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CANOPY AIR TEMPERATURES AND EVAPOTRANSPIRATION FROM IRRIGATED AND STRESSED SOYBEANS*

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ABSTRACT

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Soil-water stress as it affects the plant-water status and crop production is becoming increasingly important. When soil-water stress is severe, partial closure of the stomates causes a repartitioning of the incident energy, often resulting in increased temperatures. The effect of soil-water stress on air temperatures within a soybean canopy was studied and the increased air temperatures related to decreased evapotranspiration and plant-water stress. One treatment of soybeans was trickle-irrigated when the matric potential at the 15-cm depth was equal to —0.2 bar. Air-temperature profiles were measured in both irrigated and nonirrigated field-grown soybeans, using calibrated thermistors. Evapotranspiration was measured using a portable chamber. Plant-water status was evaluated indirectly through the use of LVDT's (linear variable displacement transducers). The measured stem-diameter changes were related to the air temperature differences in the irrigated and nonirrigated canopies. The data showed as soil-water stress became more severe, canopy air temperatures within nonirrigated soybeans increased above those within the irrigated soybean canopy. The above-canopy minus the within-canopy temperature difference between the irrigated and nonirrigated plots increased during peak radiation with little difference at night. When the plant-wilt symptoms indicated severe stress, evapotranspiration decreased 40—70% when within-canopy air temperatures increased. This increase in the canopy air temperature was related to stem-diameter shrinkage and may be an indirect measure of the plant-water status under field conditions.

INTRODUCTION

An increase in plant temperature will result in an increase in air temperature within the canopy when there is little turbulent mixing. Tanner (1963), who found significant differences between the leaf and air temperature for

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irrigated and nonirrigated potatoes, was among the earliest to use the infrared thermometer to determine leaf and air temperature differences as a result of soil-water stress. His data suggested that plant temperatures may be a valuable qualitative index to differences in plant-water stress and that this temperature difference may be a qualitative measure of transpiration differences as a result of soil-water stress.

Wiegand and Namken (1966) reported that cotton-leaf temperatures at midday of well-watered plants exposed to full radiation were 1—2° C higher than the air temperature under the subhumid conditions in Texas. Increasing plant-water stress, as indicated by a decrease in the relative water content of the leaves from 83 to 59% under similar radiation conditions, caused the leaf temperature minus air temperature differential to increase by 3.6° C. Linacre (1964, 1967) presented an extensive survey of published data for well-watered plants exposed to bright sunshine at midday. Some of his results indicated that the temperature difference can be as large as 15° C. Bartholic et al. (1972) observed leaf temperature minus air temperature differences of up to 6° C between the most and least water-stressed plots. A temperature difference of 1—2° C was associated with leaf-water potential of —17 bars, whereas the larger temperature differences were associated with leaf-water potentials ranging from —19 to —24 bars on the driest plots.

At midday the temperature of fully exposed leaves near the surface of well-watered canopies will be slightly below air temperatures in arid or semiarid climates and slightly above air temperatures in humid climates. Palmer (1967) reported cotton-leaf temperatures were about 1° C below air temperatures under well-watered conditions and 3—4° C higher than air temperatures under nonirrigated conditions in the semiarid regions of Australia.

Leaf temperature may be an indirect measure of plant-water stress and a good indicator of when to initiate irrigation. If leaf temperatures increase as a result of plant-water stress, it would then seem reasonable, with minimum advection, that the air temperature within the closed canopy would also increase. Little information is available on air temperature profiles within stressed and nonstressed soybean *(Glycine max* (L.) Merr.) canopies and on the relationship between the difference in air temperature or leaf temperature to a decrease in evapotranspiration (ET) resulting from soil-water stress. Thus, our objectives in this study were to determine the effect of soil-water stress on air temperature profiles in a soybean canopy and to relate the increased air temperatures to decreased ET and plant-water stress.

METHODS AND MATERIALS

Soybeans were grown on a Norfolk loamy sand soil (Typic Paleudult). The plots were prepared by applying 336 kg/ha of 0-20-20 fertilizer on 22 March 1976, and then plowing to a depth of 25 cm. On 6 May, 560 kg/ha of 8-24-24 fertilizer was applied and disked in. On 10 May, Trifluralin was applied at the rate of 2.3 1/ha before planting, according to South Carolina Experiment Station recommendations, and disked in. The experimental design consisted of a modified randomized block replicated four times. Each plot consisted of four rows 102 cm wide and 16.4 m long. Four varieties, Ransom, Coker 136, FFR666, and Bragg were planted on 21 May, 1976 (day 142).

Irrigation was applied when the soil matric potential at the 15-cm depth in the irrigated plot of the Ransom variety reached −0.2 bar. The water was applied through Anjac Bi-wall* tubing placed alongside the rows after the soybeans had emerged. Water was applied on demand when any one of three electric tensiometers connected in parallel indicated −0.2 bar. A total of 6 mm/day was applied automatically four times daily and was assumed to be the average ET rate during most of the growing season. Additional water was applied twice when the tensiometers showed significant drying at the 30-cm depth.

Tensiometers were installed in the Ransom and the Coker 136 varieties in both the irrigated and nonirrigated treatments at 15-, 30-, 46-, 61-, 91-, 122-, 153-, and 175-cm depths. The tensiometers were connected to mercury manometers for precise reading of hydraulic head. The group of tensiometers, located in the center of each of the plots, was read three times weekly and more frequently during periods of rainfall.

Air temperatures within the plant canopy were measured hourly, using calibrated thermistors, and recorded on a data acquisition system. The temperatures were measured at 10 cm below the soil surface and 10, 20, 30, 60, and 120 cm above the soil surface within the canopy of the Ransom variety. The thermistors were mounted in two concentric cylinders to shield them from direct radiation. The shields were 30 cm long and consisted of a 5.1-cm ID aluminum-tube inner cylinder and a 6.4-cm ID white PVC-tube outer cylinder. The air temperature sensors were set in the canopy on 9 July 1976 (day 192) when the plants were about 50 cm tall, and the canopy had about 90% full cover.

On selected days during the growing season, ET was measured with the portable chamber described by Reicosky and Peters (1977). The subplots for ET measurements were premarked so the outside edge had at least 2 m of border. Measurements were made sequentially across all treatments in replicates 2 and 3 for comparison with the microclimate data.

Other microclimatological variables, measured over a well-watered grass plot and recorded hourly, included solar radiation, net radiation, open-pan evaporation, air and dew point temperatures at 2-m height, wind velocity and direction at 2-m height, soil heat flux at 5-cm depth and soil temperature at 10-cm depth. Potential ET was calculated using the Combination Method after Van Bavel (1966).

*Mention of trade names does not imply endorsement by USDA or the South Carolina Experiment Station and is included only for the benefit of the reader.

Linear variable displacement transducers (LVDT) for stem-diameter measurements were mounted on representative plants in the irrigated and nonirrigated Ransom and Coker 136 varieties. Stem diameter was monitored with a Trans Tek Model 241-000, DC-DC, LVDT mounted about 20 cm above the soil surface. An excitation voltage of 24 V was used resulting in an LVDT output of about 3.5 V/mm. The output of the LVDT's was recorded hourly on a data acquisition system.

Biomass samples for the Ransom variety were taken weekly after the plants were about 30 cm tall. Biomass was selected by randomly measuring 0.5 m length of row and taking all plants in that section from four replications of the irrigated and nonirrigated plots. The biomass included the complete stems, leaves, and pods when they were on the plants at the time the samples were taken. The fresh and dry weights were determined and the plants were counted so that the biomass could be calculated on the per unit area basis and on a per plant basis.

RESULTS AND DISCUSSION

The irrigation and precipitation during the 1976 growing season are summarized in Fig.1. Rainfall was above normal from day 130 to 189 and then below normal rainfall until day 295. The total rainfall from day 184 to 189 (71 mm) was sufficient to completely recharge the profile. The last

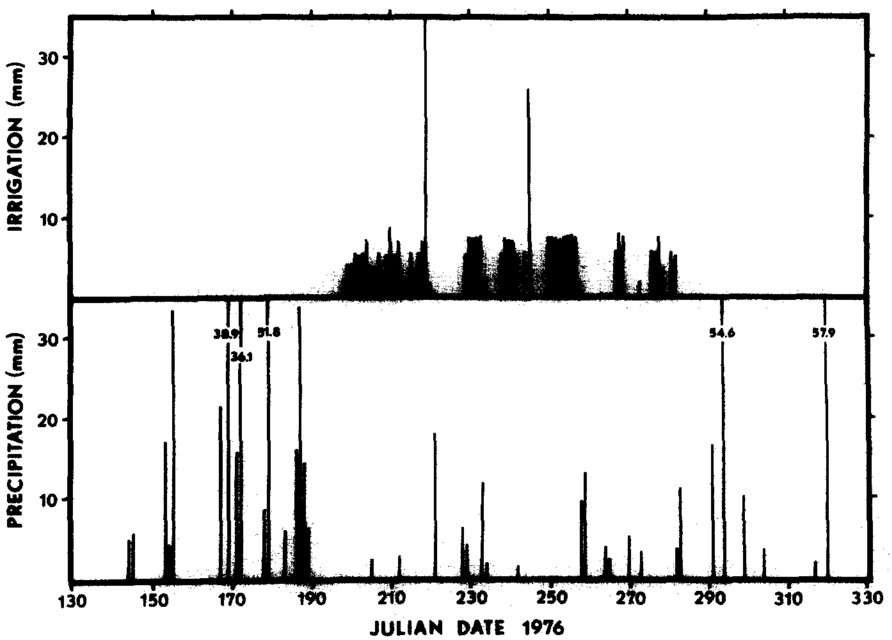

Fig.1. Summary of the irrigation and rainfall during the 1976 growing season.

day with significant rainfall on the nonirrigated plots before the drought was day 189. Irrigation application was initiated on day 198 and was uniform up to day 221 when 16.7 mm of precipitation fell. From day 210 to 219, the evaporation rate was higher than 6 mm/day and resulted in a net decrease in soil water. Hence, 33 mm of irrigation was applied to wet the upper portion of the profile on day 219.

The plant biomass for the Ransom variety as a function of time is summarized in Fig.2. After day 230, data points for irrigated plant biomass separated from those for the nonirrigated plants. If we assume leaf area and canopy development are related to biomass, then observed differences in canopy temperatures up to this date should be the result of water stress and not canopy development. After day 230, the cumulative effect of the drought may have altered the nonirrigated plant canopy enough to cause the canopy air temperatures to be different.

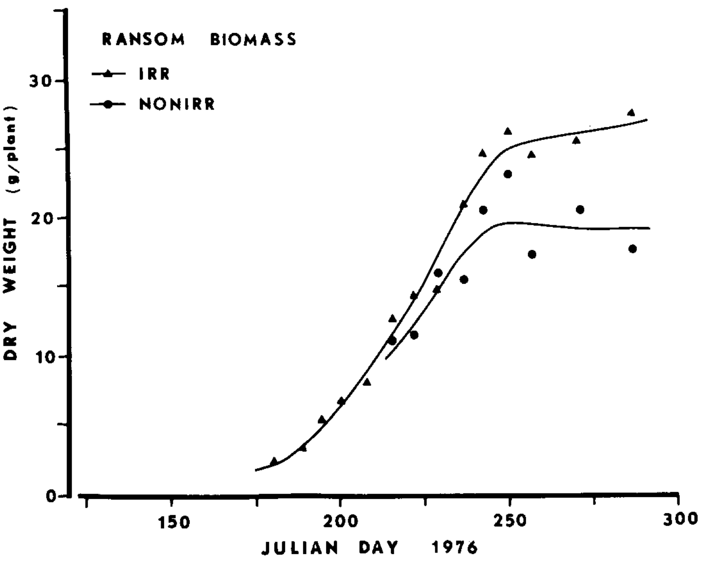

Fig.2. Plant biomass as a function of time for the irrigated and nonirrigated Ransom soybeans.

Because of the large amount of data obtained and the small temperature gradients within canopies, we selected the temperatures at the 20-cm height to show the difference in the air temperature between the irrigated and nonirrigated treatments. The air temperature profiles within the canopy were nearly vertical with little gradient as long as the sensors were located below the top of the canopies. Figure 3 shows the effects of irrigation on the air temperature within the canopies at the 20-cm height for selected days during the drought. On day 193 (3 days after the last significant rainfall), there was

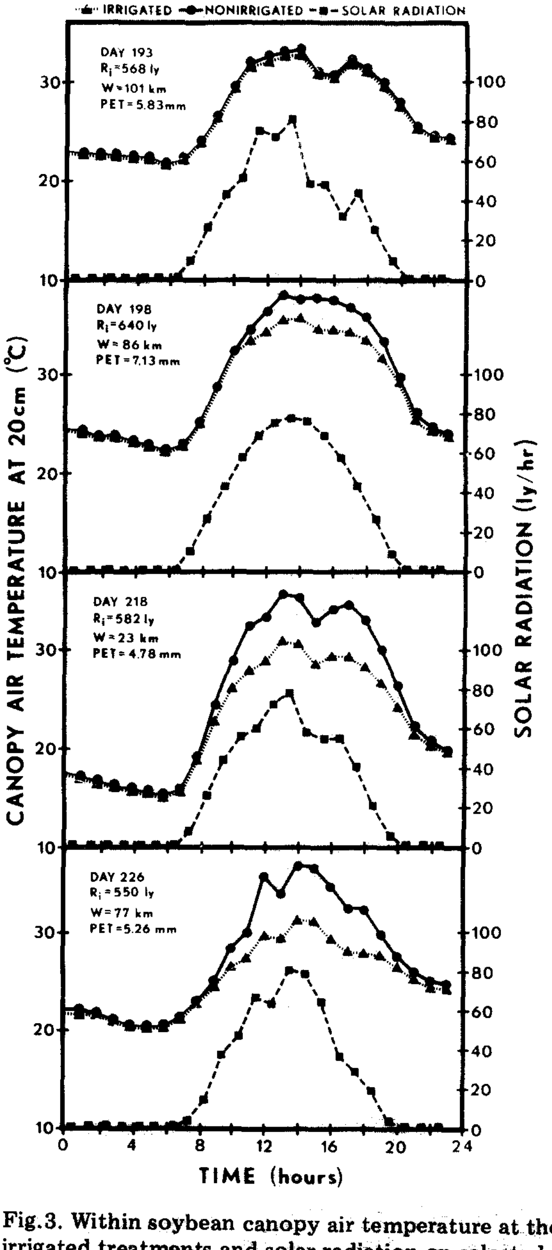

Fig.3. Within soybean canopy air temperature at the 20-cm height in irrigated and non-irrigated treatments and solar radiation on selected days during the drought. R_i = solar radiation, W = wind run, and PET = potential evapotranspiration — all are daily values.

no difference in the magnitude and in the pattern of the irrigated and non-irrigated canopy air temperatures. However, on day 198, the first irrigation was applied and there was a temperature difference between the irrigated and nonirrigated treatments. From day 198 to 221, the differences between air temperatures in the irrigated and nonirrigated treatments were related to solar radiation. The largest difference was 5.5°C on day 204 when the daily solar radiation was 585 ly. These data showed the effect of progressive drying as the plants extracted water and were stressed under the high radiation levels.

Differences between the canopy air temperatures at the 20- and 120-cm heights in the irrigated and nonirrigated treatments are shown in Fig.4. From day 193 to 198 before the first irrigation, both the irrigated and nonirrigated canopies had temperature differences, probably associated with canopy development. However, after day 198, the increasing soil-water stress resulted in consistent temperature differences between the 20-cm and the 120-cm heights on the nonirrigated treatment. A maximum temperature difference of 5.8°C was measured on the nonirrigated treatment on day 206, whereas the difference on day 208, a low-radiation day, was less than 1°C. For the irrigated treatment, the temperature differences were less than 2°C during the same period. These data suggested that differences in temperature between the within canopy and the above canopy (at full canopy) may be an indirect measure of plant-water stress and useful criteria for initiating irrigation.

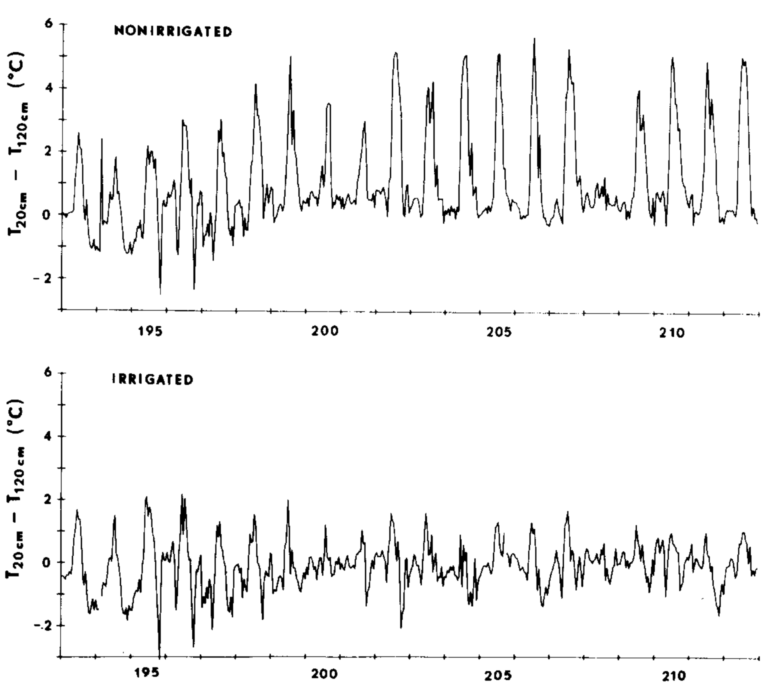

Fig.4. Soybean canopy air temperature differences between the 20- and 120-cm height in the irrigated and nonirrigated treatments as a function of time.

Temperature profiles within the canopy for times near the minimum and maximum canopy air temperatures on selected days are summarized in Fig. 5. On day 193, there was no difference between the temperature profiles for both the irrigated and nonirrigated treatments at 0500 and 1500 hr.

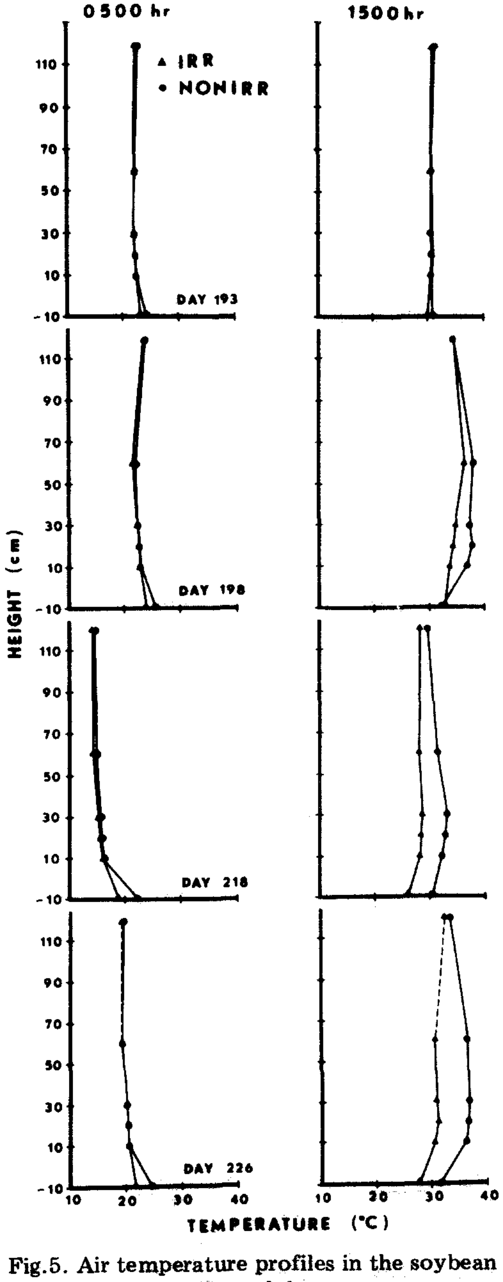

Fig. 5. Air temperature profiles in the soybean canopies near the minimum and maximum temperatures on selected days.

However, on day 198, when the irrigation was started, no difference was observed at 0500 hr, while the 1500-hr profile showed a difference of about 3°C at 20 cm. The largest temperature differences ranged from the soil surface to 30 cm and then only a small difference at 60 cm. There was no difference between the air temperature at 120 cm in the irrigated and nonirrigated plots.

The air temperature profiles in Fig.5 showed the temperature differences between irrigated and nonirrigated treatments at 0500 hr on day 218 were negligible with only a 3°C difference in soil temperature. However, at 1500 hr the temperature profiles between the irrigated and nonirrigated treatments separated with a maximum difference of 4.5°C at 30 cm. Both the soil temperature and the air temperature in the nonirrigated treatment canopy were higher. The same trend is shown on day 226 with a maximum temperature difference of 6°C within the canopy. Even though 17 mm of precipitation fell on day 221, the temperature profile 5 days after this rainfall indicated that the plants were again stressed. The cumulative pan evaporation was 29 mm during this 5-day period, which was larger than the 17 mm of precipitation that fell on day 221. These data suggested plants used most of the precipitation and experienced nearly the same degree of stress as on day 218.

The soil matric potential profiles for about the same days as shown in Fig.5. are summarized in Fig.6. After the last significant rainfall, the soil

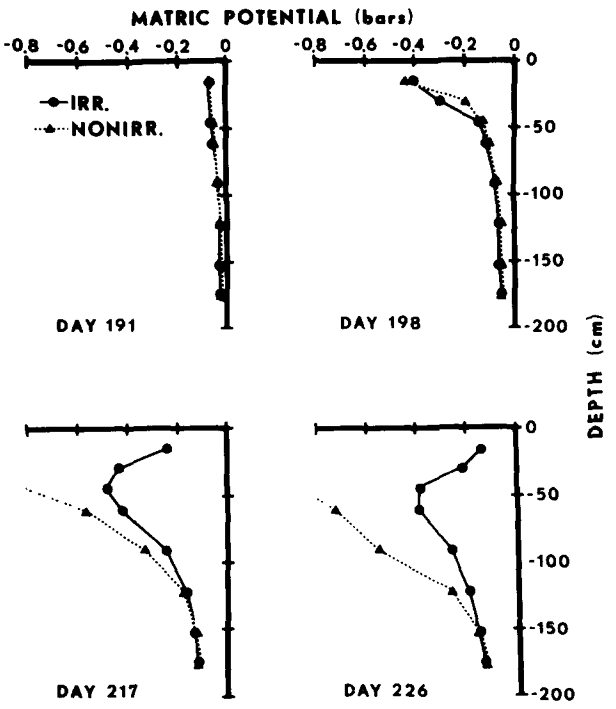

Fig.6. Soil matric-potential profiles in the irrigated and nonirrigated plots of Ransom soybeans corresponding to the days in Fig.5.

profiles were full with no difference between the nonirrigated and the irrigated plots. However, after irrigation was started (day 198), the matric potential in the surface layers was more negative on the nonirrigated plots as a result of the drought. On day 217, the matric potential profiles for the irrigated and nonirrigated treatments were different with the nonirrigated plants extracting water from the 45- to 90-cm depth. On day 226, 5 days after 16 mm of precipitation, the matric potential profiles showed water extraction from the 122-cm depth on the nonirrigated treatment.
Even with irrigation, the data indicated water was extracted at the 45- and 60-cm depth by the irrigated plants, even though the matric potential in the surface layer was maintained near −0.2 bar.

Evapotranspiration and canopy air temperature at 20 cm for 3 days during the dry period are summarized in Table 1. Under high radiation, ET was about 0.6 mm/hr on the irrigated plots, whereas it ranged from 0.13 to 0.38 mm/hr on the nonirrigated plots. The differences in the canopy air temperature of the irrigated and nonirrigated plots corresponding to these ET data ranged from 3.7 to 6.2°C and were associated with a 40–70% decrease in ET on the nonirrigated plots. Day 232 was generally cloudy and had lower ET values on the irrigated plots. The smaller temperature differences on this day were probably associated with the higher average wind velocities during the measurement period that resulted in more turbulent mixing in the canopy. Although the differences in canopy air temperature between the irrigated and nonirrigated plots as a result of soil-water stress were related to a decrease in ET, the relationship was not distinct. These data suggested that wind velocity as well as radiation are important in determining the magnitude of the temperature difference.

Because stomatal closure during high-radiation periods resulted in an increase in leaf and canopy air temperature, we might expect the temperature difference to be related to solar radiation. The temperature differences on this day were probably associated with the higher average wind velocities during the measurement period that resulted in more turbulent mixing in the canopy. Although the differences in canopy air temperature between the irrigated and nonirrigated plots as a result of soil-water stress were related to a decrease in ET, the relationship was not distinct. These data suggested that wind velocity as well as radiation are important in determining the magnitude of the temperature difference.

Horton et al. (1970) related the difference between the canopy surface temperature and the air temperature, as a result of soil-water stress, to plant-water stress as measured by changes in stem diameter. Their data showed a close relationship between the canopy and air temperature difference and the stem-diameter changes which reflected plant-water stress. The change in stem diameters for the irrigated and nonirrigated Ransom soybeans in our experiment on days 216 and 218 are shown in Fig.8. These data showed a larger diurnal change for the nonirrigated treatment, indicating more stress especially on day 218, a high radiation day.

TABLE I

Canopy air temperatures at 20 cm and evapotranspiration from Ransom soybeans during the drought

Day	Treatment	Time	R_I	$T_{20\ cm}$*1	ET	$\Delta T_{20\ cm}$	Decrease In ET
		(hr)	(ly/min)	(°C)	(mm/hr)	(°C)	(%)
Day 218*2	irr.	1131	0.57	28.3	0.35	—	—
	nonirr.	1149	0.41	33.3	0.15	5.0	57
	irr.	1218	1.41	28.8	0.55	—	—
	nonirr.	1107	1.25	32.5	0.16	3.7	71
	irr.	1357	1.49	30.6	0.56	—	—
	nonirr.	1332	1.47	35.5	0.13	4.9	77
	irr.	1620	1.01	29.4	0.50	—	—
	nonirr.	1554	1.07	34.2	0.15	4.8	70
Day 226*3	irr	1454	1.24	31.2	0.60	—	—
	nonirr.	1433	1.26	36.7	0.38	5.5	37
	irr.	1535	1.17	30.1	0.56	—	—
	nonirr.	1511	1.22	36.3	0.34	6.2	39
Day 232*4	irr.	1441	0.77	26.7	0.37	—	—
	nonirr.	1421	0.74	28.2	0.24	1.5	35
	irr.	1527	0.56	26.3	0.32	—	—
	nonirr.	1500	0.79	28.4	0.15	2.1	33

*1 Air temperatures from linear interpolation between hourly values.
*2 Average wind velocity = 3.3 km/hr.
*3 Average wind velocity = 5.9 km/hr.
*4 Average wind velocity = 15.2 km/hr.

The differences between the temperature measured at the 120- and 20-cm heights for both the irrigated and nonirrigated treatments are plotted vs the stem-diameter change on day 218 in Fig.9. The diameter change was calculated in the same manner as that of Huck and Klepper (1977). We assumed a linear growth rate between maximum diameters near sunrise on successive mornings. The difference between this assumed diameter and the actual diameter at any time was considered due to plant-water stress.

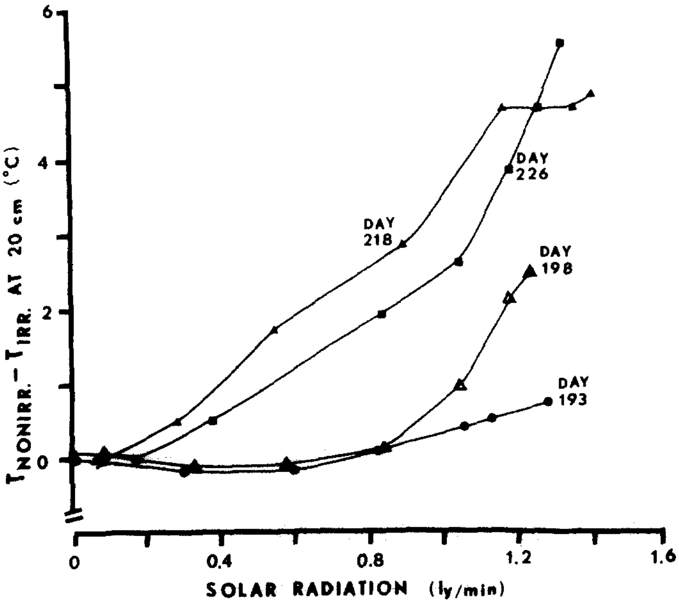

Fig.7. Soybean canopy air temperature difference between irrigated and nonirrigated plots at 20 cm as a function of incoming radiation for various days.

Fig.9 shows the dramatic effect of irrigation on the above-canopy minus the within-canopy temperature difference and stem-diameter change. The values near the data points indicate the hour at which that data point was collected. These data show a smaller hysteresis loop for the irrigated treatment than for the nonirrigated treatment. The point at 1500 hr shows the effect of a cloud passing over (a decrease in solar radiation). The area within the loop reflects qualitatively the integrated stress. The size of the loop is probably a result of a combination of factors that include tissue elasticity, the lag of air temperature behind solar radiation, and soil hydraulic properties. The large diameter changes and temperature differences on the nonirrigated treatment suggest the temperature difference may be an indirect measure of plant-water status. This is in general agreement with the earlier work of Wiegand and Namken (1966), who showed similar results for cotton-leaf temperatures under field conditions.

The evaporative demand had a significant effect on the above-canopy minus the within-canopy temperature difference and diameter change. On day 218, the daily solar radiation was 582 ly and the open-pan evaporation 4.9 mm. For comparison, on day 216, the daily solar radiation was 153 ly and open-pan evaporation 2.5 mm. The hysteretic relationship on day 216 was similar to that on day 218 but the magnitude was much smaller (data not shown). The maximum temperature difference on the nonirrigated

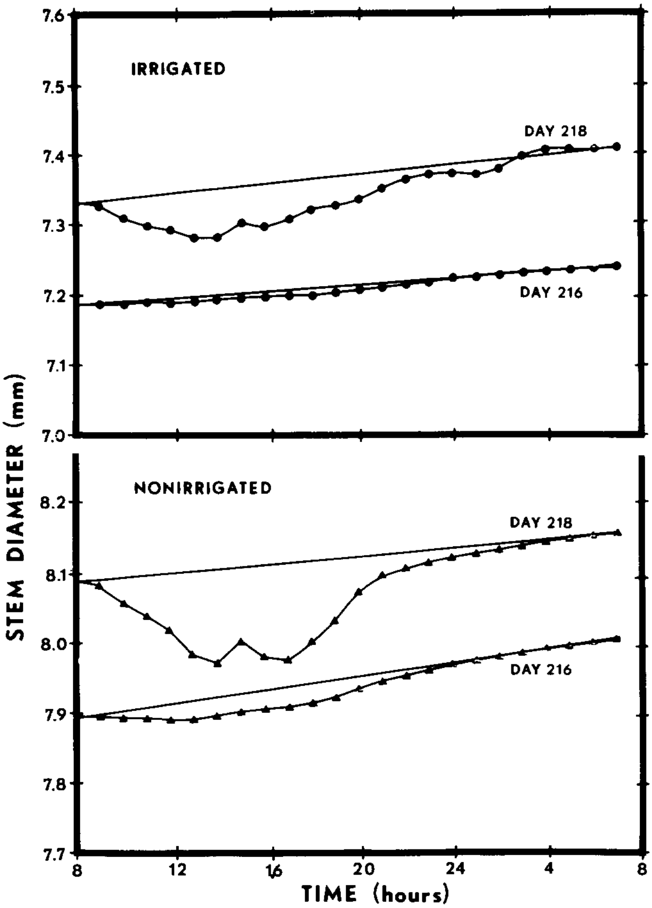

Fig.8. Irrigated and nonirrigated soybean stem diameters as a function of time on days 216 and 218.

treatment on day 218 was 4.7° C, whereas on day 216 the difference was 0.9° C, reflecting the change in evaporative demand.

This work indicated canopy air temperatures may be used as an indirect indicator of plant-water stress. As drought progresses, the within-canopy minus the above-canopy temperature difference between the irrigated and nonirrigated treatment plots increased under peak radiation loads with little difference at night. The close relationship between the temperature difference and the solar radiation suggest stomatal closure by the plants as indicated by decreased evapotranspiration. With appreciable soil-water stress, the energy used in evapotranspiration was dissipated in the form of sensible heat and increased the plant and canopy air temperatures. The 40–70% decrease in ET associated with the 4–5° C increase in the canopy air temperature suggested an indirect measure of decreased ET resulting

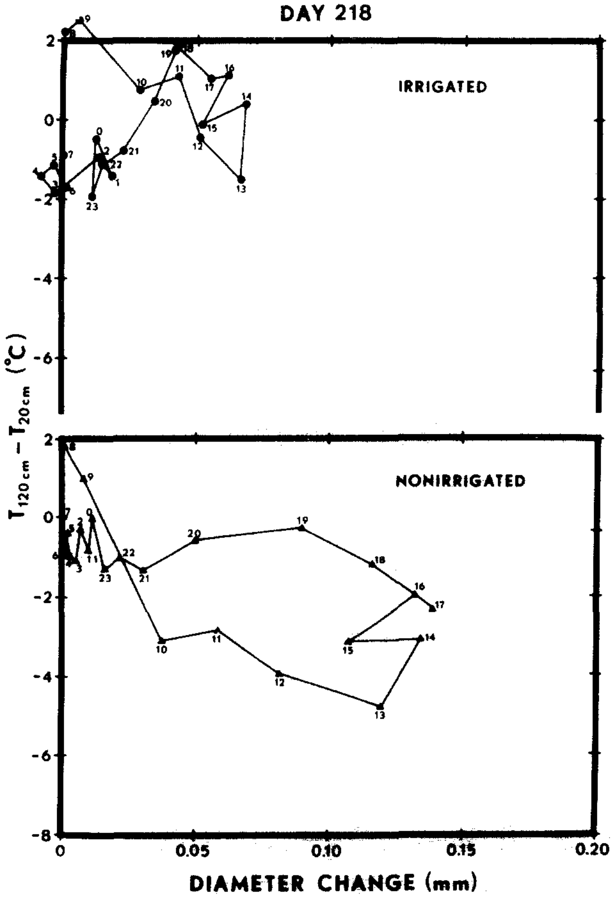

Fig.9. The difference between the above-canopy and within-canopy air temperatures for soybeans as a function of stem-diameter change on day 218.

from soil-water stress. This analysis is valid only when canopy cover is complete as was the case in this work. For developing canopies other critera are needed.

The increase in canopy air temperature was related to the stem-diameter shrinkage and indicated changes in plant-water status. The increase in canopy air temperature was an indirect measure of the plant-water status under these conditions. Our results suggest a need for more work evaluating the effect of irrigation on the air temperature within the canopy and whether this would be a valid criterion for initiating an irrigation system in the humid Southeast.

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