation (shallow tank), kilos per square meter		.04	.07	.09	.32	.46	.59	.08	.78	.84	.68	.59	.51	.31	.10	.07
Wind, miles per hour		.1	1.3	1.7	1.9	4.0	3.9	3.9	4.1	4.2	4.4	3.1	1.3	1.6	.5	0
Air temperature, °C		24.4	27.8	30.6	33.6	35.3	36.0	38.5	39.0	40.7	40.2	40.9	37.7	37.5	27.9	25.3
Saturation deficit, mm. Hg		10.9	15.0	17.8	23.2	28.0	31.0	33.5	38.1	44.7	43.7	40.3	39.4	39.2	15.6	15.9
Sunshine differential, °C		0	6.7	13.3	16.7	18.9	20.0	20.6	20.8	20.6	19.4	18.8	16.7	13.9	5.6	0

The trend of the temperatures of the wilted leaves was considerably above air temperature, while the turgid leaves after 1 p. m. maintained temperatures between 1° and 3.5° C. below air temperature.

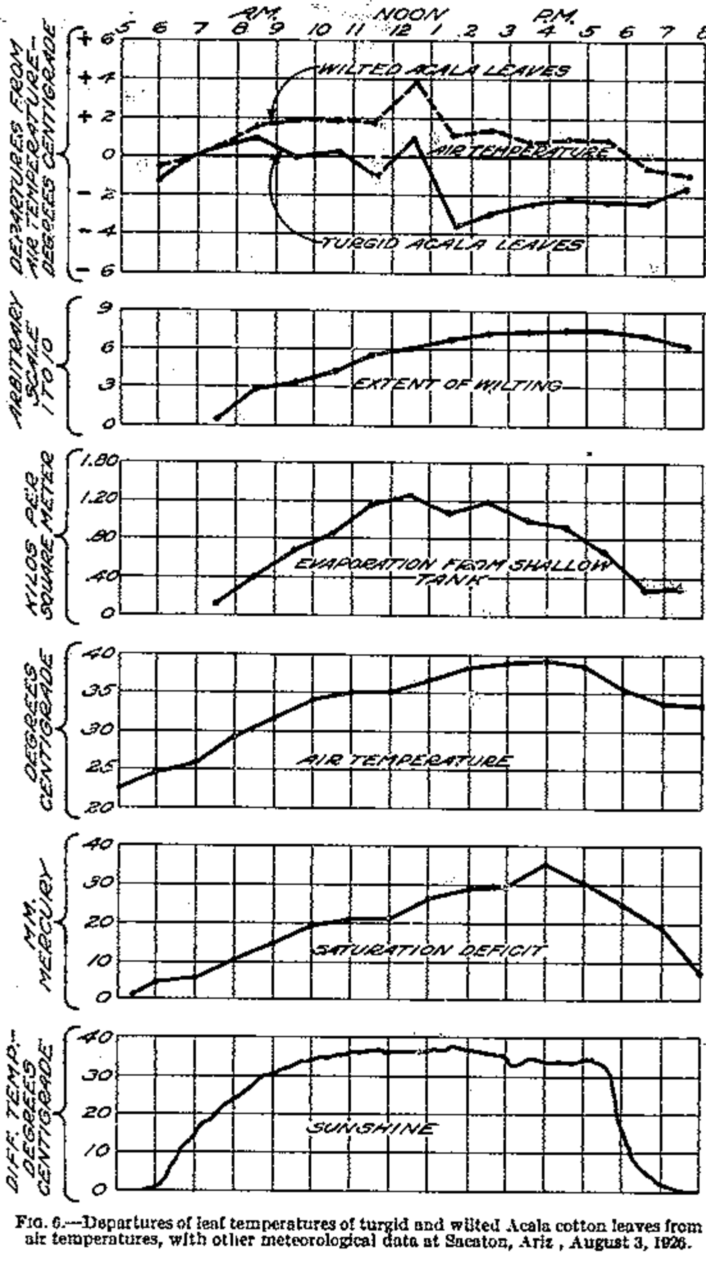

FIG. 6.—Departures of leaf temperatures of turgid and wilted Acala cotton leaves from air temperatures, with other meteorological data at Sacaton, Ariz., August 3, 1926.

The curves as a whole could be considered as very smooth were it not for the marked rise in leaf temperatures at 12.30 p. m. An adequate explanation of this rise is not reflected in any of the hourly data for the climatic factors or in the detailed leaf temperature or transpiration measurements.

Pots 88, 89, 202, and 203 of the water-requirement series were used in the measurements of August 3, pots 202 and 203 being wilted on that day. The same pots were used again on August 25, but the plants in pots 88 and 202 were wilted and those in pots 89 and 203 were turgid. Previous to the measurements of August 3 the transpiration rate of each of the four pots of plants had been very nearly the same. The total transpiration of the turgid plants was 4.1 times that of the wilted plants on August 3 and 3.8 times on August 25.

The results of measurements of August 25 are given in Table 6 and Figure 7.

The measurements of August 25 again bring out marked and consistent differences in the temperatures of the leaves of plants in the dry and moist soils. The greatest temperature difference between wilted and turgid leaves occurred during the middle of the afternoon. The average difference in the leaf temperatures of the plants during this 2-hour period was approximately 5.5° C. The most severe wilting was recorded at 3, 4, and 5 p. m. Between 3 and 5 p. m. the turgid plants transpired 1,100 grams of water and the wilted plants 40 grams. For the full day the two pots of turgid plants lost 6,145 grams and the wilted plants 1,600 grams.

The leaf-temperature measurements of August 25 are shown in Figure 10 as actual leaf temperatures rather than as departures from air temperatures.

The mean difference in the temperatures of the turgid and wilted leaves between the hours of 7 a. m. and 6 p. m. was 2.66° C. on August 3 and 3.94° on August 25. The mean air temperature for the same hours was lower on August 3 than on August 25 (34.7° and 36.5°, respectively), as was the mean saturation deficit (22.2 and 32.7 mm. Hg., respectively). The total evaporation from the shallow tank from 7 a. m. to 6 p. m. was 7.27 kilograms on August 3 and 8.20 kilograms on August 25. It is to be recalled that the ratios of the transpiration of the turgid plants to that of the wilted plants was approximately the same, being 4.1 and 3.8, respectively, on the two days. The actual transpiration values can not be compared, as the plants made some growth during the intervening period and the previously wilted plants had lost a few leaves. It is probable that the greater difference between the turgid and wilted leaves on August 25 was the result of a greater difference in the transpiration rates of the turgid and wilted plants on that date, as this could occur without affecting the transpiration ratios. There was, however, a difference in the method of selecting leaves for the temperature measurements on the two days. On August 3 the same leaves were measured each hour regardless of exposure, while on August 25 leaves were selected for maximum exposure at the time of each measurement. The variability of temperatures of the leaves making up the hourly series was less on August 25 than on August 3, with the result that the average difference in the temperature of the turgid and wilted leaves for the hours from 7 a. m. to 6 p. m. divided by the average probable error of the difference was 10.6 (2.66÷0.25) on August 3 and 20.7 (3.94÷0.19) on August 25.

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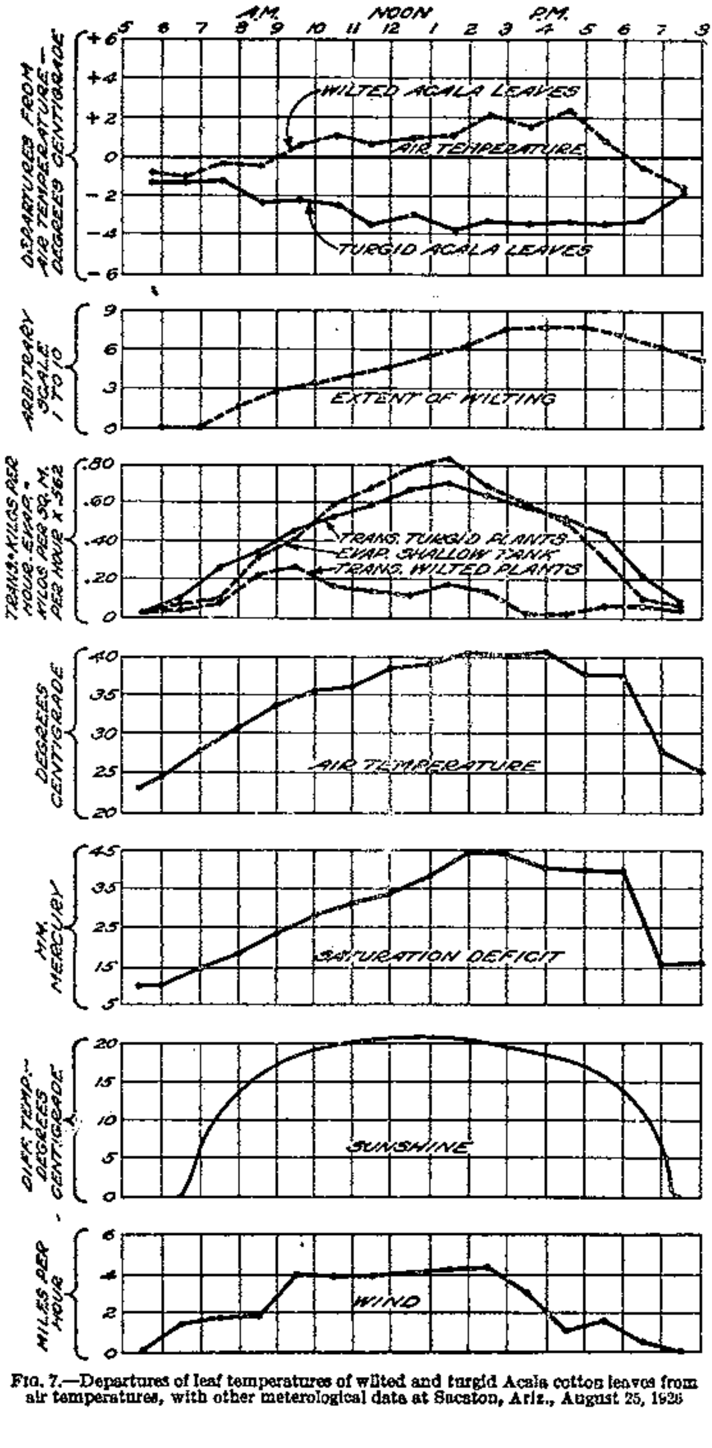

FIG. 7.—Departures of leaf temperatures of wilted and turgid Acala cotton leaves from air temperatures, with other meterological data at Sacaton, Ariz., August 25, 1926

ENERGY OF TRANSPIRATION AND RADIATION COMPARED

The temperature of a leaf may be influenced by any of the factors contributing to the immediate environment of the plant, by the extent to which it is exposed to these factors, and by the physiological and morphological characteristics of the plant itself. If the factors contributing to the temperature of a leaf were held constant, then the temperature of the leaf would increase or decrease until the summation of the effective energy values of the factors tending to increase leaf temperatures were equal to the effective energy values of the processes tending to decrease leaf temperatures. A leaf which is not transpiring may be expected to rise above the temperature of the air until the heat lost by radiation, convection currents, and conduction is equal to the heat absorbed from radiation or produced by the metabolic processes of the leaf itself.

Briggs and Shantz (*6*) calculated the ratio of the energy from direct solar radiation intercepted by plants at Akron, Colo., to the energy requirements for the observed transpiration of midday. Their values in 12 measurements ranged from 0.44 for Galgalos wheat in the hail screen inclosure to 1.01 for alfalfa in the open. They found that the solar radiation intercepted by the plant was insufficient in every case, except for alfalfa in the open, to account for the observed transpiration.

If we can apply Newton's law of cooling [4] to the rate at which heat is given off to or absorbed from the surroundings by a leaf, it then becomes possible to estimate by leaf temperatures the ratio of the energy absorbed by the leaf from radiation to the energy dissipated in transpiration.

On August 25, between 3 and 5 p. m., the turgid leaves maintained temperatures averaging approximately 3.4° C. below the air temperature, and the wilted leaves were found to be 2.1° above air temperature. The turgid plants during this period transpired 1,100 grams of water and the wilted plants 40 grams. Assuming equal leaf areas, these relations indicate that the temperature of the wilted leaves would have been approximately 0.2° higher if there had been no transpiration, or 2.3° above air temperature. In applying Newton's law, the total effective radiant energy received by the wilted leaves may be represented by 2.3. The transpiration of the turgid leaves balanced this radiant energy proportional to 2.3 plus the energy received by the leaves through conduction and convection from the surrounding air proportional to 3.4° (the temperature which they maintained below the air), or a total 5.7°. The ratio of radiant energy absorbed by the leaves to the energy dissipated through transpiration is then 2.3÷5.7, or 0.40. In other words, by this estimate only 40 per cent of the energy required for the transpiration during these hours is accounted for in radiations received from the sun, sky, or surroundings.

A value of 1 would be obtained by the leaf-temperature method only when turgid leaves were at air temperature, while values above unity would result when the temperatures of turgid leaves were

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[4] In the case of a body surrounded by a gas, Newton supposed that the rate of cooling, i. e., the quantity of heat lost in unit time, was proportional to the difference in temperature between the body and the surrounding medium. This relation, which is known as Newton's law of cooling, holds only for small excesses of temperature.

higher than the air. Investigators working under more humid conditions have generally found the temperatures of leaves to be above rather than below the temperature of the air, which would indicate that in those cases the rate of transpiration was insufficient to dissipate the energy received by radiation.

LEAF-TEMPERATURE DIFFERENCES INVERSELY PROPORTIONAL TO CORRESPONDING DIFFERENCES IN TRANSPIRATION RATES

The inverse relation between the differences in the hourly temperatures of turgid and wilted Acala cotton leaves and the corresponding differences in the transpiration rates of the plants of August 25 point to the existence of a high degree of correlation between these variables.[6] That such a relationship should exist might naturally be assumed, but a definite determination is needed. The differences

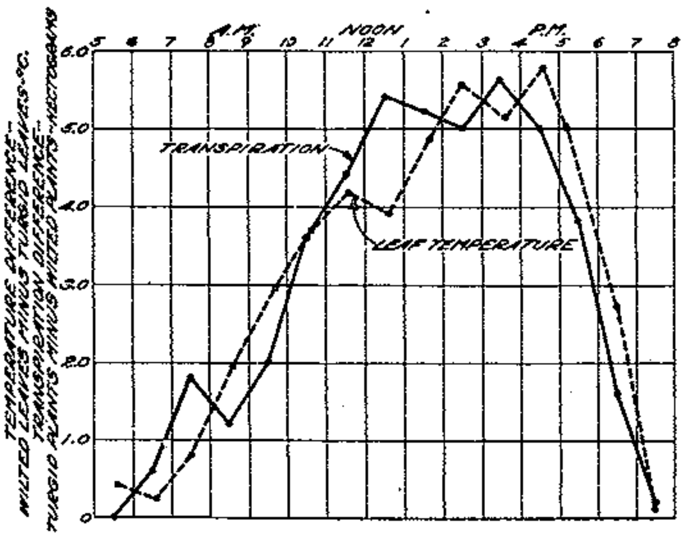

FIG. 8.—Hourly differences in temperatures of turgid and wilted Acala cotton leaves (wilted minus turgid) and corresponding but inverse hourly differences in transpiration rates (turgid minus wilted), August 25, 1926

in the hourly transpiration rates of the plants of August 25 and the inverse differences in the leaf temperatures are graphically shown in Figure 8.

The values for transpiration represent the mean hourly difference between two sets of four plants each. The leaf temperatures are the differences in the mean values of 24 leaves taken on each of the two sets during a 15-minute period at approximately the middle of each hour. A total of 720 leaf-temperature measurements contribute to

[6] Clum (*8, p. 216*) endeavored to correlate differences in leaf temperatures with differences in transpiration rates and by his data was led to the following statement: "In general, the plants in dry soil and the vaselined leaves were 2° to 4° C. warmer than the controls. * * * But in no case was a definite correlation found ... between the difference of the transpiration rates of two leaves or plants, and the difference of their temperatures." Clum's conclusion is drawn from temperature and transpiration measurements on single leaves. The transpiration rates of the differently treated leaves were measured with Ganong potometers, and the temperature measurements were those secured from a thermocouple, a junction of which was threaded through the leaf tissues. Clum's failure to obtain a correlation can doubtless be attributed to the methods which he employed, and he later observes that the difference in the temperature on the two sides of the midrib of cabbage leaves was often as great as the difference between leaves with different transpiration rates.

these graphs, each temperature measurement being the mean of the temperatures of the two points of the upper leaf surface which were brought into contact with the junctions.

The coefficient of correlation between leaf-temperature differences and differences in the transpiration rates of the two sets of plants is -0.929 ± 0.025.

A correlation of this magnitude can leave little question as to the inverse proportionality between leaf temperatures and transpiration rates. When it is not essential that the transpiration of a leaf be expressed in absolute units, it is suggested that the leaf temperatures of different plants may furnish valuable indexes to their relative transpiration rates provided the leaves are comparable in other respects. The determination of leaf temperatures by the method here described is both more convenient and more rapid than are the usual methods employed in measuring transpiration rates.

LEAF TEMPERATURE IN RELATION TO VARIETY, CLIMATE, AND SOIL

COMPARISON OF LEAF TEMPERATURES OF PIMA AND ACALA COTTON VARIETIES

The first comparative measurements made in developing the present method of measuring leaf temperatures were comparisons of the leaf temperatures of the Pima Egyptian and the Acala upland cottons. The results were consistent in showing that the Pima leaves were cooler than the Acala. To throw additional light on this observed difference, two cans of each variety were placed on the automatic balances so that hourly comparisons of the fluctuations in their transpiration rates and leaf-temperature differences might be obtained for a full day. The temperatures of 24 leaves of each variety with as nearly as possible the same exposure were measured each hour, on August 10. These readings alternated in sets of 12 between the two varieties. The results of the observations are shown in Table 7 and illustrated graphically in Figure 9.

Figure 9 shows that the Pima cotton maintained lower leaf temperatures than the Acala until sunset. The differences were not significant during the first hour of the day, but the Pima leaves were cooler. At the last hour of the day the Pima leaves were slightly warmer than Acala, there being a difference of $0.22° \pm 0.04°$ C. The greatest departures from air temperature and the greatest differences between the two cottons occurred during the middle of the day. Between 1 and 2 o'clock the Acala leaves showed a mean temperature departure from the air of $-4.4°$, with the individual leaves ranging from $-2.3°$ to an outstanding measurement of $-6.4°$. The Pima leaves at this hour had a mean departure of $-6.3°$, with individual leaves ranging from $-5.0°$ to $-7.8°$. Between 6 a. m. and 7 p. m. the Pima leaves averaged 1.47° below the Acala.

A comparison of the hourly fluctuations in the transpiration rates of the Acala and Pima plants does not show any outstanding difference in the responses of the two varieties to the hourly changes in the environmental factors. The graphs express only the hourly transpiration of each variety as a percentage of the total of that variety for the day and tell nothing about the actual water loss per unit of leaf surface. It is highly probable that the Pima leaves were transpiring water more rapidly per unit of leaf surface than the Acala leaves. The correlation previously found between the transpiration rates and leaf temperatures would warrant this conclusion and there is the additional fact, to be set forth later, that the Pima cotton had a water

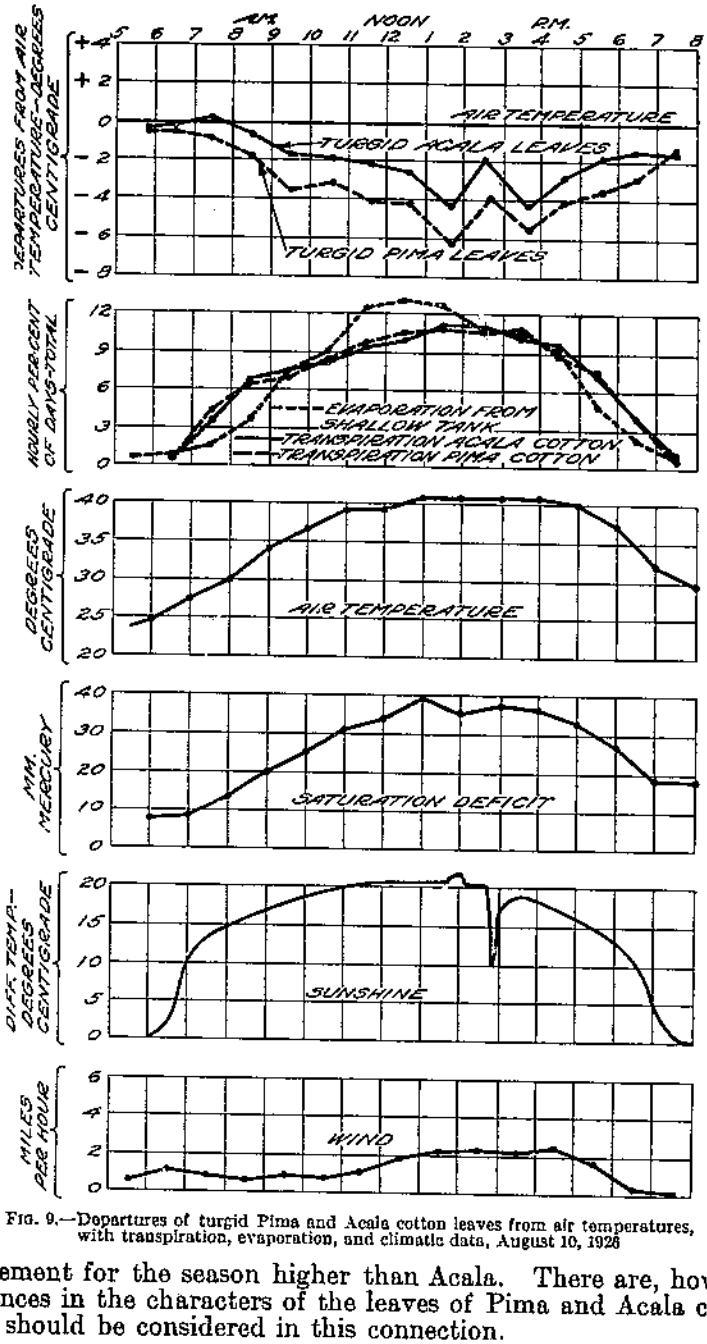

FIG. 9.—Departures of turgid Pima and Acala cotton leaves from air temperatures, with transpiration, evaporation, and climatic data, August 10, 1926

requirement for the season higher than Acala. There are, however differences in the characters of the leaves of Pima and Acala cotton which should be considered in this connection.

Table 7.—*Hourly comparison of leaf-temperature departures and transpiration rates of Pima and Acala cotton and measurements of climatic factors, August 10, 1926*

Items compared	Hours of forenoon observations							Hours of afternoon observations								
	5.45 to 5.56	6.23 to 6.38	7.24 to 7.39	8.20 to 8.34	9.27 to 9.42	10.31 to 10.46	11.25 to 11.45	12.25 to 12.43	1.30 to 1.52	2.30 to 2.44	3.29 to 3.49	4.25 to 4.41	5.19 to 5.34	6.21 to 6.38	7.20 to 7.35
Mean temperature departures, °C.:															
Turgid Acala leaves	−0.30 ±.037	−0.15 ±.043	0.25 ±.081	−0.60 ±.081	−1.69 ±.149	−1.87 ±.181	−2.12 ±.278	−2.29 ±.093	−4.36 ±.115	−1.90 ±.179	−4.40 ±.072	−2.79 ±.091	−1.80 ±.118	−1.46 ±.083	−1.57 ±.036
Turgid Pima leaves	−.49 ±.079	−.42 ±.074	−.82 ±.089	−1.80 ±.056	−3.52 ±.117	−3.12 ±.055	−4.12 ±.150	−4.28 ±.119	−6.30 ±.120	−3.89 ±.129	−5.55 ±.150	−4.01 ±.120	−3.52 ±.091	−2.81 ±.110	−1.35 ±.020
Difference, Acala−Pima	.19 ±.087	.27 ±.085	1.07 ±.120	1.20 ±.096	1.83 ±.187	1.25 ±.187	2.00 ±.312	1.99 ±.151	1.94 ±.166	1.99 ±.220	1.15 ±.166	1.22 ±.151	1.72 ±.149	1.35 ±.138	−.22 ±.041
	Hour 5 to 6	*Hour 6 to 7*	*Hour 7 to 8*	*Hour 8 to 9*	*Hour 9 to 10*	*Hour 10 to 11*	*Hour 11 to 12*	*Hour 12 to 1*	*Hour 1 to 2*	*Hour 2 to 3*	*Hour 3 to 4*	*Hour 4 to 5*	*Hour 5 to 6*	*Hour 6 to 7*	*Hour 7 to 8*
Transpiration, kilos per hour:															
Acala plants	0	0.06	0.34	0.66	0.74	0.80	0.92	0.98	1.06	1.08	1.00	0.94	0.70	0.40	0.10
Hourly percentage of day's total	0	.6	3.5	6.8	7.6	8.2	9.4	10.0	10.8	11.0	10.2	9.6	7.2	4.1	1.0
Pima plants	0	.04	.32	.48	.52	.62	.72	.78	.80	.78	.80	.66	.54	.28	.04
Hourly percentage of day's total	0	.5	4.3	6.5	7.0	8.4	9.8	10.6	10.8	10.6	10.8	8.9	7.3	3.8	.5
Evaporation, shallow tank, kilos per square meter	.06	.08	.14	.36	.74	.88	1.22	1.26	1.22	1.05	1.06	.87	.47	.22	.09
Hourly percentage of day's total	.6	.8	1.5	3.7	7.6	9.1	12.5	13.1	12.7	10.9	10.4	9.0	4.9	2.3	.9
Wind, miles per hour	.3	1.2	.9	.6	.9	.7	1.1	1.8	2.1	2.2	2.1	2.4	1.6	.2	0
	Hour 6	*Hour 7*	*Hour 8*	*Hour 9*	*Hour 10*	*Hour 11*	*Hour 12*	*Hour 1*	*Hour 2*	*Hour 3*	*Hour 4*	*Hour 5*	*Hour 6*	*Hour 7*	*Hour 8*
Air temperature, °C	24.6	27.1	29.8	34.0	36.5	39.0	39.1	40.8	40.8	40.7	40.8	39.3	37.1	32.0	29.8
Saturation deficit, mm. Hg	7.4	8.1	13.4	19.6	24.6	30.7	33.5	39.1	35.1	37.3	36.1	32.5	27.2	18.3	17.8
Sunshine differential, °C	0	10.5	15.0	16.6	18.3	20.0	20.6	20.6	21.7	16.7	18.3	16.1	12.8	5.5	0

The Pima leaf (*19*) is comparatively thick and leathery, nearly glabrous, somewhat shiny of surface, and dark olive green in color. The Acala leaf is comparatively thin and soft and somewhat hairy, especially along the veins. The leaf is dull of surface, and the color is a lighter green than that of the Pima.

The shiny surface of the Pima leaf may have acted to reduce light absorption, and the somewhat hairy condition of the Acala leaf may have contributed slightly to the higher leaf temperatures which were observed; but the thinner character of the Acala leaf, as well as the lighter color, it would seem, should have acted to produce lower leaf temperatures. The leaves of the two cottons are further contrasted in that the Acala leaf presents a comparatively flat surface to the sun, while the surface of the Pima leaf is depressed at the primary veins and elevated along the folds from the sinuses to the insertion of the petiole. This difference in exposure made it more difficult to secure surfaces of the Pima leaves normal to the rays of the sun, as did the comparative absence of phototropic response. However, the difference in exposure could not have been more than 10 per cent in the leaves selected. Since a larger proportion of Acala leaves are fully exposed to the light, it is very probable that the actual difference in the temperature of all leaves of the two varieties is considerably greater than these comparisons indicate.

In Figure 10 the measurements of August 10, 20, and 25 have been brought together and are shown graphically as actual leaf temperatures.

Marked differences having been observed in the temperatures of Pima and Acala leaves when the plants were abundantly supplied with water, it seemed desirable that comparisons be made between these varieties when the plants were wilted.

TABLE 8.—*Differences between the temperatures of wilted Acala and Pima cotton leaves compared with differences between turgid leaves*

Items compared		Temperatures (°C.)					
		Turgid leaves		Wilted leaves		Difference: Acala and Pima	
		Acala	Pima	Acala	Pima	Turgid	Wilted
Pima and Acala in different cans	Time	1.20	1.17	1.30	1.33	3.2±0.23	2.7±0.28
	Wilted	−1.5±0.15	−4.7±0.17	1.8±0.16	−0.9±0.23		
Pima and Acala in same cans	Time	2.24	2.15	1.38	1.41	3.5±0.27	1.3±0.21
	Wilted	[1]−1.8±0.17	[1]−5.3±0.20	+0.4±0.16	−0.9±0.14		
Mean		−1.7±0.08	−5.0±0.09	+1.1±0.19	−0.9±0.13	3.4±0.12	2.0±0.23

[1] Same plants 1 hour later.

The results of a series of leaf-temperature measurements on wilted plants of these varieties is set forth in Table 8. The results show that differences in temperature still exist when the plants are suffering from a water shortage and point to the conclusion that the physiological responses of the two varieties to water shortage are in this respect not different. In one of the two comparisons between wilted leaves the

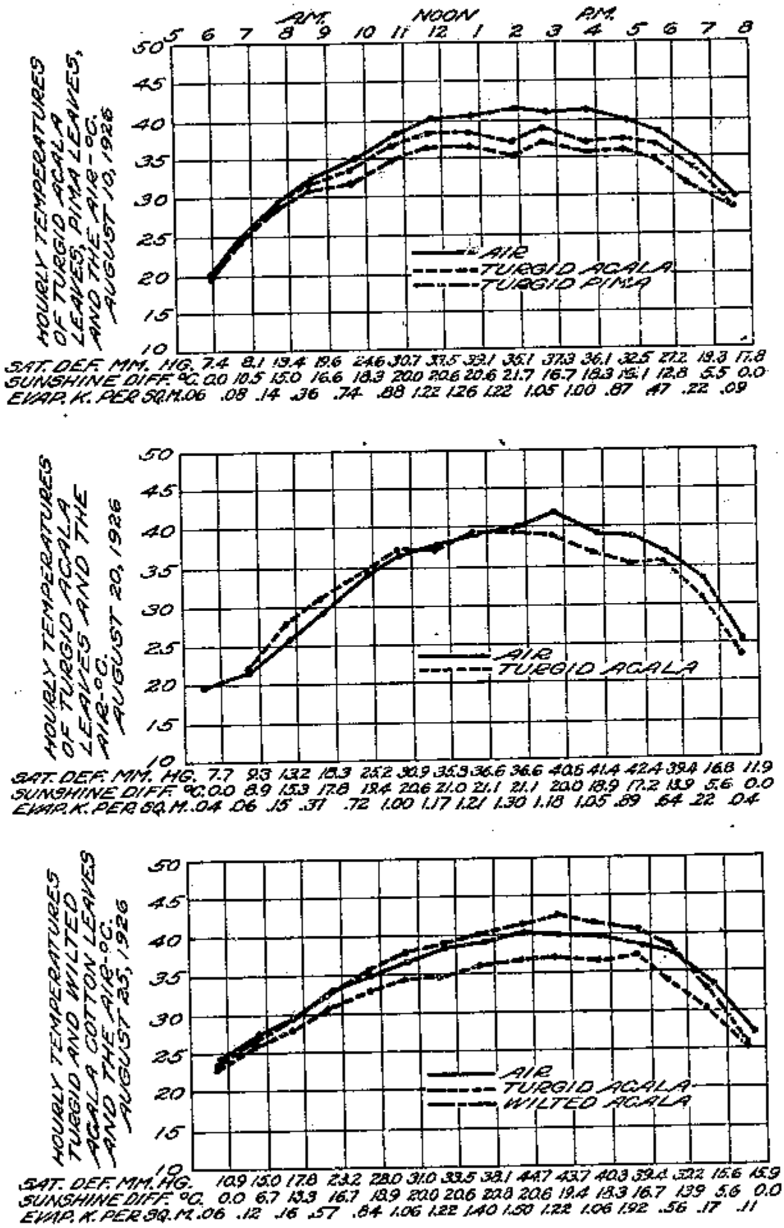

FIG. 10.—Temperatures of turgid Pima and Acala cotton leaves on August 10, turgid Acala leaves on August 20, and turgid and wilted Acala leaves on August 25. The intensity of climatic factors on the different days are shown numerically

plants compared were growing together in the same pots, which fact would dismiss any possibility of the differences found being due to differences in their treatments.

Customary notes with regard to wilting were made on these plants at 3 p. m., approximately one and one-half hours after the temperature measurements. At 3 p. m. the Acala plants in pots 37 to 42 showed a mean wilting on the 1-to-10 scale of 6.9. The wilted Pima plants at the same hour averaged 7.1. In the second comparison shown in the table the Pima and Acala plants were growing in pairs in the same pots, Nos. 43, 44, and 45. The mean wilting of this Acala was 7.7 and of the Pima 8.0. It is improbable that at the time of the measurements the wilting of any of these plants was much greater than 5 or 5.5.

A mean difference of 2.0° ± 0.23° C. is shown between the wilted Pima and wilted Acala leaves, while the corresponding difference between the turgid Pima and turgid Acala leaves is 3.4° ± 0.12°. The mean difference in temperature of wilted Pima and wilted Acala cotton in this case is 40 per cent less than the mean difference between turgid Pima and turgid Acala cotton.

Ten comparisons were made between the leaf temperatures of Pima Egyptian and Acala upland cotton in addition to the hourly comparisons of August 10. The departures of the leaf temperature from air temperature of the two varieties are shown in Table 9 and the differences in the corresponding readings in Table 10.

In all of the comparisons the Pima leaves were cooler than the Acala leaves. The differences ranged from 1.6° ± 0.23° C. to 3.5° ± 0.26°, with a mean difference of 2.44° ± 0.146°. In each comparison the difference in the temperature of the leaves of the two varieties exceeded the probable error of the difference by at least three times, and for the whole series the individual differences averaged 7.5 times the probable errors.

OKRA-LEAF ACALA AND NORMAL ACALA LEAVES

Okra-leaf Acala is a mutant of the Acala stock, with leaves parted nearly to the base into three to five narrow lobes. The pronounced difference in the type of leaf between this form and normal Acala made it of interest to compare their relative leaf temperatures.

Six comparisons were made between the leaf temperatures of normal Acala and okra-leaf Acala. The average difference was 1.02° ± 0.393° C. For the series the average difference is two and one-half times the probable error. In three of the six comparisons the okra-leaf Acala leaves were cooler by a significant difference, and in one of the six comparisons the leaf temperature of the two cottons showed no difference. (See Table 10.)

LEAVES OF ACALA GROWN IN SHADE COOLER THAN THOSE IN THE OPEN

A series of plants grown under a partial muslin shade were available to test the effect of shade upon leaf temperatures. The leaves of these plants were much larger than the leaves of the plants freely exposed to the light, and the ratio of seed cotton to total dry weight was higher.

A mean temperature difference of 1.92° ± 0.176° C. was found between the leaves of Acala plants grown with shade and in the open.

Five comparisons were made between the plants in the shade and in the open, the shaded plants being cooler by a significant difference in each case, the individual differences averaging seven times the corresponding probable errors. The results of these comparisons are included in Tables 9 and 10.

LEAVES COATED WITH WHITEWASH COOLER

As it appeared possible that whitewashing the leaves might lower leaf temperatures, reduce the rate of transpiration, and ameliorate the effects of the extreme climatic conditions, a set of plants in cans and a plot of field cotton were covered with whitewash. A noticeably greater amount of chlorophyll was present in the whitewashed leaves than in the leaves of plants exposed directly to the light.

The coefficient of light absorption of leaves whitewashed as heavily as these is doubtless very low, but since the green color of the leaves was not entirely obscured, the coefficient would be somewhat higher than that of a surface such as white blotting paper, which is reported as having a coefficient of absorption of about 0.20.

TABLE 9.—*Comparative departures of leaf temperatures from air temperatures of different cotton varieties and of Acala cotton under different treatments, Sacaton, Ariz., 1926*

[The leaves selected were all turgid, all fairly mature, and as nearly as possible normal to the rays of the sun]

Date		Times and departures (°C.)						Approximate air temperature °C
		Acala, whitewashed	Pima, normal treatment	Acala, grown under muslin shade	Okra-leaf Acala	Acala, normal treatment	Acala on saline soil	
July 28	Time	4.34	4.03	4.40	4.21	4.07		4.20
		−4.7±0.22	−3.9±0.15	−4.1±0.18	−2.3±0.15	−2.3±0.18		36
July 30	Time		11.20			11.24		11.20
			−2.5±0.29			.2±0.23		38
	Time		11.30			11.35		11.30
			−2.0±0.40			−.2±0.29		38
	Time	1.43	1.29	1.51	1.34	1.31		1.40
		−5.4±0.20	−3.4±0.30	−2.9±0.20	−2.8±0.27	−.6±0.35		40
	Time	2.20	2.00	2.23	2.10	2.05		2.10
		−3.7±0.25	−3.3±0.34	−2.1±0.12	−2.1±0.47	−1.0±0.29		41
	Time		2.58			2.54		3.00
			−3.4±0.22			−1.5±0.19		41
August 16	Time	1.58	1.17	2.03	1.24	1.21	1.49	1.30
		−4.8±0.26	−4.7±0.17	−4.1±0.21	−1.8±0.34	−1.5±0.14	−1.1±0.19	37
	Time		2.15		2.28	2.24	2.35	2.25
			−5.3±0.20		−3.4±0.33	−1.8±0.17	−.5±0.19	38
August 17	Time	3.27	3.10	3.33	3.17	3.14	3.23	3.15
		−3.4±0.18	−3.0±0.17	−3.1±0.11	−2.2±0.16	−1.3±0.19	−.5±0.19	39
	Time		3.40			3.44		3.40
			−3.9±0.35			−1.0±0.29		39
Mean values: Of first series, August 16, 17		−4.1	−3.9	−3.6	−2.0	−1.4	−.8	
All, irrespective of time		−4.4	−3.5	−3.3	−2.4	−1.1	−.7	

The leaf temperatures of whitewashed Acala cotton plants were measured and compared with the leaf temperatures of control plants on five occasions. The leaves of the whitewashed plants were found to be cooler by a mean difference of 3.06° ± 0.393° C. Each of the five comparisons gave significant differences and the average difference was nine and one-half times the probable error. The results are included in Tables 9 and 10.

ACALA COTTON IN SALINE SOIL

The leaf temperatures of Acala cotton growing in a saline soil were compared with those of Acala cotton in the less saline control soil. Three comparisons were made, and in each case higher leaf temperatures were found for the saline-soil plants. The differences were 0.4° ± 0.24°, 1.3° ± 0.25°, and 0.8° ± 0.27° C., and the mean difference was 0.83°. The differences in leaf temperature between the control and the saline soil, though all in the same direction, lack significance in one of the comparisons. The mean difference is three and three-tenths times the probable error.

TABLE 10.—*Differences in the leaf temperatures of Acala and Pima cotton, Acala and okra-leaf Acala, and Acala under various growing conditions, Sacaton, Ariz., 1926*

Date	Pima cooler than Acala (°C.)	Difference ÷ probable error	Okra-leaf Acala cooler than Acala (°C.)	Difference ÷ probable error	White-washed Acala cooler than Acala (°C.)	Difference ÷ probable error	Shaded Acala cooler than Acala (°C.)	Difference ÷ probable error	Acala cooler than Acala in saline soil (°C.)	Difference ÷ probable error
July 28	1.6 ±0.23	7.0	0 ±0.23	0	2.4 ±0.28	8.6	1.8 ±0.25	7.2		
	2.7 ±0.37	7.3								
	1.8 ±0.49	3.7								
July 30	2.8 ±0.46	6.1	2.2 ±0.44	5.0	4.8 ±0.40	12.0	2.3 ±0.40	5.8		
	2.3 ±0.45	5.1	1.1 ±0.55	2.0	2.7 ±0.38	7.1	1.1 ±0.31	3.6		
	1.9 ±0.29	6.5								
August 16	3.2 ±0.22	14.5	0.3 ±0.37	.8	3.3 ±0.29	11.4	2.0 ±0.25	10.4	0.4 ±0.24	1.7
	3.5 ±0.26	13.5	1.6 ±0.37	4.3					1.3 ±0.25	5.2
August 17	1.7 ±0.25	6.8	0.9 ±0.25	3.6	2.1 ±0.26	8.1	1.8 ±0.22	8.2	0.8 ±0.27	3.0
	2.0 ±0.45	6.4								
Mean	2.44 ±0.146	7.7	1.02 ±0.393	2.6	3.06 ±0.340	9.4	1.92 ±0.176	7.0	0.83	3.3

The soil in which two sets of the plants were grown was originally the same, and the treatments differed only in that the plants of one set were watered from a well, the water of which had a salt content about four times as great as the water used for the control plants. The last leaf-temperature comparison was made on August 17 and the plants were cropped on August 22. After cropping the two soils had the following characteristics: Specific electrical conductivity, saturated soils, saline 0.0035, control 0.0016; freezing-point depression, saturated soils, saline 0.41° C., control 0.15°. The mean freezing-point depression of the expressed leaf sap of the two sets of plants (July 21 and July 26) was 1.28° for the controls and 1.39° for the saline-soil plants, showing a higher osmotic concentration of the saline-soil plants, which agrees with observations (*17*) on field plants.

LEAF AND AIR TEMPERATURES AT SACATON, ARIZ.

The leaf temperatures of cotton at Sacaton, Ariz., are usually considerably lower than air temperatures, which is somewhat in contrast to the findings of those who have measured leaf temperatures of other plants in more humid regions. Clum (*8*) at Cornell University found leaf temperatures to vary from 3° to 10° C. above air temperature. Miller and Saunders (*29*) in Kansas report the leaf temperatures of corn, sorghum, soy beans, and cowpeas with respect to air temperatures as +.06°, −.02°, +.5°, −.2°, respectively, and alfalfa leaves as being consistently less than 1° below air temperature. Seeley (*30*) in Michigan found the temperatures of strawberry leaves on clear days to average 8.4° above air temperature. Smith (*32*) working in the Tropics observed leaf temperatures 15° above air temperatures. Balls (*1*) working with cotton in Egypt, under probably more humid conditions than those prevailing at Sacaton, reports that the temperatures of old leaves rarely fell below air temperatures but frequently rose above them, varying from −3° to +10°.

The average temperatures of turgid cotton leaves at Sacaton exceeded air temperature on only one occasion (Table 9), during the middle of the day, but were occasionally found to be higher than air temperatures during the morning hours when the saturation deficits were comparatively low. (Fig. 10.) Mean leaf temperatures more than 5° C. below air temperatures were observed on two different days for Pima Egyptian cotton, the average of 10 series of measurements being −3.5° with respect to air temperatures. The corresponding temperatures of the leaves of Acala upland cotton were −1.1° with respect to air temperatures.

It seems reasonable to attribute the relatively low leaf temperatures found for cotton at Sacaton to the rather arid climatic conditions, since the water requirement of this plant when compared to that of other crops (*4*) does not suggest an unusually high transpiration rate.

TABULATED DATA

The data of the observations relative to varieties, treatments, and soil factors are summarized in Tables 9 and 10. Table 9 shows the comparative departures of leaf temperatures from air temperatures, and Table 10 shows the differences in the leaf temperatures. Every series of temperature measurements made on any of the plants has been included in these tables except those which have been considered in previous tables.

During the summer three or four of the comparisons were discontinued because of a passing cloud or a broken thermocouple, and in one instance a portion of a series had to be discarded when the first readings indicated that some moisture remained on the air junction of the thermocouple after a standardization. It also occasionally happened that the action of the galvanometer indicated that a poor hold had been secured on a leaf, in which case a new leaf or a new hold was taken without waiting for the galvanometer to come to rest.

The different varieties and treatments are arranged in Table 9 in the order of increasing mean-leaf temperatures, and it may be noted that there are few deviations from this order for any of the varieties or treatments that are comparable with respect to time. The agreement in the relative leaf temperatures on the different days is largely attributable to the fact that the plants were grown in the water-requirement series in which the soil moisture was systematically maintained at or near the moisture equivalent percentage. This fact largely precluded the possibility of differences in leaf temperatures of the different varieties or treatments due to variations in the moisture content of the soil. Each set of the water-requirement plants was made up of six to nine cans, and in measuring leaf temperatures for the comparisons shown in Table 9 it was customary to take the temperature of but a single leaf from any plant.

LEAF TEMPERATURE AND WATER REQUIREMENT

The six sets of plants are arranged in the order of their increasing water requirements in Table 11, and opposite each is placed the average departure from air temperature of the leaves of these plants. The Acala cotton grown in the saline soil had the lowest water requirement and the highest leaf temperature, and next in order of water requirements were the whitewashed Acala, the normal Acala, the okra-leaf Acala, the Acala grown under the muslin shade, and the Pima cotton. The increasing water requirements were accompanied by decreasing leaf temperatures throughout the series, with the exception of whitewashed Acala, which had the coolest leaves but ranked second in the water-requirement comparison.

TABLE 11.—*Leaf temperature departures of cotton varieties compared with water-requirement values, Sacaton, Ariz., 1926*

Variety and treatment	Pot Nos.	Water requirement	Departure of leaf temperatures from air temperatures, means of full series Aug. 16 and 17 (°C.)
Acala, saline soil	184 to 189	841±4.9	−0.3
Acala, whitewashed	196 to 201	887±9.1	−4.1
Acala, normal	13 to 21	891±5.6	−1.4
Okra-leaf Acala, normal	25 to 33	902±8.1	−2.0
Acala, under muslin shade	215 to 220	909±10.9	−3.6
Pima, normal	1 to 9	1042±7.4	−3.9

Although a general agreement appears to exist between leaf temperatures and water requirements when ranks alone are considered, this must be in part a coincidence, since the differences in the water requirements of the second, third, fourth, and fifth members of the series are not significant. It is probable that certain of the agreements are directly attributable to differences in the relative transpiration rates which are reflected in the water-requirement values, but a consistent inverse relationship between leaf temperatures and water-requirement values can not be expected, since water requirement is dependent upon the two variables, rate of growth and water loss, only one of which could influence leaf temperature.

YIELDS OF ACALA COTTON IN RELATION TO TEMPERATURE

Notwithstanding the interest and economic importance which are to be attached to temperature optimums, our knowledge in this regard is extremely limited. Particular ranges of temperatures are recognized as being most favorable for a number of crop plants, but hese ranges are poorly defined. Data concerning optimums for cotton are fully as meager as for other agricultural plants. While cotton is generally considered as being a hot-climate plant, conclusions in this regard have been influenced at least in part by the association of the long season required for the setting and maturation of a crop with high temperatures.

In the Southwest, periods of extreme heat are looked upon as being injurious. Cook (*9*) has observed the influence of the advent of high summer temperatures on the development of the fruiting branches of the Pima Egyptian variety in the Yuma Valley, and King and Leding (*23*) have noted that the unusually warm summer of 1924 at Sacaton, unaccompanied as it was by the usual rains, while favorable to crop plants in general, affected cotton adversely. Their data, however, do not show that the yields of Pima cotton were lower than usual. This variety may set a large proportion of its bolls during the hot summer weather, whereas upland cottons frequently shed profusely. Under even more extreme conditions at Indio, Calif., it has been noted that a large proportion of the upland crop is set during intervals of cool weather in the late summer. The senior writer (*13*) found that Durango cotton plants matured a good crop of bolls when the temperatures at night were increased to 90° F. whereas very few bolls were set on plants given night temperatures of 65° F. The experiments were conducted under the cool coastal conditions near San Diego, Calif., where the temperature during the day was seldom above 80° F.

Marked differences occur in the number of immature bolls shed by the Pima Egyptian and Acala upland cottons in the Southwest. Concerning this difference in the shedding of the two varieties Cook (*10*) has observed: "Egyptian cotton may retain nearly all of its buds and young bolls while upland varieties in adjacent rows are shedding nearly all of their buds." Loomis (*26*) found no great difference in the number of floral buds shed by the two varieties in 1924 and 1925. Kearney and Peebles (*20*), working with Pima×Acala hybrids, have supplied evidence that there are genetic factors for shedding which segregate and recombine in the usual manner.

The boll shedding of Acala as recorded by King, Loomis, and Varmette (*24*) was 70.3 and 71.7 per cent, respectively, in 1922 and 1923, while they found Pima shedding for the same years to be 17.5 and 29.3 per cent. Notwithstanding the marked differences in their shedding percentages, the differences in the acre yields of seed cotton between the Pima and Acala varieties in some years is not large, since Pima plants produce fewer flowers (*24*) and smaller bolls than Acala plants. The ratio of weight of seed cotton to the weight of the plants, exclusive of seed cotton, was found to be very similar for the two varieties in 1926, in a comparison of 20 consecutive plants, alternating in groups of 5 of each variety. The ratio of weight of seed cotton to vegetative weight for Acala was 0.399 ± 0.019, while the corresponding ratio in Pima was 0.422 ± 0.017, a difference that is not significant. In adjacent rows the observed boll shedding between July 12 and September 18 of Pima was 4.6 and of Acala 62 per cent.

Data furnished by the senior writer (*14*) indicate that the excessive shedding of upland cottons in the Southwest is associated at least in part with photosynthetic nutritional relationships. It was found that 25 Acala upland cotton plants which were defruited twice during the summer of 1926 set 84 and 93 per cent more bolls in the 20-day periods following the two defruitings than did control plants. The nutritional relationship between fruitfulness and shedding of cotton has been further substantiated by the work of Mason (*27*) and Ewing (*16*). Measurements of boll growth have shown that an Acala cotton plant must manufacture and translocate to each of its bolls an average of approximately 0.17 gram of organic material per day over a 40-day period for normal boll growth alone, and vegetative growth has been observed to be largely inhibited by a heavy setting of bolls.

Counts were made in the fall of 1926 of the number of leaves and bolls on upland cotton plants in different cotton districts of California and at Sacaton, Ariz. These data brought out marked differences in the ratio of number of leaves to number of bolls in the different localities. In the Imperial Valley at Meloland representative plants in one field had 23 leaves to each boll, while south across the international boundary the ratio was approximately 6 leaves to 1 boll, the latter bolls, however, being rather small. At Shafter, in the San Joaquin Valley, values ranging from 5 to 10 leaves per boll were obtained, the mean lying between 6 and 7. In a representative field at Sacaton the ratio was found to be approximately 7 leaves to 1 boll. In the Coachella Valley the ratio in a very good field was 6.2. At San Bernardino, which is cooler, a mean value of 4.2 was obtained, and at Perris with good Kekchi plants the value was 2.6. For small plants at Pala which had received but one very late irrigation the ratio was 5.4. While the values seemed to be largely influenced by the soil types and treatments, the observations suggested that fewer leaves were required to produce a boll of cotton in the cooler localities.

It has been pointed out that the wilting of cotton leaves is a common occurrence in the Southwest and that when caused by a deficiency of soil moisture it is accompanied by increased leaf temperatures. Data by Thoday (*33*), working with *Helianthus annuus*, show that turgid leaves may assimilate carbon dioxide 10 times as fast as flaccid leaves and twice as fast as leaves which are referred to as limp.

High temperatures may have injurious effects on leaf tissue, and it is a matter of common knowledge that excessive leaf temperatures are unfavorable to plant growth and photosynthesis. Howard (*18*), working with cherry laurel, found that the rate of carbon assimilation increased steadily with temperature until a maximum (about 37.5° C. or approximately 100° F.) was reached, above which temperature the rate of assimilation rapidly decreased. She found also that at temperatures above 25° there was a continuous falling off in assimilation with the increasing duration of the high temperatures, the higher the temperature the more rapid the decline. Little is known concerning the optimum temperatures for different plant species.

Attention has not previously been called to the differential annual fluctuations in the yields of Pima Egyptian and Acala upland cotton with respect to high summer temperatures. The yields of Acala cotton have been comparatively low at Sacaton in each of the years characterized by high average maximum summer temperatures, while the yields of Pima cotton during the same 6-year period showed less variability and apparently little relation to the Acala yields or to maximum temperatures. The relative yields of Pima Egyptian and Acala upland cotton in comparative yield tests and the mean maximum summer temperatures for the years 1921 to 1926 are shown in Table 12.

TABLE 12.—*Yields of Acala and Pima cotton in comparative tests as related to average maximum summer temperatures at the United States Field Station, Sacaton, Ariz.,*[1] *1921–1926*

Year	Temperature (°F.)					Acre yields of seed cotton (pounds)	
	June	July	Aug.	Sept.	Mean	Acala	Pima
1921	100.9	98.6	96.4	96.3	98.1	1,914	1,996
1922	103.6	102.0	101.1	98.2	101.3	1,647	2,050
1923	99.8	100.2	96.9	94.7	97.9	2,406	2,367
1924	103.7	102.0	103.6	99.0	102.1	1,560	2,026
1925	98.0	103.0	98.2	93.9	98.3	2,641	1,643
1926	103.6	102.5	100.7	96.2	100.8	1,733	1,888

[1] The yield data shown in this table for 1921, 1922, and 1923, are from King and Leding (23, *Table 4*), for 1924 from the same investigators (25, *Table 7*), and for 1925 and 1926 from unpublished plot records supplied by C. J. King, superintendent of the station. The two varieties have been compared for six years in different plots in the same block (C2-8 to C2-15). The soil throughout this block is exceptionally uniform and productive. For 1921, 1922, and 1923 the comparisons are of single quarter-acre plots (26.5 by 410 feet) under normal irrigation. The 1924, 1925, and 1926 comparisons are of 3, 4, and 4 plots of each variety for the respective years. More frequent irrigations were applied to a number of these plots during the last three years than is the usual custom under normal treatment. The acre yields in pounds of those plots irrigated according to usual custom were as follows: In 1924 (1 plot each), Acala, 1,360; Pima, 2,002. In 1925 (2 plots each), Acala, 2,503; Pima, 1,498. In 1926 (1½ plots each), Acala, 1,625; Pima, 1,830.

The years 1921, 1923, and 1925 had average maximum summer temperatures below 100° F., and the three highest Acala yields occurred in these years. The years 1922, 1924, and 1926 had maximum summer temperatures averaging more than 100°, and the Acala yields were comparatively low. The mean Acala yields were 40 per cent greater during the three cooler years than during the years marked by maximum temperatures above 100°. The mean yields of Pima cotton, however, are not significantly different between the three hot years and the three cooler years.

The remarkable agreement between the yield of Acala and the mean temperature can be brought out by arranging the years in the order of their mean temperature and comparing this with the standing of the years in yield. The same method brings out the difference between Acala and Pima. (Table 13.)

The correlation of rank which measures the agreement between series of ranks on the same scale as a product moment correlation shows Acala, 0.97 ± 0.02; Pima, 0.085 ± 0.08.

TABLE 13.—*Ranks of mean maximum summer temperatures (lowest to highest) and corresponding rank of the yields of Acala and Pima cotton for the years 1921 to 1926*

Year	Temperature rank	Acala yield	Pima yield
1923	1	2	1
1921	2	3	4
1925	3	1	6
1926	4	4	5
1922	5	5	2
1924	6	6	3

If the behavior of Acala cotton during the years from 1921 to 1926 can be looked upon as being in any way indicative of what the future behavior of this variety might be in years marked by high average summer temperatures, it is then desirable to look into the records of the summer temperatures in years past. The mean maximum summer temperatures for the years from 1908 to 1926 are shown in Table 14. During the 19-year period there are but six summers with maximum temperatures averaging less than 100° F., and on such a basis the promise of future good Acala years would become a matter of great uncertainty. Mean maximum temperatures, however, do not furnish a wholly satisfactory basis for yearly comparisons, since the same mean maximum temperature in one year may represent fairly uniform conditions, whereas in another year it may be the result of wide fluctuations above and below the mean, the first year proving highly favorable and the second year more or less disastrous. Maximum temperatures above 110° are not uncommon at Sacaton.

TABLE 14.—*Mean maximum temperatures at Sacaton, Ariz., during June, July, August, and September, 1908 to 1926*

Year	June	July	Aug.	Sept.	Mean	Year	June	July	Aug.	Sept.	Mean
	° F	*° F*	*° F*	*° F*	*° F*		*° F*	*° F*	*° F*	*° F*	*° F*
1908	101.9	102.4	102.2	98.8	101.3	1919	100.6	97.7	99.5	93.2	97.8
1909	103.6	103.2	101.2	97.4	101.4	1920	101.0	101.0	99.0	98.0	99.8
1910	104.9	106.2	104.6	103.4	104.8	1921	100.9	98.6	96.4	96.3	98.1
1911	103.2	99.3	102.8	98.7	101.0	1922	103.6	102.6	101.1	98.2	101.4
1912	104.1	101.4	100.2	97.7	100.9	1923	99.8	100.2	96.9	94.7	97.9
1913	100.9	103.2	104.2	100.9	102.3	1924	103.7	102.0	103.5	99.0	102.1
1914	102.5	103.1	104.1	100.2	102.5	1925	98.0	102.0	98.2	93.9	98.4
1915	103.9	105.1	106.0	100.5	103.9	1926	103.6	102.5	100.7	96.2	100.8
1916	105.9	105.7	103.4	99.7	103.7						
1917	103.6	102.0	99.9	95.7	100.3	Mean	102.5	102.0	101.1	97.9	100.9
1918	101.9	100.1	97.1	97.9	99.3						

That the relation between temperatures and yields of Acala cotton is not confined to Sacaton, on the Gila River, but has also been noted in the neighboring Salt River Valley, was brought to the attention of the writer by a statement of S. H. Hastings, formerly superintendent of the Sacaton station, now ranch manager of the Southwest Cotton Co. Records of yields on comparable land on the ranches of this company showed that the Acala variety produced less cotton in 1924 and 1926 than in 1923 and 1925. Mr. Hastings has found poor Acala years to be better Pima years, with the year-to-year fluctuations in the Acala yields greater than the fluctuations in Pima yields.

The yields shown by King and Leding (*23*) for a number of upland cottons grown at Sacaton in the years from 1920 to 1924 indicate that the upland yields obtained in 1922 were lower than in the cooler years of 1921 and 1923, with the exception of a low Durango yield in 1921. The yields of the upland varieties, Hartsville, Durango, Acala, Lone Star, and Mebane, were distinctly higher in 1923 than in the hotter years 1922 and 1924.

The differences in the temperatures of wilted and turgid leaves have been found to be proportional to the corresponding differences in the transpiration rates. Between turgid and severely wilted leaves the temperature differences were found to be as great as 5.5° C. (approximately 10° F.), and differences between the temperatures of Pima and Acala cotton leaves approximately half as great were observed. The water requirement of Pima cotton was found to be considerably higher than that of Acala cotton at Sacaton in 1926, which, with the leaf-temperature difference, strongly suggests a higher transpiration rate. If higher water-requirement values are in part indicative of higher transpiration rates and in turn of lower leaf temperatures, then it follows that under irrigation in the regions characterized by excessive temperatures a high water requirement may be a more desirable character than a low water requirement. There are limits to the desirability of this, however, since during hours or seasons when excessive temperatures do not prevail photosynthesis would be expected to proceed more rapidly in warmer rather than in cooler leaves.

Under field conditions a plant growing in a deep, open soil with a high water-holding capacity should show less frequent water-stress symptoms than a plant in a poor or shallow soil. Likewise a plant with a highly developed root system should be at an advantage over a plant which had made an excessive vegetative development without a corresponding extension of its roots. It would also follow that leaf temperatures on clear days would be higher during humid periods than during dry periods.

In the foregoing paragraphs of this section the yields of Acala upland and Pima Egyptian cotton have been compared with the mean maximum summer temperatures. In presenting these data it was fully appreciated that no single expression could adequately summarize the intensity of the climatic factors and that all of the elements making up a climate, though their fluctuations may be correlated, affect plant growth individually and that plant growth is likewise influenced by soil variables and by cultural treatments. It is also clearly recognized that the results of measurements of a single physiological variable can not be expected, in general, to throw very much light on plant behavior. However, in a region characterized by excessive temperatures it seems logical that the temperatures of the leaves of crop plants should furnish at least one measure of their relative ability to adjust themselves to such an environment. When comparative yields show that a variety characterized by high leaf temperatures has behaved unsatisfactorily in a number of years marked by high summer temperatures, whereas a variety with lower leaf temperatures has shown no relation between its yields and maximum temperatures, the facts suggest that the differences in yields are associated with the observed differences in their leaf temperatures.

SUMMARY AND CONCLUSIONS

This bulletin deals with the leaf temperatures of the cotton plant in the Southwest. The experimental plants were grown at Sacaton, Ariz., as a part of a water-requirement series.

The leaf-temperature measurements were made by the thermoelectric method, in terms of the departures of the leaf temperatures from the temperature of the air. In measuring leaf temperatures a leaf was folded upward in such a manner that two portions of the upper leaf surface were brought firmly together over one junction of the thermocouple, while the second junction, freely exposed to the air, was protected from the direct rays of the sun by two slightly separated slips of white paper. The thermocouples were connected by long extension wires to a galvanometer permanently mounted on a screened porch overlooking the experimental plants.

Leaves selected for similar exposure and age were found to vary in temperature. The variations were, in general, greatest during the hours of highest transpiration and of greatest intensity of climatic factors. The standard deviation of a series of 48 cotton leaves selected for similar exposure each hour throughout a day ranged from 0.301° to 1.280° C.

An average difference of 2.0° C. was found between cotton leaves nearly normal to the sun and leaves at an angle approaching 90° from the normal position.

Young leaves were found to be cooler than old leaves. A mean difference of 1.4° ± 0.25° C. was found in the temperature of leaves differing in age by three to five weeks.

A maximum mean difference of 5.5° C. was found in the temperature of wilted and turgid Acala cotton leaves.

It was found by calculation from leaf-temperature differences that approximately 40 per cent of the energy required for the transpiration of cotton plants in mid-afternoon at Sacaton was derived from radiations intercepted by the leaf.

A correlation coefficient of —0.929 ± 0.025 was found between the differences in the leaf temperatures and the differences in the transpiration rates of turgid and wilted Acala cotton plants.

The temperatures of turgid Pima Egyptian cotton leaves were found to be lower at each hour of the day before sunset than the temperatures of turgid Acala upland cotton leaves, with the greatest differences during the hours of highest transpiration rates. There were no significant differences in the hourly fluctuations in the transpiration rates of Pima and Acala cotton when these were expressed as the hourly percentage of the day's total.

Wilted Pima cotton leaves were found to be cooler than wilted Acala cotton leaves when the two varieties were growing in the same cans.

Turgid Pima Egyptian cotton leaves were cooler than turgid Acala upland cotton leaves by an average of 2.44° C. in 10 comparisons. The mean difference for the 10 comparisons was seven and five-tenths times the probable error.

During the middle of the day, when fully exposed to the light, the Pima leaves were found to have mean temperatures ranging from 2.0° to 5.3° C. below air temperature. The mean temperatures of Acala leaves during the same hours varied from +0.2° to −2.5° with respect to air temperature.

The leaves of okra-leaf Acala cotton were cooler than the leaves of Acala cotton in five out of six comparisons by 1.02° C., with an average difference of two and five-tenths times the probable error for the six comparisons.

The leaves of Acala cotton plants grown under a muslin shade were cooler than the leaves of freely exposed plants by 1.92° C., with an average difference of seven times the probable error for the five comparisons.

Leaves of whitewashed Acala cotton plants were cooler than leaves of untreated Acala cotton by 3.06° C., with an average difference of nine and five-tenths times the probable error for the five comparisons.

Leaves of Acala cotton plants growing in a saline soil were warmer than the leaves of Acala cotton growing in a control soil by 0.83° C., with an average difference of three and three-tenths times the probable error for the three comparisons.

The leaf temperatures of the different cotton varieties and of the Acala cotton under different treatments were compared with the water requirements of the same plants. While some evidence of a negative correlation was found, such a relationship would always be uncertain, since a water-requirement value is made up of two variables, only one of which affects leaf temperatures.

Attention is called to the fact that over a 6-year period the yields of Acala upland cotton have been relatively low at Sacaton during those years marked by an average maximum summer temperature above 100° F. The Acala yields averaged 40 per cent greater during the three cooler years than during the years with average maximum summer temperatures above 100°. During the same 6-year period, the alternate years of which had mean maximum summer temperatures above 100°, the yields of Pima Egyptian cotton fluctuated less, and the fluctuations showed no relationship to the mean maximum temperatures of the summer. The correlation of rank between the yearly mean maximum summer temperatures (lowest to highest) and the yields of cotton (highest to lowest) for Acala was 0.97 ± 0.02 and for Pima 0.085 ± 0.08. It appears probable that the differences in the yields of Acala upland cotton in the years of higher and lower summer temperatures as compared to the yields of Pima Egyptian cotton are associated with the differences found in leaf temperatures of the two cottons. It is pointed out that in a 19-year period there have been but 6 years with average maximum summer temperatures below 100° at Sacaton.

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