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PLANT AND AIR TEMPERATURES IN DIFFERENTIALLY-IRRIGATED CORN*

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ABSTRACT

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Studies by Jackson et al. (1977) and Idso et al. (1977) indicate that wheat is not stressed for water unless leaf temperature exceeds air temperature. One objective of the study reported here was to determine relationships between leaf temperature and air temperature within corn canopies as a function of water stress. A second objective was to evaluate effects of varying levels of plant water stress on crop temperature. A third objective was to establish the relationship between plant water stress and crop temperature in corn (*Zea mays* L.) with the aim of providing practical water resource management tools.

Meteorological, physiological and phenological measurements were made in nine plots of corn, grown on Valentine fine sand (Typic ustipsamment) at the Sandhills Agricultural Laboratory located near Tryon, Nebraska. Each plot received one of seven different irrigation treatments. Canopy temperatures were measured with an infrared thermometer at midday throughout the growing season. Air and leaf temperature measurements were made on an hourly basis with thermocouples. Physiological and phenological observations were made weekly.

The average midday difference in canopy temperature between stressed and non-stressed areas was as large as 7.0°C. In fully-irrigated plots, the standard deviation of midday canopy temperature was about 0.3°C but in non-irrigated areas it reached, at times, 4.2°C. It is concluded that a standard deviation of temperature in a plot exceeding 0.3°C signifies that some plants are experiencing water stress. This behaviour can indicate the need for irrigation.

Daily profiles of leaf and air temperature in stressed and non-stressed canopies were found to be similar. Profiles tended to be lapse before crop cover was complete and inverted later in the season. At any level within the stressed canopy, plants were warmer than at the same level within the non-stressed canopy. The midday temperature of sunlit leaves of non-stressed and moderately stressed plants was generally 1-2°C below air temperature. The temperature of sunlit leaves in severely stressed plants was as much as 4.6°C above air temperature. It was observed that corn plants may be subject to water stress and still be cooler than air temperature.

INTRODUCTION

Leaves of moisture stressed plants have been found to be warmer than those of non-stressed plants. Temperature differences between stressed and

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stressed leaves reported for various crops range from +2 to +8°C (Miller, 1963; Eaton, 1929; Millar et al., 1971; Ehrler et al., 1978).

Wiegand and Namken (1966) found that the difference in temperature between stressed and non-stressed cotton (*Gossypium hirsutum* L.) leaves ranged from 2.5 to 4.5°C when solar radiation flux density was 200 W m⁻² to 1100 W m⁻², respectively.

Wanner (1963) suggested that the temperature difference between stressed and non-stressed potato (*Solanum tuberosum* L.) leaves gives a qualitative indication of the differences in transpiration. He concluded that with a better understanding of heat and vapor transfer processes at the plant surface, leaf temperature measurements may provide quantitative data on plant water status.

Ehrler (1973) stated that long-term measurements of leaf temperature provide an indirect indication of stomatal behavior. Ehrler et al. (1978) demonstrated that canopy temperature in wheat increased as plant water potential decreased. Differences in canopy temperature between stressed and non-stressed wheat plants were shown to be a reliable indicator of plant water status.

Clark and Hiler (1973) found that stomatal resistance in peas (*Vigna sativa* L.) increased as moisture stress developed, resulting in increased leaf temperature. They concluded that the status of water in plants represents an integration of the atmospheric demand, soil-water potential, rooting density, soil distribution and other plant characteristics, as well. Thus, for a true measure of plant water deficit, measurements should be made on the plant surface rather than in the soil or the atmosphere.

Winstanley and Van Bavel (1972) and Nixon et al. (1972) suggest that a large variability in canopy temperature should signal the onset of water deficits due to the inhomogeneous soil moisture retention properties in large fields. Ehrler (1973) and Ehrler et al. (1978) showed that the differential in leaf—canopy temperature can be used to signal the need for irrigation. Ritchie (1977) suggested using the temperature difference between stressed and non-stressed plants to detect the occurrence of soil water deficits.

In view of the above-stated findings a study was designed with the following objectives: (1) to evaluate the effects of varying levels of plant water stress on crop temperatures; (2) to establish the relationship between plant water stress and crop temperature in corn with the aim of providing practical water resource management tools (e.g. irrigation scheduling, drought surveillance); and (3) to determine the relationships between leaf temperature and canopy temperature within corn canopies as a function of water stress.

METHODS AND MATERIALS

The study was conducted at the University of Nebraska Sandhills Agricultural Laboratory, located near Tryon, Nebraska (41°47'N; 100°50'W; 975 m above m.s.l.). Details of the experimental site and research procedures are given in Blad et al. (1981a).

TABLE I

The seven irrigation treatments used for the study

Treatment	Growth stage		
	Vegetative	Pollination	Grain filling
1	G	I	I
2	I	G	I
3	I	I	G
4	G	I	G
5	I	G	G
6	G	G	G
7	G	G	I

(I) all rows in a plot received a full irrigation during that growth period. (G) an irrigation gradient was established so that one side of the plots received 100% of its water need while the opposite side received essentially one of its needs.

Seven irrigation treatments (Table I) based upon combinations of two basic irrigation procedures were imposed on plots of corn (*Zea mays* L. cv Pioneer 3780) planted in 0.75 m rows (the plots were 24 rows wide). Full irrigation (I) consisted of resupplying by irrigation 100% of the water used to all rows in a plot. The amount of water to be supplied through irrigation was determined by measuring soil moisture depletion with a neutron probe. Gradient irrigation (G) consisted of applying full irrigation to row 1 of a plot and applying progressively less water to each succeeding row, until rows 2 through 24 received essentially no irrigation.

Canopy temperatures were measured daily with an infrared thermometer (IRT) between 1200 and 1330 solar time on rows 2, 6, 10, 14, 18 and 22 of each plot. Readings began on June 1 and continued throughout the growing season, except for a few days when measurement was not possible. Two infrared thermometers were used. A Telatemp model 44 was used between June 13 and July 17. A Barnes model PRT5 was used for the remainder of the season. The area viewed by the IRTs was calculated to be about 2 m² (2 m × 0.95 m). The viewing angle decreased from about 22 to about 10 degrees from the horizontal as the crop increased in height.

In one plot (hereafter, called the instrumented plot), air and leaf temperatures were measured at three different levels within the canopy in rows 2, 6, 10, 14, 18 and 22. The bottom, middle and top of the canopy were designated as levels 1, 2 and 3, respectively. The thermocouples in levels 2 and 3 were raised as the crop grew. The crop reached its full height by July 26 and no further adjustments in instrument height were made after that date.

Leaf temperatures were measured at each level with a set of 5 or 6 evaporative constantan thermocouples (0.13 mm diameter) which were wired in parallel. The junctions of each thermocouple were distributed among a number of different leaves. They were taped to the lower surfaces using the method described by Blad et al. (1981b).

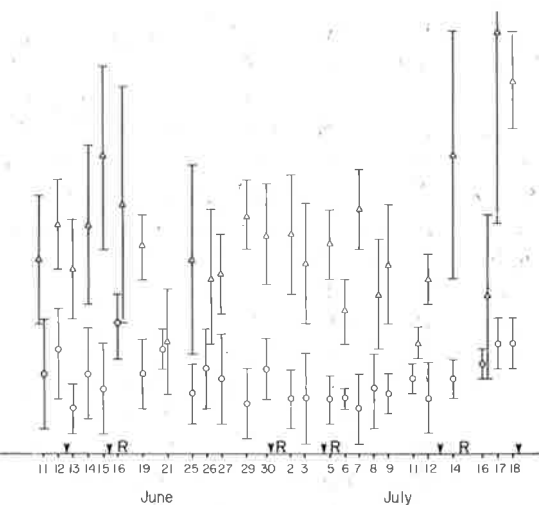
copper-constantan air thermocouples, embedded in 6 mm diameter teflons to dampen rapid fluctuations in air temperature, were placed at level one air thermocouple was also mounted permanently in row 2 at a height 3 m above ground. Air thermocouples were radiation shielded with a par-coated shield 80 mm in diameter.

RESULTS AND DISCUSSION

Temperature differences between stressed and non-stressed areas

The average midday IRT-measured temperature difference between row 22 and row 2 (notated as $*T_{22} = T_{22} - T_2$) was larger on gradient (G) plots than on fully irrigated (I) plots during the vegetative (Fig. 1), the pollination (Fig. 2) and the grain-filling (Fig. 3) periods.

The standard deviation of $*T_{22}$ (designated σ_T), which represents the day spatial variability in canopy temperature, averaged 1.0°C on I plots and 1.2°C on G plots prior to mid-July when nearly full plant cover was developed. Thereafter σ_T decreased to 0.3°C on I plots but remained about 1.0°C on G plots (Table II), though on some days σ_T on G plots was as high as 4.2°C . The large temperature variability in the G plots results from microscale variations in soil water retention characteristics and from differences in the amount of irrigation applied to row 22 during various growth stages. In some G plots row 22 was fully irrigated during a previous growth period but in other plots it received no irrigation. On several days



1. The average difference in midday canopy temperature between row 22 (stressed, triangles) and row 2 (non-stressed, circles) on plots receiving a gradient treatment and in fully irrigated plots during vegetative growth. Standard deviation of each data point is indicated with a bar. The occurrence of rainfall is indicated with an R and irrigations are indicated with arrows.

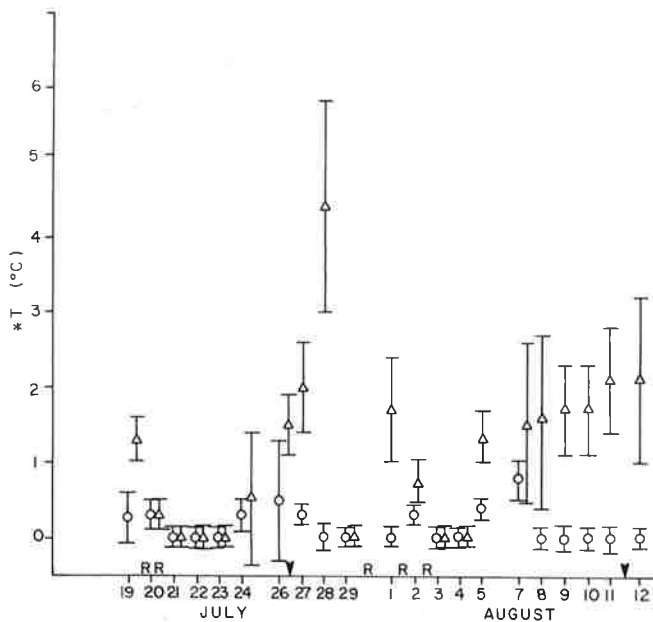


Fig. 2. As Fig. 1 but for the pollination period.

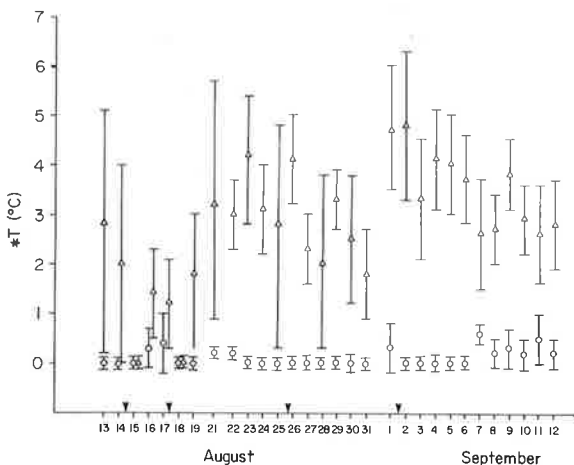


Fig. 3. As Fig. 1 but for the grain-filling period. The low $*T$ and σ_T value for the stre plots on August 18 was due to cool overcast weather.

during the pollination period σ_T was small because of cool, cloudy and weather.

Rainfall or irrigation caused minor reductions in σ_T during much of the vegetative period. During the late vegetative, pollination and grain-filling periods σ_T on well-irrigated plots increased prior to irrigation and showed a significant reduction after irrigation on July 13, July 26, August 17 and September 1

average midday temperature differences between row 22 and row 2 ($*T_{22}$) for the different growth stages of fully-irrigated (I) and gradient (G) plots. (The standard deviation of $*T_{22}$ (σ_T) is also given. $*T_{22}$ and σ_T were computed using data for all days and using clear-day data only)

of	I Plots		G Plots	
	$*T_{22} \pm \sigma_T$ (All daily values)	$*T_{22} \pm \sigma_T$ (Clear days only)	$*T_{22} \pm \sigma_T$ (All daily values)	$*T_{22} \pm \sigma_T$ (Clear days only)
ative	0.4 \pm 0.8	0.2 \pm 1.0	2.9 \pm 1.3	2.7 \pm 1.2
tion	0.2 \pm 0.3	0.2 \pm 0.3	1.2 \pm 1.1	1.8 \pm 1.0
illing	0.1 \pm 0.2	0.2 \pm 0.3	2.8 \pm 1.2	3.1 \pm 1.1

the oblique IRT viewing angles used in this study, values of σ_T above 1.0°C occurred when some plants began to experience water stress. This result compares favorably with the findings of Heermann and Duke (1978) who found that σ_T was about 0.2°C in well-irrigated corn when the IRT was taken at oblique viewing angles. At vertical viewing angles they observed that σ_T was approximately 1.5°C.

On the basis of these findings, it appears that the irrigations on July 13, July 26 and August 17 were one or two days too late to prevent stress in the gradient watered plots. The irrigation of September 1 was timely — applied as it was in the evening of the day on which stress was first observed. The irrigations of August 11, 14 and 25 were made prior to the appearance of plant stress.

Irrigations were scheduled with the aid of the neutron probe. That method generally gave satisfactory results. These findings suggest the possibility of using crop temperature and σ_T measurements to evaluate and compare the effectiveness of various methods for scheduling irrigation and for evaluating the uniformity of irrigation applications made with different systems and techniques. The use of σ_T to schedule irrigations also offers possibilities. If σ_T increases above the average expected value, 0.3°C in this study, the need for irrigation is indicated.

Temperature as an indicator of severity of stress

Differences in temperature between stressed and non-stressed crops did not begin to develop until after 1100 solar time. However, on September 1 in the instrumented plot, $*T_{22}$ was 1.5°C at 0800 and 3.5°C at 0900 h, indicating that stomata were already closing on the plants in row 22. This result, in an increase in the severity of water stress experienced by the plants, suggests that the timing of crop temperature measurements may also be used to distinguish the degree to which plants are stressed for water. Research to verify this hypothesis is now underway at our laboratory.

Daily patterns of leaf and air temperature

Before crop cover was complete, the vertical leaf temperature profiles in the instrumented plot tended to lapse in both stressed and non-stressed areas during the day. After crop cover was complete, the vertical leaf temperature profiles during the day were generally inverted. This was primarily due to the absorption of solar radiation by leaves near the top of the canopy, and the shading of leaves within the canopy. Differences in leaf temperatures at corresponding levels also increased across the plot because of reduced transpiration in the water stressed plants.

A typical daily pattern of thermocouple-measured leaf and infrared measured canopy temperatures under conditions of clear skies with moderately strong winds, is given in Fig. 4. Canopy temperatures measured with the IRT closely followed the temperature of sunlit leaves in both the stressed and non-stressed areas (row 22 and row 2, respectively).

The vertical air temperature gradients (Fig. 5) in the non-stressed row (22) followed the same pattern as the leaf temperature gradients, that is, both were inverted. However, in the more open canopy in the stressed row (2) there was sufficient mixing to cause the air temperature profile to be nearly isothermal even though the leaf temperature gradient was inverted.

As transpiration rates decrease, leaf temperatures increase (Hsiao, 1973) and the proportion of absorbed radiant energy converted to sensible heat increases. This causes the air in stressed areas to be warmer than in non-stressed areas. Thus, data on air temperature differences between stressed

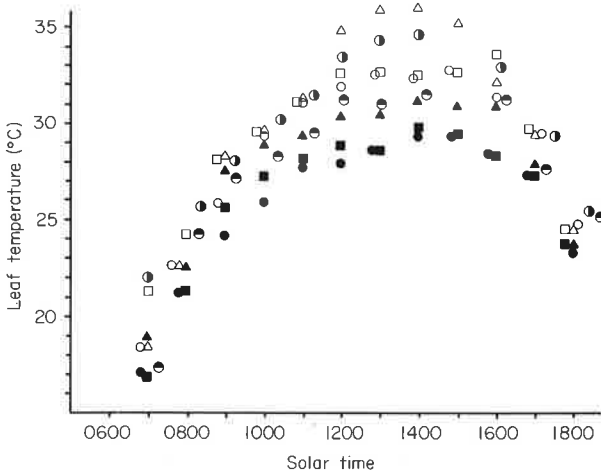
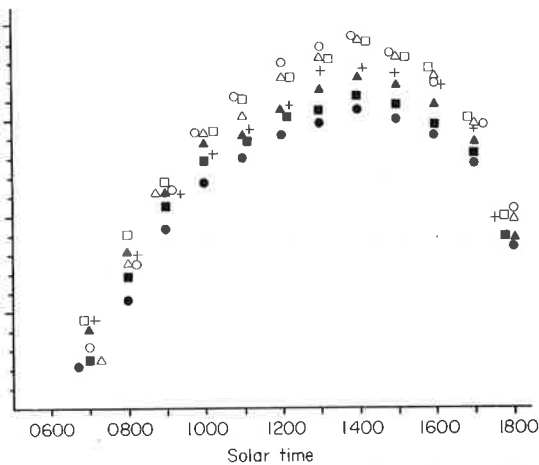
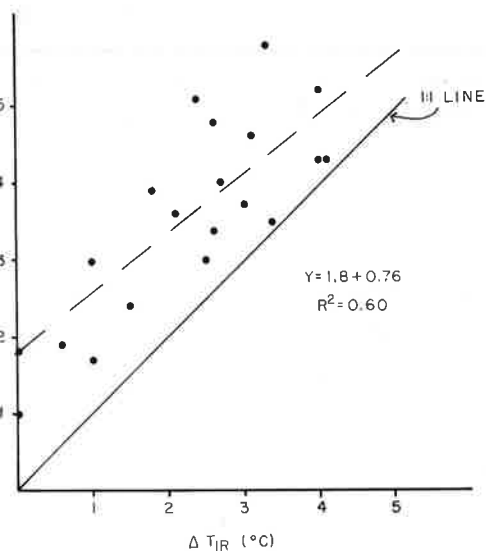


Fig. 4. Daily pattern of leaf temperatures on August 22, 1978, in row 2 (non-stressed) and row 22 (stressed) at the bottom of the canopy, middle of the canopy and at the top of the canopy. (Row 2: canopy top, ▲; mid-canopy, ■; canopy bottom, ●. Row 22: canopy top, △; mid-canopy, □; canopy bottom, ○. T_{IR} row 22, ⊙; T_{IR} row 2, ⊚.) Infrared canopy temperatures (T_{IR}) are also plotted.



5. Daily pattern of air temperature (T_A) on August 22, 1978, in row 2 and row 22 at bottom of the canopy, the middle of the canopy and at the top of the canopy. (Row canopy top, \blacktriangle ; mid-canopy, \blacksquare ; canopy bottom, \bullet . Row 22: canopy top, \triangle ; mid-canopy, \square ; canopy bottom, \circ .) Air temperature at three meters above the soil surface in row 2 is denoted (+).



6. Midday air temperature differences (ΔT_A) between the top of canopy of row 22 (stressed) and row 2 (non-stressed) in plot 22 and midday canopy temperature differences (ΔT_{IR}) of the same two rows. Data are from August 8—September 4, 1978.

non-stressed canopies, could be suggestive of leaf temperature differences. This possibility was investigated by comparing upper level midday temperature differences with the midday infrared canopy temperature differences on 20 days between August 8 and September 4 (Fig. 6). Air

temperature differences tended to be slightly larger than canopy temperature differences.

It was observed that leaf temperatures tended to fluctuate rapidly but temperatures did not. This may account for much of the observed scatter seen in Fig. 6. Thus, canopy air temperature differences may be the most stable indicator of plant moisture stress than instantaneous measurements of leaf temperature, especially under variable climatic conditions.

Leaf and air temperature differences

One common index of plant moisture status is the difference (ΔT) in midday leaf temperature (T_L) and air temperature (T_A) where $\Delta T = T_L - T_A$. Jackson et al. (1977) have shown that the value of ΔT obtained at midday is partly dependent on the location at which air temperature (T_A) is measured. Accordingly, we computed ΔT of leaves at the top of the canopy in rows 10, 14 and 22 using the temperature of the adjacent air (T_j) in each row and the temperature of the air at 3 m (T_3) above the soil surface in row 2 (Fig. 7). Thus, $\Delta T_j = T_L - T_j$ and $\Delta T_3 = T_L - T_3$.

ΔT_j values did not always follow the leaf temperature differences across the plot (see the July 25–September 5 data in Fig. 7) but ΔT_3 values did. The failure of the ΔT_j to follow leaf temperature difference is a result of an increase in the temperature of the air adjacent to the warmer leaves. Hence it may be difficult to compare ΔT measurements between stressed and non-stressed areas without using a common reference air temperature.

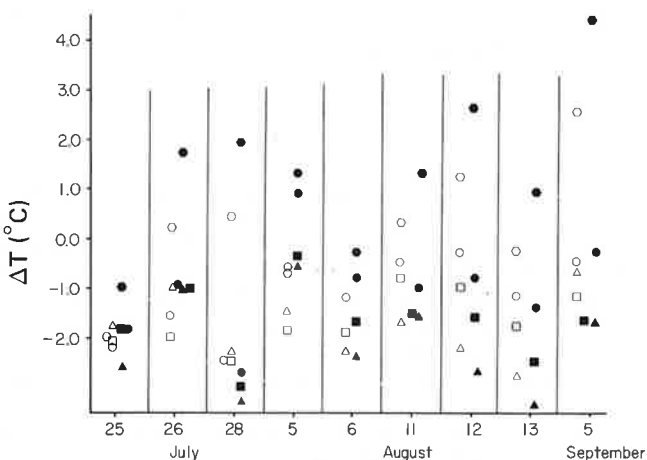


Fig. 7. Midday differences between leaf temperatures at the top of the canopy (T_L) and adjacent air temperature (T_j , open symbols). Differences also were computed using temperature from three meters above the ground in row 2 (T_3 , closed symbols). (Row Δ , \blacktriangle : row 10; \square , \blacksquare : row 14; \circ , \bullet : row 22; \circ , \bullet .) Calculations were performed on data from rows 2, 10, 14 and 22 on plot 22 for nine clear days between July 25 and September 1978.

Jackson et al. (1977) found that in a plant with adequate water supply ΔT will be near zero or negative, but if it is water stressed ΔT will be greater than zero. Although this finding was verified by Jackson et al. for wheat, we did not find it true in our study with corn. We found instead, that while the plants in rows 10 and 14 were warmer than the plants in row 2, and plants under stress, ΔT in those two rows remained negative. Only in row 22 was ΔT found to be positive. We also observed that yields were reduced in proportion to the degree of stress experienced by the plants in rows 10 and 14. This suggests that corn is probably more sensitive to water stress than is wheat, and that the use of ΔT values to indicate water stress may well be soil, plant and climate specific.

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