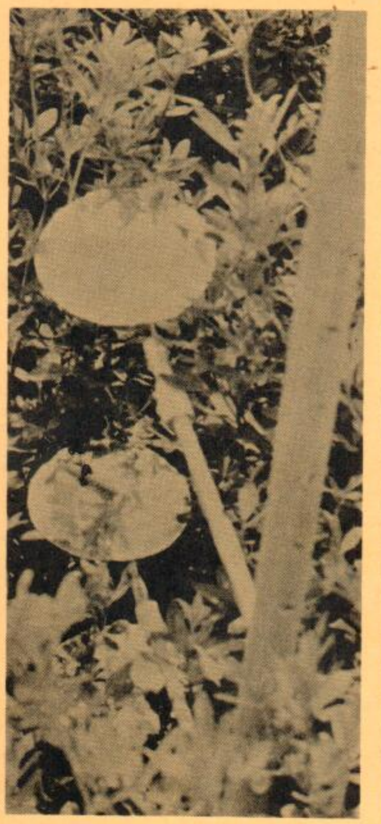
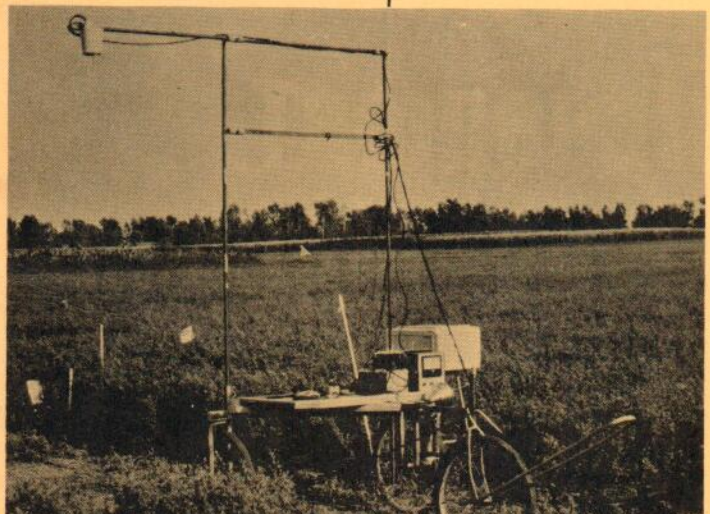
Temperatures of alfalfa, sorghum, soybean and grass as measured with leaf thermocouples and an infrared thermometer



BY SILVIO STEINMETZ



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BLAINE L. BLAD

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TEMPERATURES OF ALFALFA, SORGHUM, SOYBEAN AND GRASS AS MEASURED WITH LEAF THERMOCOUPLES AND AN INFRARED THERMOMETER

by

Silvio Steinmetz

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S. Steinmetz

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agreement with $T_{TC\ 1}$.

Comparison of the crop temperature measured with leaf thermocouple ($T_{TC\ 3}$) indicated that, with adequate moisture supply, grass was the warmest crop followed by sorghum, soybean and alfalfa. The difference between grass and alfalfa was found to be as great as 3 C during hours of high transpiration demand (near solar noon). Similar temperature patterns were obtained with T_{IR} data although the magnitudes were slightly different.

If all the factors that affect crop temperature are constant the temperature of a crop is inversely related to its transpiration rates i.e., the cooler the crop the greater the transpiration. Based on that premise water use by the crops was alfalfa   soybean   sorghum   grass.

Both leaf thermocouples and IR thermometer data indicated practically no temperature difference between broadcast and row soybean and sorghum plots at the levels of crop cover (75%) in this study.

ABSTRACT

In order to obtain accurate measurements of crop temperature it is necessary to understand how various plant, soil and meteorological factors affect crop temperature as measured with different techniques. This study was designed to evaluate the influence of several of these factors on crop temperature as measured with leaf thermocouples and an infrared thermometer. Specifically, the objectives of this study were: 1) to determine the influence of percent cover, leaf area index, planting pattern, plant morphology, etc. on the agreement of crop temperature as measured with attached leaf thermocouples and an infrared thermometer; 2) to detect temperature differences between different types of crops when subject to similar environmental conditions and 3) to study the effect of planting pattern on crop temperature.

Plant, air and soil temperature were measured on plots of alfalfa, grass, soybean and sorghum. Crop temperature was measured at three canopy levels with evanohm-constantan thermocouples and with an infrared thermometer. Data were collected in 1976 on July 24-25 (24 hr period), August 2-3 (27 hr period) and on August 17-18 (36 hr period) with clear or nearly clear skies.

During daytime the temperature given by the infrared thermometer (T_{IR}) showed better agreement with temperature measured by the thermocouples on sunlit leaves ($T_{TC\ 3}$) than with the temperature given by the thermocouples at the lower canopy levels. This was particularly true for alfalfa and soybeans. In sorghum T_{IR} agreed about equally well with $T_{TC\ 3}$, $T_{TC\ 2}$, and $T_{TC\ 1}$. Generally the agreement between T_{IR} and $T_{TC\ 3}$ was better than 1 C.

At night, T_{IR} was 1 to 3 C warmer than T_{TC}. T_{IR} showed the closest

I. INTRODUCTION AND OBJECTIVES

For vascular plants leaves constitute the major sites for the exchange of energy and mass between the plant and its external environment. The effectiveness of this exchange system is dependent on temperature, therefore accurate plant temperature measurement may provide useful information about physical and biological plant processes. Thus crop temperature data can be used to: 1) to detect vegetation under water stress and 2) to estimate evapotranspiration (ET) rates.

With the advent of instruments for detecting surface temperature that can be carried in satellites or other airborne platforms, the measurement of crop temperature has taken on added significance. Measurements of the crop temperature using instruments near the surface are required to provide "surface truth" against which to compare crop temperatures obtained by aircraft or satellite as well as to evaluate, in a detailed way, the plant responses to its environment.

Results from studies comparing the temperature measured by infrared thermometer, (T_{IR}) and attached leaf thermocouples (T_{TC}) have raised several questions such as: 1) to what extent do leaf area index, percent cover, and stage of growth affect the agreement of T_{IR} and T_{TC} for different crops? 2) where should leaf thermocouples be placed in a plant canopy so as to provide a representative measure of crop temperature? 3) how does the crop temperature at various levels compare with air temperature at those levels? the study reported below was designed to answer some of these questions and to provide further understanding of factors related to the agreement of temperature as measured with these two methods.

The objectives of the research reported in this thesis are: 1) to analyze the influence of crop morphology, percent ground cover, leaf area index, stage of growth and soil temperature on the agreement of crop temperature measured with leaf thermocouples and with an infrared thermometer; 2) to detect possible temperature differences among several contrasting types of vegetation such as grass (Festuca elatior), alfalfa (Medicago sativa L.), soybean (Glycine max L.) and sorghum (Sorghum bicolor L.) when subject to similar environmental conditions; and 3) to evaluate the effect of planting pattern on crop temperature.

II. REVIEW OF LITERATURE

2.1 Crop Temperature Measurement Techniques

2.1.1 Leaf Thermocouple

Attachment of small thermocouples to leaf surfaces is one method for measurement of plant temperature. There are several types of thermocouples as well as many techniques for attaching them to leaves. It is difficult to insure that a thermocouple is within the leaf boundary layer or to place a sufficient number to obtain an accurate estimate of the average plant temperature. It is also difficult to attach thermocouples so that they maintain good thermal contact with the leaf.

Gale et al. (1970) compared the temperature measured with an iron-constantan contact thermometer (the thermocouple junction is mounted on a spring that can be attached to the leaf) against that of an iron-constantan thermocouple attached by cellotape to the lower surface of a sugar beet leaf. Results showed that temperature measured with the contact thermometer was lower than that measured with the thermocouple. Temperatures of the upper and lower leaf epidermis, as measured by the contact thermometer, were within $\pm$ 0.5 C. They also measured, under field conditions, the temperature of two leaves of a potted Swiss chard plant with a contact thermometer and with thermocouples inserted within the mesophyll. Under varying conditions of air temperature, wind speed and transpiration rates there was generally good agreement between the two methods. Gale et al. (1970) also found close agreement in the temperature of a potted ornamental plant (*Ficus elastica*) measured with the contact thermometer and that obtained with an infrared thermometer.

Lomas et al. (1971) compared the leaf temperature of potato plants measured with copper-constantan thermocouples clamped on the leaf and with thermocouple needles inserted into the leaf midrib against air temperature measured in a standard meteorological shelter and in miniature meteorological shelters placed in the upper part of the canopy. The leaf temperature measured with thermocouple needles and thermocouple clips showed very good agreement (0.1 C). During midday clip thermocouples showed, in general, higher temperatures than needle thermocouples. This suggests that the surface of the leaf was warmer than its interior. The leaf temperature was almost identical with air temperature measured in the miniature shelters but it did not agree very well with air temperature measured in the standard meteorological screen. Lomas et al. concluded that small and well-ventilated miniature screens exposed at the top of the canopy level can provide accurate leaf temperature data.

As mentioned previously, it is difficult to place the leaf thermocouple within the leaf boundary layer. The larger a thermocouple bead the greater the chance of measuring some combination of air and leaf temperature instead of measuring the leaf temperature. Beadle et al. (1973) tested two types of evanohm-constantan thermocouples for measuring leaf temperatures of stressed and non-stressed corn and sorghum plants held in a gas exchange cuvette. The two types tested were: 1) 0.025 mm junction-welded and 2) 0.125 mm beaded thermocouples. The results showed that the 0.125 mm beaded thermocouples were unsuitable for accurate readings of surface leaf temperature because they always gave smaller temperature differences between the leaf and air than did the 0.025 mm thermocouple. Because of their intimate contact with the leaf, 0.025 mm thermocouples reduced errors in the temperature measurements and provided a more accurate leaf temperature value.

2.1.2 Infrared Thermometry

Temperature measurement with an infrared thermometer is considered to be an improvement over the use of contact sensors, such as leaf thermocouples, because it does not alter the condition of the leaf (Tanner, 1963).

To measure crop temperature accurately with the IR thermometer the crop emissivity (ε_c) and the incoming longwave radiation (B*) must be known. Fuchs and Tanner (1966), for example, show that the real temperature of vegetated surfaces can be measured with errors in the range of 0.1 to 0.3 C if ε_c and B* are known. Data collected over sudan grass on a clear day at Arlington, WI, indicated that, at 1400 hours CST, when B* was 132 wm^{-2}, the "apparent radiative temperature" of the surface was 33.4 C. Corrections accounting for ε_c and B* gave a surface temperature of 34.8 C. By 1900 hours CST a light haze covered the sky and B* was then 295 wm^{-2}. An apparent surface temperature of 24.5 C was recorded whereas the corrected surface temperature was 25.1 C.

2.1.3 Thermal Scanners

Bartholic et al. (1972) measured the temperature of cotton under stress and non-stress conditions with aircraft-mounted thermal scanners from an altitude of 600 m. The agreement between the "surface truth" temperature (obtained with a precision radiation thermometer) and the thermal scanner temperature was very good. They concluded that thermal scanners can be used to measure crop temperature to infer water stress conditions of plants in the field.

Blad and Rosenberg (1976) used thermal imagery to show that wheat and alfalfa, under conditions of minimal moisture stress, had approximately the same temperature and that both were cooler than pasture.

Heilman et al. (1976) used thermal scanners to measure soybean, sorghum and millet temperatures. Atmospheric attenuation of IR radiation led to errors of 2 to 6 C (compared with leaf thermocouple measurements). Therefore uncorrected scanner (not corrected for emissivity nor for atmospheric attenuation) measurements can be used to obtain relative temperature differences between surfaces.

2.1.4 Comparisions of Crop Temperature as Measured with Leaf Thermocouples and an Infrared Thermometer

Research has shown many factors such as soil temperature, percent cover, leaf area index and others which might influence the agreement between crop temperature as measured with leaf thermocouples (T_{TC}) and an infrared thermometer (T_{IR}). The influence of these factors would be mainly on T_{IR} because of the area "viewed" and consequently the radiation sensed by the infrared thermometer.

Lourence et al. (1965) found that the major disagreement between T_{IR} and T_{TC} of tall fescue occurred during the daylight hours. They stated that the leaf thermocouples overestimated the surface temperature of the crop due to radiation errors. At night, however, T_{IR} was generally warmer than T_{TC}.

Landsberg et al. (1974) used two sets of five thermocouples each attached to leaves spaced evenly through an apple tree in order to estimate the average leaf temperature. They also measured the temperature of sunlit and shaded leaves with an IR thermometer. The results show that the average leaf temperature, measured with the randomly distributed thermocouples, was within the range of temperature of sunlit and shaded leaves measured with the IR thermometer.

Blad and Rosenberg (1976) found that the temperature of alfalfa measured with leaf thermocouple and IR thermometer did not consistently agree to better than 1 to 2 C even though there were periods when the agreement was better than 0.5 C. The agreement improved as the crop cover increased and it was generally best during mid and late afternoon and worse in the early morning.

Research has not yet provided enough information about the influence of the soil temperature, percent cover, type of canopy, on the temperature given by IR thermometry. Blad et al. (1975) for example, observed that the type of canopy and the percent cover influenced the agreement between T_{TC} and T_{IR}. The agreement was better for millet than for sorghum, especially late in the growing season when the crop was well established. They also found that the daytime agreement was much better (1 C) than at night (1 to 3 C). Determination of LE fluxes (using a crop temperature based model) suggested that T_{TC} gave more accurate measurements of crop temperature than did T_{IR}. Blad et al. (1975) raised some questions that need to be answered to better understand the agreement between T_{TC} and T_{IR}. These include: 1) is the soil temperature warmer than air at night in certain crops? 2) does the emissivity of the crop change during night because of dew formation? 3) to what extent does a dry or moist soil surface affect the agreement between T_{IR} and T_{TC}? 4) to what extent do leaf area index, percent cover, and stage of growth affect the agreement of T_{IR} and T_{TC} for different crop types? 5) where should leaf thermocouples be placed in the plant canopy so as to provide a representative measure of crop temperature? and 6) how does the crop temperature at various levels in the plant canopy compare with air temperature at those levels?

2.2 Temperature Differences Between Crops

Teare and Kanemasu (1972) found that the air temperature profile within a sorghum canopy was warmer and more nearly isothermal than in a soybean canopy. Compared to soybean the sorghum canopy showed greater stomatal-diffusion resistance which resulted in less transpiration and a warmer and drier microclimate. Kanemasu et al. (1976) reported that soybean plants were 2 to 3 C cooler than sorghum.

Blad and Rosenberg (1974) reported that wheat and alfalfa were at approximately the same temperature and both were cooler than pasture. They also observed that an irrigated corn field was warmer than an alfalfa field.

2.3 Factors Affecting Leaf Temperature

Numerous factors affect leaf temperature such as: transpiration rate, solar radiation, wind speed, leaf position, cloudiness and air temperature. In this section, however, only those closely related to the objectives of this study will be reviewed.

2.3.1 Transpiration

Transpiration is one of the most important factors controlling leaf temperature. If all the other factors that affect crop temperature are constant, the crop temperature will be inversely related to its transpiration rate.

Several workers have demonstrated the effect of transpiration upon leaf temperature. Tanner (1963) found that a decrease of 10% in the transpiration rates of a full cover alfalfa-brome caused a temperature increase of about 1.0 C. Gates (1964) calculated that for each 0.10 mm hr^{-1} of transpiration, the effective radiation load on a leaf is reduced 0.10 ly min^{-1}. Compared with no transpiration, transpiration at a rate of 0.10 mm hr^{-1} would lower the leaf temperature 5, 2.5 and 1.0 C below the non-transpiring leaf at wind speeds of 1.6, 8.0 and 24.1 km per hour, respectively.

Lange (1965) demonstrated the effect of transpiration in cooling the leaves of a desert species (Citrullus colocynthis). The leaf temperature was 10 to 12 C below air temperature which reached as high as 50 C for the entire period of exposure to the sun.

Pallas and Harris (1964) reported that leaf temperature of cotton was highly correlated with transpiration under most conditions and that leaf temperature falls below ambient air temperature when light intensity and relative humidity are low. van Bavel and Ehrler (1968) observed that leaf temperature of a well watered sorghum plot was consistently lower than air temperature. Differences varied from 3 C in early morning to 10 C in early evening.

Blad and Rosenberg (1974) found that ET rates for alfalfa were 20 to 25 percent higher than in pasture. These findings were corroborated by the same authors (1976) using thermal imagery. Kanemasu et al. (1976) reported that evapotranspiration rates from soybean were about 10% greater than from sorghum.

2.3.2 Air Temperature

Linacre (1964) established an important concept concerning the plant temperature - air temperature relationship. He explained that the temperature of leaves supplied with ample water and fully exposed to sunlight was equal to air temperature at 33 C. If ambient temperature was below 33 C, leaves were warmer than air; above 33 C they were cooler than air.

Kanemasu et al. (1976) showed that under advective conditions the cross over point (air temperature becomes warmer than leaf temperature) was 31 C for soybean and 33 C for sorghum. Blad and Rosenberg (1976) found that alfalfa was often 5 to 7 C cooler than air temperature and that the cross over point occurred in a temperature range from about 23 to 30 C.

2.3.3 Cloudiness

Clouds play an important role in controlling the plant-environment relationship. Clouds change the energy balance and consequently, the leaf temperature pattern. Curtis (1936) indicated that radiation to cold skies plays a very important role in cooling plant leaves. In his experiment, thermocouples were inserted into three leaves on the northeast side of an orange tree where they were exposed to the sky but shielded from the sun by the remainder of the tree. A cardboard shield about 40 cm wide x 50 cm long was held at a distance of about 50 cm from the leaves to shield them from the sky and then removed. Leaf temperature measurements were made on a clear and on a cloudy day. Results showed that on a cloudy day the presence or the absence of the cardboard shielding or not shielding the leaves from the sky had almost no effect on leaf temperatures. However, on a clear day the leaf temperatures were greatly influenced by radiation to the sky.

Waggoner and Shaw (1972) found that on clear days upper leaves of tomatoes were warmer (32.8 C) than the lower ones (26.6 C). On a cloudy day, however, the two levels were at about identical temperatures (difference of 0.3 C). On a clear night the upper canopy was 1.3 C cooler than the lower canopy. On a cloudy night, the difference was only 0.4 C. Lomas et al. (1972) showed that on a cool day potato leaf temperature was several degrees higher than air temperature during sunny periods but was near the air temperature under cloudy conditions.

Stone et al. (1975) studied the effects of clouds on sorghum canopy temperature. Their results show that canopy temperature is very responsive to changes in the incoming shortwave radiation. Fluctuations of as much as 3 C was observed in the sorghum temperature in a three minute period. They also found that approximately 1 to 2 minutes were required for the sorghum plants to reach the steady-state temperature on the descent portion of a radiation change. Based on these findings Stone et al. (1975) stated that care should be taken when attempting to estimate canopy temperature using IR thermometry on days of variable radiation.

2.4 Application of Crop Temperature Data

Many physiological processes in plants are influenced by leaf temperature. Transpiration, a major cooling mechanism of plants, controls the water content of the plants, which in turn affects stomatal resistances thereby, influencing photosynthetic rates. The accurate measurement of crop temperature may provide means to detect vegetation under water stress and/or to estimate evapotranspiration rates.

2.4.1 Detection of Plant Water Stress

Many workers have found that crop temperature is a valuable tool in detecting plants in water stress. Several techniques have been used to show the relationship between plant water stress and crop temperature. Ehrler and van Bavel (1967), for example, used the difference between sorghum temperature (T_C) and air temperature (T_A) (T_C-T_A) = Δ T to show that leaf temperatures (T_L) were strongly related to soil water availability. On irrigated plots T_L was considerably below T_A during most of the 24-hour period, but in the dry soils T_L was as much as 5 C higher than T_A during the daytime period. Wiegand and Namken (1966) found that a decrease in plant relative turgidity from 83 to 59% caused a 3.6 C increase in leaf temperature and a 2.7 to 3.7 C increase in ΔT.

Carlson et al. (1972) showed that Δ T increased as the leaf relative water content (RWC) of the plant decreased. An increase in T_A caused T_L to increase. The increase in T_L was dependent on RWC; at low levels of RWC, the response of T_L to an increase in T_A was greater than at high levels of RWC.

Lomas et al. (1972) found that temperatures of potato leaves were as high as 9 C above T_A in dry soil. However, T_C remained below T_A on irrigated plots even under warm, dry winds ("sharav") condition.

The Δ T concept was also used by Ehrler et al. (1976) and by Jackson et al. (1976) who developed a concept called "stress degree day" (SDD = the summation of the daily difference between T_C and T_A at 1400 hours). The plant water potential and the soil water content are correlated with SDD. The magnitude of SDD can be used to evaluate plant responses, such as yield, to various levels of drought stress (Idso et al. 1977). It also has potential for scheduling irrigation.

Millar et al. (1971) found that T_L of barley was influenced by both soil moisture content and weather conditions. T_L of plants growing in dry soil was consistently higher than T_L of plants in moist soil. Maximum differences were 6.5 C and 2 C on warm and cool days, respectively. They concluded that differences in temperature of similarly exposed leaves are a sensitive indicator of plant water stress. Myers (1970) stated that remote sensing of crop temperature may be a useful technique to evaluate crop moisture stress. This was verified by Bartholic et al. (1972). They found, using thermal imagery, that temperature differences were as great as 6 C between the most and the least water stressed cotton plants. They concluded that thermal scanners can be used to evaluate relative plant water stress and thus indicate the need for irrigation.

Plant temperature can also be used to detect the occurrence and extent of soil salinity. Meyers (1970) determined a relationship between soil salinity and cotton leaf temperature showing that as soil salinity increased from 0.5 to 15 millimhos cm^{-1} the leaf temperature increased by 2.7 C on June 2 and 5.4 C on June 16. The different temperature response of the cotton plants on these two days is explained by a higher ambient temperature (34 C versus 32 C) greater direct solar plus diffuse sky radiation load on the plants (1.04 cal cm^{-2} min^{-1} versus 0.86 cal cm^{-2} min^{-1}), and greater soil moisture stress (-1.1 bar versus -2.6 bar) on June 16 compared with June 2.

2.4.2 Determination of Evapotranspiration Rates

Crop temperature can be used as input into certain resistance models for calculating evapotranspiration rates. Brown and Rosenberg (1973) developed and tested a resistance model to estimate sugar beet evapotranspiration. The Brown and Rosenberg model utilizes a procedure to estimate the crop temperature. Their model can be simplified by using crop surface temperature data. LE can then be calculated from surface temperature and easily obtained meteorological parameters such as T_A (air temperature, e_a (vapor pressure of air), R_n (net radiation), and u (horizontal wind speed). The Brown and Rosenberg model can thus be simplified to the following equation

$$- LE = \rho \ C_p \frac{(T_a - T_s)}{r_a} + R_n + S \qquad [Eq. 1]$$

where ρ is the density of moist air, C_p is the specific heat of moist air at constant pressure, T_s is surface or crop canopy temperature, T_a is air temperature, R_n is net radiation, S is soil heat flux and r_a is the boundary layer resistance. All terms in equation 1 can be easily measured except r_a which must be estimated from a functional relationship with wind speed. From equation 1 it can be seen that, with the other parameters held constant, the cooler the crop the greater the LE.

Brown (1974) used equation 1 to calculate LE from stressed and non-stressed cotton fields using the surface temperature data obtained by Bartholic et al. (1972). A difference in LE as great as 0.48 cal cm^{-2} min^{-1} was found between two adjacent (stressed and non-stressed) plots with a surface temperature difference of 6 C. Based on these results he concluded it was possible to use crop surface temperature data for calculating LE over large areas. Verma et al. (1976) showed that LE estimates made with equation 1 are more sensitive to errors in crop temperature than to errors in r_a. Thus, accurate crop temperature measurements are essential for reliable estimates of LE with this model.

Stone and Horton (1974) tested two surface temperature based methods of estimating ET against three conventional methods. The two methods that used surface temperature were those of 1) Bartholic, Namken and Wiegand (BNW); and 2) equation 1 (called BR by Stone and Horton).* The three conventional methods were the 1) van Bavel, 2) Penman and 3) the Bowen ratio-energy balance models. Stone and Horton concluded that both temperature based methods can be used to determine ET rates of vegetated surfaces.

Blad and Rosenberg (1976) tested the equation 1 against the Bowen ratio-energy balance (BREB) model. Their results show that daily LE estimates given by the equation 1 were within 10% of the estimates made by BREB model. Similar results were reported by Verma et al. (1976) who found that daily LE estimates given by the equation 1 were within 10% of lysimetric and BREB values.

*After Brown and Rosenberg, but incorrectly attributed.

Heilman et al. (1976) used a thermal scanner to obtain surface temperatures of soybean, sorghum and millet. These data were used as imput into a slightly modified form of equation 1 to estimate ET. They found that the estimates of ET using corrected temperatures (corrected to account for atmospheric attenuation of the thermal radiation between the surface and the scanner) differed from lysimetric measurements by - 0.40 to 0.17 cal cm^{-2} min^{-1}. Accurate crop temperature measurement is essential to obtain reasonable ET estimates. Heilman et al. suggested that accurate measurement of "surface truth" will permit extrapolation of scanner measurements to actual surface temperatures.

III. MATERIALS AND METHODS

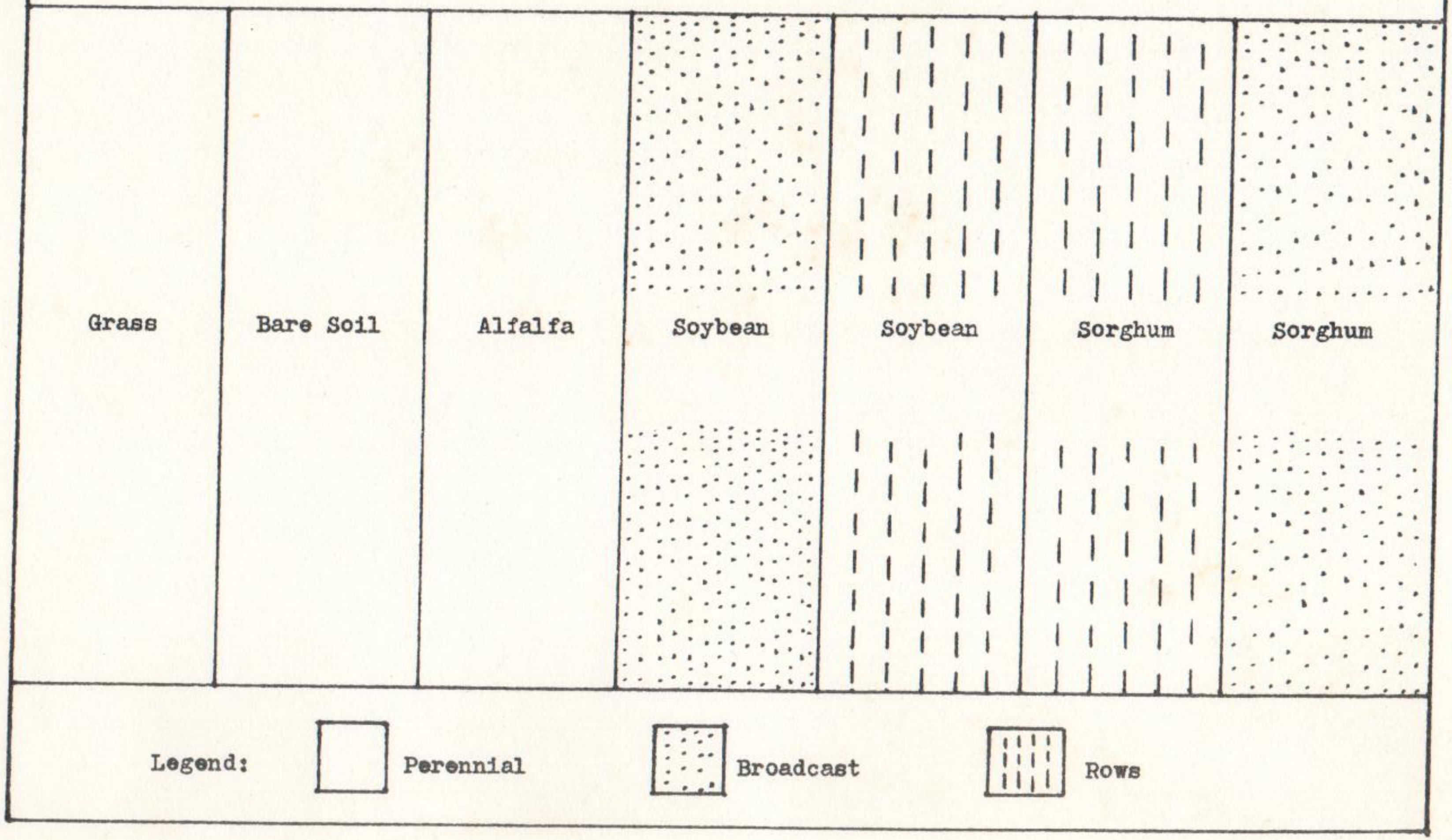
3.1 Experimental Site

This study was conducted at the University of Nebraska Agricultural Meteorology Laboratory near Mead, Nebraska (41° 09' N; 96° 30' W, 354 m above m.s.l.). The soil in the area has been classified by the Soil Conservation Service (Saunders County Survey, 1965) as Sharpsburg silty clay loam.

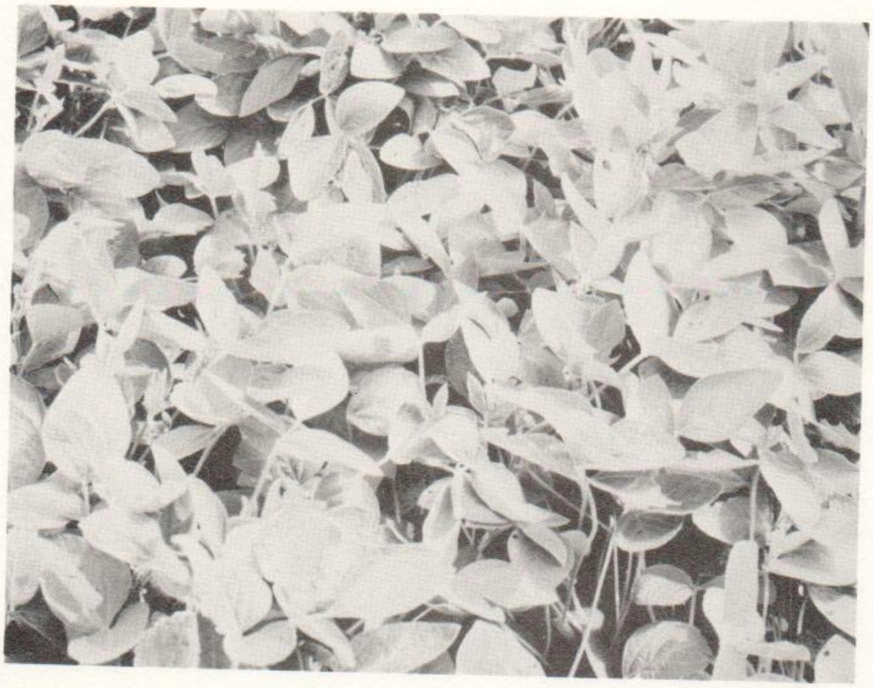
Measurements were made on seven different plots, adjacent to an alfalfa field, each of which was ten meters long (N to S) and three meters wide (E to W) (Fig. 1). Six of these plots were cropped and one was bare soil. Four types of crops were used: alfalfa (*Medicago sativa L.*); soybean (*Glycine max L.*); sorghum (*Sorghum biocolor L.*) and grass (*Festuca elatior*).

Sorghum and soybeans were planted on May 21, 1976 in two different planting systems, rows and broadcast. Rows were 50 cm wide and the plants were spaced about 3 cm apart. Seeds of sorghum and soybean were also broadcast in a planting pattern that assured early and complete ground cover. These two planting systems were intended to provide different percentages of ground cover. Fig. 2 through 5 show the crop cover conditions of soybean row, soybean broadcast, sorghum row and sorghum broadcast plots on July 24 and August 3, 1976. A section of the adjacent alfalfa field was used in the first part of the experiment (from July 24-25 to August 2-3) because of a poor stand in the alfalfa plot included in the experimental design. All plots were well irrigated three days before the beginning of the study. No further irrigation was applied until the end of the experiment.

Fig. 1. Field layout of the experimental plots indicating the crops and planting patterns for soybean or sorghum. Details are given in section 3.1.



(a)



(b)

Fig. 2. Photograph of a section of the (a) soybean row and (b) soybean broadcast plots on July 24, 1976.

(a)

(b)

Fig. 3. Photograph of a section of the (a) soybean row and (b) soybean broadcast plots on Aug. 3, 1976.

(a)

(b)

Fig. 4. Photograph of a section of the (a) sorghum row and (b) sorghum broadcast plots on July 24, 1976.

(a)

(b)

Fig. 5. Photograph of a section of the (a) sorghum row and (b) sorghum broadcast plots on August 3, 1976.

3.2 Plant and Soil Measurements

Crop temperature, soil moisture, plant height and percent of crop cover were measured during each of three periods (July 24-25; Aug. 2-3; and Aug. 17-18). The soil moisture in the 0-15 cm layer was determined by gravimetric sampling. The percent moisture values were converted to soil water potential using the curve in Fig. 6. The plant height was measured on ten randomly chosen plants in each plot. The percent cover was estimated visually. All the plants included in a 50 x 50 cm square, placed randomly in each plot, were cut and the leaf area was determined with a Hayashi-Denko Automatic Area Meter Model AAM-E.[1]

3.3 Thermocouple Construction

3.3.1 Leaf Thermocouples

The evanohm-constantan (5 mil) thermocouples were manufactured using the following technique. Evanohm and constantan wires were twisted tightly, welded and then untwisted in such a way that the bead was the only contact between the two different materials. Evanohm was used instead of copper because it is mechanically stronger, has a lower thermal conductivity, and has the same electrical properties as copper, (Beadle et al., 1972).

Each assembly of six thermocouples in parallel was about 60 cm long so that it could be attached to six different plant leaves. The thermocouples were insulated individually with a heat-shrinkage tubing to within about 3 cm of the bead. The last 3 cm was insulated by spraying Acra-Seal[2] on the bare wires.

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[1] Yen Enterprises, Inc. Terminal Tower Bldg., Cleveland, Ohio 44113.

[2] Acra-Seal - Part No. M4-12, Radiator Specialty Co., Charlotte, NC 28237.

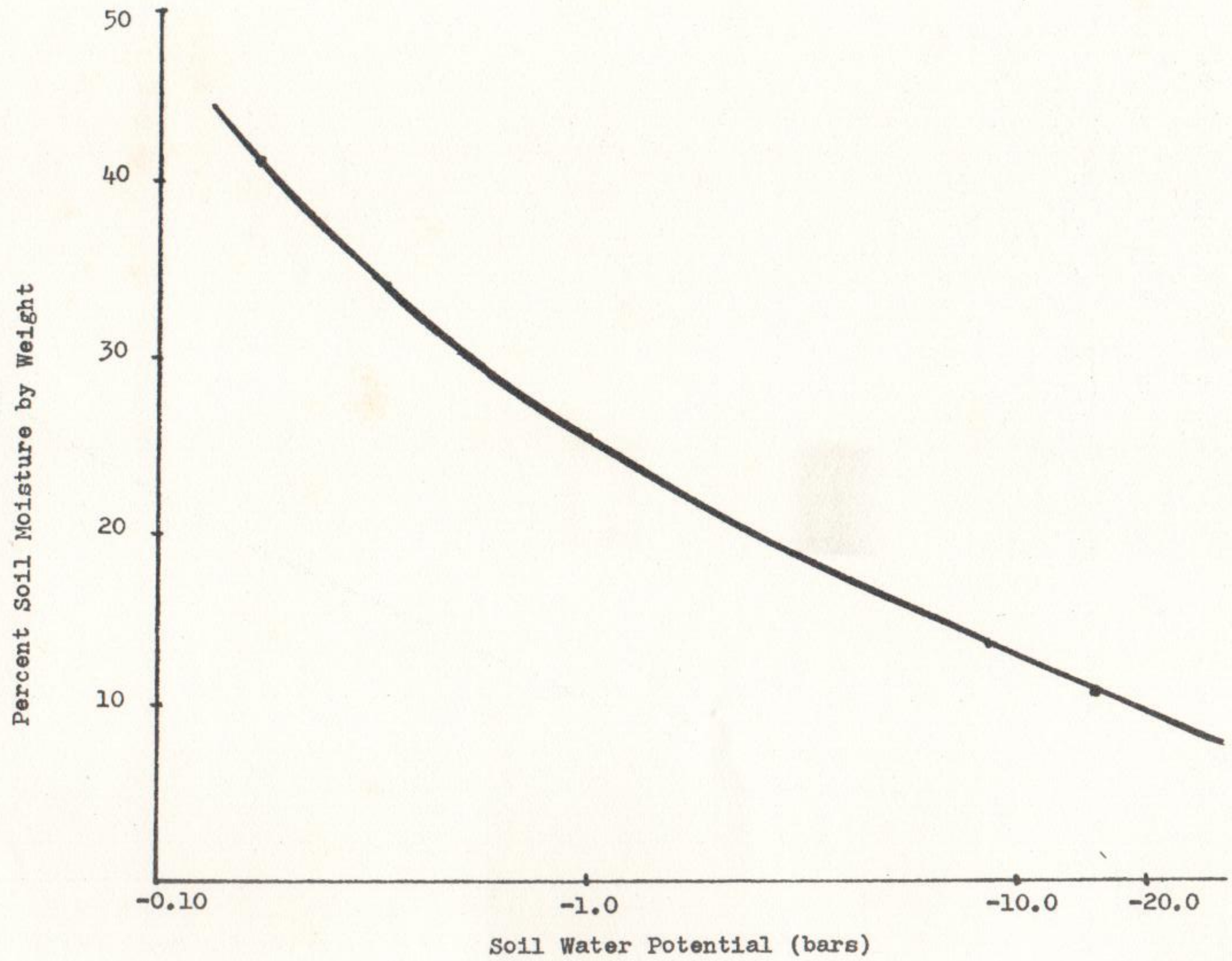

Fig. 6. Relationship of soil moisture percent by weight and soil water potential (After Hales 1968 unpublished data).

3.3.2 Air and Soil Thermocouples

Both air and soil thermocouples were built with 10 mil copper-constantan wires. These were twisted together for about 3 mm and then soldered. The air thermocouple in each plot at the highest level in the canopy (level 3) was inserted in a 6 mm diameter insulated Teflon plug to damp the rapid fluctuation in temperature and provide a stable reference.

Soil thermocouple sets were composed of four thermocouples wired in parallel. These were insulated in the following manner: the extremity (3 to 4 cm) of each thermocouple was dipped into a glue (Ply Bond[3]) about four times. Each coat was applied only after the preceeding one had dried completely. Three additional coatings with Scotch Kote[4] electrical coating were applied later. All thermocouples showed a negligible electrical leakage when immersed in water.

3.4 Placement of the Temperature Sensors within the Canopy

3.4.1 Placement of the Air Thermocouples

Except for the grass, each plot had air thermocouples at three levels. The levels were numbered as 3, 2 and 1 for the upper, medium and lower part of the canopy, respectively. The air thermocouples were supported by three horizontal wooden dowels (18 cm long and 0.6 cm diameter) which could be adjusted to different levels along a vertical wooden support (1 m long and 1.9 cm diameter dowel). The thermocouples were raised as the crops grew (Table 1). The thermocouples were radiation

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[3]GC Electronics - Division of Hydrometals, Inc., Rockford, IL 61101.

[4]Electro-Products Division of 3M Company, St. Paul, MN 55101.

Table 1. Heights of the air thermocouple placed within the crop canopy during three study periods.

Date 1977	Crop	Heights of the air thermocouples in cm from the ground		
		Level 3	Level 2	Level 1
July 24-25	Alfalfa	43	27	11
	Grass	6		
	Soybean Broadcast	63	43	19
	Soybean Row	59	39	19
	Sorghum Broadcast	63	47	31
	Sorghum Row	63	47	31
August 2-3	Alfalfa	51	35	19
	Grass	9		
	Soybean Broadcast	71	51	27
	Soybean Row	71	51	27
	Sorghum Broadcast	63	27	31
	Sorghum Row	63	47	31
August 17-18	Alfalfa	53	37	21
	Grass	9		
	Soybean Broadcast	79	55	35
	Soybean Row	79	55	35
	Sorghum Broadcast	63	67	31
	Sorghum Row	63	47	31

shielded with a Mylard[5] shield 8 cm in diameter. The shield was placed about 1 cm above each air thermocouple. A thin wire frame (0.7 mm in diameter) served as a support for the shield. A plastic ring insulated the wire frame from the thermocouple wire. Fig. 7 shows the placement of the air thermocouples in the alfalfa plot.

The thermocouple at the highest level (3) in each plot served as the reference temperature (1/4 C resolution). All other temperature sensors of that plot were wired differentially (1/40 C resolution) to that reference thermocouple. See Fig. A-1 for electrical wiring diagram.

3.4.2 Placement of the Leaf Thermocouples

Difficulties were encountered in finding a practical and efficient method to attach thermocouples to the leaves. Two techniques were tested: 1) Acra-Seal glue was placed at the thermocouple's beads, in a very small amount so that just the bead would stick to the lower side of the leaves. The leaves were bent to an upright position and the thermocouples placed in such a way that they remained pressed against the leaves as they returned to their normal position. Two major problems were observed with this technique: a) the thermocouples did not stay attached to leaves very long, especially on windy and rainy days; and b) after two or three days the leaves showed a yellow coloration (burning effect) in the region where Acra-Seal glue was used.

The thermocouples were also attached to the leaves in the following way: the thermocouples were bent at an angle of 90^{o} about 3 mm from the beads. A small piece of filament tape[6] was placed several

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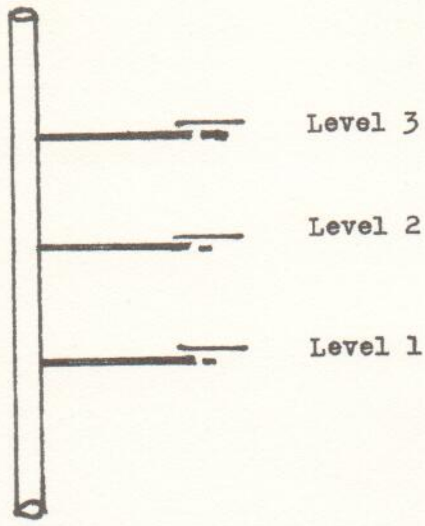
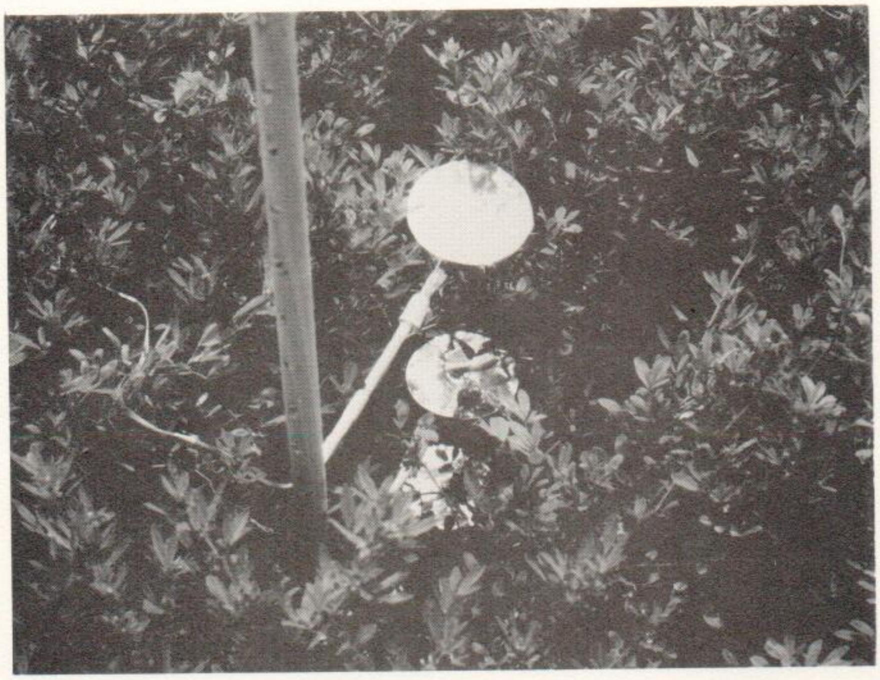
[5]Mylard - Avery Products Corp., Painesville, OH 44077.

[6]Filament tape - 3M Company, St. Paul, MN 55101.



(a)



(b)

Fig. 7. (a) Sketch of the air thermocouple placement within the canopy and (b) photograph of the 3 air thermocouples within the alfalfa canopy.

mm from the bead and used to hold the thermocouple against the leaf. Fig. 8 shows a thermocouple attached to a sorghum leaf. This second technique gave vastly improved results.

Three sets of six thermocouples wired in parallel were attached to 18 leaves of several plants in each plot. In each plot the thermocouples were attached within three different canopy levels. At level 3 all six thermocouples were placed on sunlit leaves, half of the thermocouples were attached to sunlit leaves and half to the shaded leaves at level 2 and all thermocouples at level 1, were on shaded leaves. Two sets of thermocouples were placed at a single level in the grass. The thermocouples were placed near the area viewed by the IR thermometer.

3.4.3 Placement of the Soil Thermocouples

Two sets of soil thermocouples were installed in each plot. Each individual thermocouple was placed 12 cm apart and as near the surface as possible without being exposed. The temperature of both thermocouple sets were averaged.

3.5 Infrared Thermometer Techniques and Calculations

Two IR thermometers were used during this study. During the first two periods of measurements (July 24-25 and August 2-3) a Barnes IT-3 S/ 3[7] model was used. On August 2-3 signals from the instrument were not very stable and during an attempt to determine the crop emissivity on August 4, it became completely unstable.

During the third period of measurements (August 17-18) a second but

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[7]Barnes Engineering Co., 30 Commerce Rd., Stamford, Conn. 06902.

Fig. 8. Evanohm-constantan thermocouple (indicated by arrow) attached to a sorghum leaf.

similar IT -3 instrument was used. The instrument used during July 24-25 and August 2-3 will be labeled as IRT #1 and the one used during August 17-18 will be called IRT #2.

3.5.1 Theoretical Consideration

The energy flux R, from an object is related to its surface temperature by

$$R = \varepsilon \sigma T^4 \qquad \text{[Eq. 2]}$$

where ε is the emissivity, σ is the Stefan-Boltzmann constant, and T is absolute temperature (K) of the radiating surface.

The total radiative flux density from any object includes the emitted and the reflected radiation if the object does not behave as a "black body". The total outgoing longwave radiative flux density, R_{LW}, may thus be stated as:

$$R_{LW} = \varepsilon \sigma T^4 + (1 - \varepsilon) B^* \qquad \text{[Eq. 3]}$$

where B* is the flux density of the incoming longwave radiation (8-14 μ m). B* can be calculated directly in the field, if the emissivity of the aluminum plate $_p$ is known, from the equation derived by Fuchs and Tanner (1966):

$$B^* = \frac{R_{bp} - \varepsilon_p T_p^4}{1 - \varepsilon_p} \qquad \text{[Eq. 4]}$$

where R_{bp} is the radiative flux density from the plate measured with the IR thermometer and T_p is the temperature of the plate. T_p was measured with four thermocouples wired in parallel embedded very near the surface of the plate.

The emissivity of the crop (ε_c) can be calculated from the equation:

$$\varepsilon_c = \frac{R_{bc} - B^*}{B^* + \sigma T_c^4} \qquad \text{[Eq. 5]}$$

where R_{bc} in the radiative flux sensed by the IRT over the sample surface without the cone (black body source of radiation).

Finally, the plant canopy temperature sensed by the IR thermometer is calculated from the following expression:

$$T_{IR} = \left[\frac{R_{bc} - (1-\varepsilon_c)B^*}{\varepsilon_c\ \sigma}\right]^{1/4} \qquad \text{[Eq. 6]}$$

3.5.2 Infrared Thermometer Calibration

Each of the two IR thermometers were calibrated using a procedure similar to that of Conaway and van Bavel (1966). The exact procedure used is described in detail by Blad and Rosenberg (1975). The "blackbody" radiation source was immersed in a water bath and the water temperature was varied in steps of 3 to 5 C over the range from 5 to 50 C. The calibration equations were developed using multiple regression techniques.

3.5.3 Emissivity of the Aluminum Plate

Blad and Rosenberg's (1976) method (a simplified version of that presented by Conaway and van Bavel (1966)) was used to determine the emissivity of the aluminum plate. The emissivity of a newly painted aluminum plate[8] and a weathered one were calculated and their values were 0.610 and 0.619, respectively. These two calculations were done using IRT #1. Plate emissivity, after extensive weathering, was determined with the IRT #2 to be 0.636.

3.5.4 Emissivity of the Plant Canopy

The emissivity of the four vegetated surfaces (alfalfa, grass, soybean and sorghum) and of the bare soil were estimated by the method

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[8] Morris Paint Co., St. Louis, Missouri.

proposed by Fuchs and Tanner (1966). However, a large plastic garbage can whose inside was covered with aluminum foil was used instead of the "pop-tent". The container had one hole in the closed end where the sensing head of the IRT was placed. The container was fitted with four movable legs so that its height could be adjusted to a few cm below the top of the plant canopy. The IRT sensing head was about 70 cm above the upper part of the canopy. Nine measurements were made over each plot at three different sites. Care was taken to not enclose the plants for more than 15 seconds at a time. Fuchs and Tanner (1966) observed that if the cover is left for more than 15 seconds, the energy balance of the crop is changed. After each set of three readings over the crop or soil, the IRT sensing head was placed over the aluminum plate in order to measure B*.

Emissivities of the surfaces was determined on the night of August 23, 1976 when the sky was completely clear. Readings were made over the normal sorghum crop and again with the heads removed. On soybean and sorghum plots, emissivities were calculated for the two planting patterns separately. Emissivities for the bare soil and the six cropped surfaces are presented on Table 2.

3.5.5 Radiative Temperature Measurements in the Experimental Plots

The IR thermometer was mounted three meters above the ground on a cart which was pulled manually and placed at predetermined stations (Fig. 9). Two areas of each plot (stations #1 and #2) were "viewed" by the IRT and the readings averaged to obtain T_{IR}. The alfalfa, grass, bare soil, soybean broadcast and sorghum broadcast stations were about 80 cm apart. In the soybean and sorghum row plots, the IRT "viewed" one area within the rows and a second area between the rows. Results showed

Table 2. Emissivities of Bare Soil and Six Vegetative Surfaces Determined on August 23, 1976.

	Planting	Emissivities	
Crop	Pattern	Normal	Heads Removed
Alfalfa		.981	
Grass		.977	
Bare Soil		.954	
Soybean	Rows	.976	
Soybean	Broadcast	.971	
Sorghum	Rows	.971	.974
Sorghum	Broadcast	.971	.974

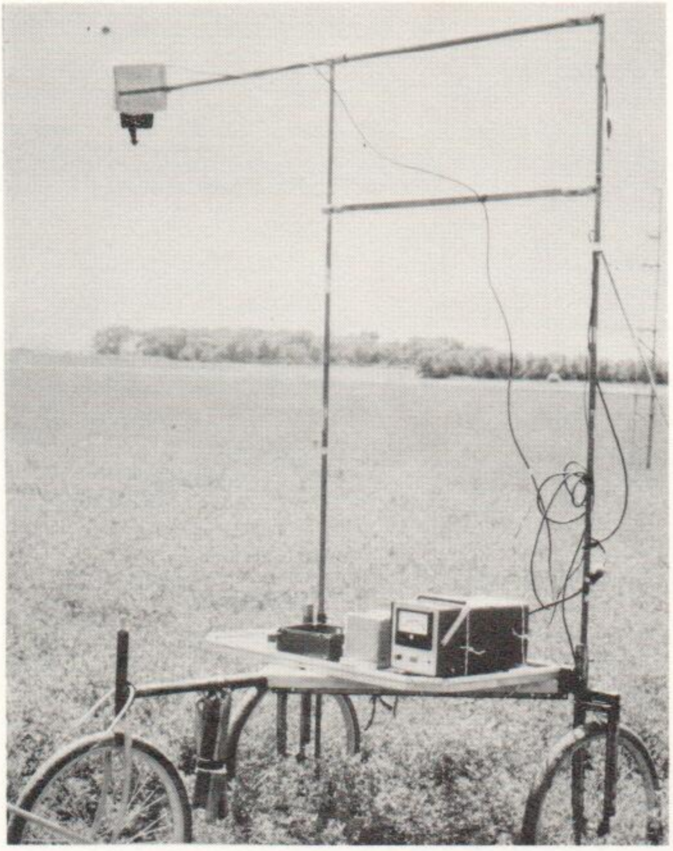

Fig. 9. Infrared thermometer mounted on the cart 3 meters above the ground.

that temperature at these two stations were similar.

At the beginning of each recording cycle, the IRT was located over the aluminum plate and at appropriate times it was moved to alfalfa (stations #1 and #2), grass (stations #1 and #2) and so on. The person pulling the cart and the person stationed near the data logging system in the laboratory communicated by walkie-talkie when the cart was to be moved from station to station. We planned to collect temperature data during over at least 24 hour periods at four stages of growth representing percent cover of about 25, 50, 75, and 100% in the soybean and sorghum row plots. Due to technical problems it was possible to collect data only during three periods (July 24-25, August 2-3 and August 17-18) and only after cover was about 75%.

3.6 Meteorological Instrumentation and Data Collection

3.6.1 General Meteorological Instrumentation

The following meterological data were automatically recorded every 15 minutes in the main alfalfa field: 1) Global radiation - measured with an Eppley pyranometer[9]; 2) Wind speed measured with three cup light chopping casella anemometer [model 442 (2)][10]; 3) Wind direction measured with a wind direction indicator [model 413][11]; 4) Air temperature - at 2 m above the ground and 5) Dew point temperature at 2 m - measured with a Honeywell dew probe [model SP 129A - 413][12].

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[9]The Eppley Laboratory, New Port, RI 02840.

[10]Science Associates Inc., 230 Nassan St., Princeton, NJ 08540.

[11]Science Associates Inc., 230 Nassan St., Princeton, NJ 08540.

[12]Minneapolis-Honeywell Co., 2753 4th Ave. South, Minneapolis 8, MN.

3.6.2 Data Acquisition System

All meteorological data were recorded by an 80 channel datex meteorological data-logging system[13]. The system digitized data from the field and recorded these on punched paper tape. The system was adjusted so that three seconds elapsed between the recording of sucessive signals. This provided enough time to move the IR thermometer from one station to another. Recording cycles took about four minutes to complete and were repeated every 15 minutes. The data was converted to parametric form through a series of computer programs and was plotted with a Cal Comp plotter (Brown and Rosenberg, 1969).

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[13] Datex Division, Conrac Corp., 1600 South Mountain Ave., Duarte, CA 91010.

IV. RESULTS AND DISCUSSION

4.1 Weather Conditions

Table 3 gives details of the weather conditions during the three data collection periods.

On July 24, the first day of measurements, the skies were clear. The wind speed from 0900 to 1500 hours was about 3 m sec^{-1} but it was very calm for the remainder of the day. By 2100 hours heavy dew deposition was observed on all crops. During the entire night the skies were clear and the air was calm. A few cirrus clouds were observed in the early morning (between 0600 and 0800 hours) of July 25 but it is unlikely that they significantly affected the IR thermometer measurements. Winds averaged about 3 m sec^{-1} from 1200 to 2000 hours and was lower before and after this period. Both days were relatively warm and humid.

On August 2, a few small cumulus clouds developed in the morning, but they did not obscure the sun. By 1600 hours the skies were completely clear. It was a very calm day except from 0700 to 1000 hours when the wind speed was about 2.5 m sec^{-1}. The night was calm and very cool. Heavy dew was observed on all crops. August 3 was warmer than the previous day. The skies were clear except for a small period in the morning when some cumulus developed. The day was windy (about 4.5 m sec^{-1}).

August 17 was a hot (34.8 C at 1400 hr.) and windy day. It was the warmest day during the three study periods. Winds as strong as 6 m sec^{-1} occured near noon. Winds were from the SE and S and advected hot dry air into the region. The skies were clear except for a few small cumulus clouds in the early afternoon. Moderate dew was observed in most crops during the late night and early morning. August 18 was also clear, hot and windy.

Table 3. Lysimetric evapotranspiration of alfalfa and weather conditions for the three study periods. Instruments were located 2 m above the surface.

Date	Evapotranspiration	Weather conditions					
		24 hour average					at 1400 hr
		R_s	T	e	u	Wind direction	T
1976	mm day^{-1}	Cal cm^{-2}	^oC	mb	m sec^{-1}		^oC
July 24	9.25	672	22.6	17.6	.94	NE - SE	28.7
July 25	9.25	658	19.6	19.6	1.12	E - SE	31.0
August 2	8.74	653	20.1	14.5	.69	NW, NE, S	23.6
August 3	9.15	588	19.9	13.8	1.91	SE, SW	27.3
August 17	* 2.06	592	28.1	22.0	3.07	SE, S	34.8
August 18	* 2.05	608	27.0	21.1	2.71	SE - SW	33.8

* Recently harvested alfalfa

4.2 Plant and Soil Data

Soil water potential, percent cover, leaf area index, and plant height in each of six plots are presented in Table 4. Alfalfa data were obtained from two different plots. During the July 24-25 and August 2-3 periods measurements were made in the main alfalfa field. A second alfalfa plot was used on August 17-18 because the main field had been recently harvested.

4.3 Crop, Air and Soil Temperature Measurements

4.3.1 July 24-25, 1976

Patterns of crop, air and soil temperature for all crops are presented in Figs. 10 to 15.

a) Leaf Temperature Profile

The temperature profile was influenced by the type of crop canopy. In alfalfa and soybean, for example, there was generally a clear distinction between the temperature of the three layers during the day. $T_{TC\ 3}$ was usually warmer than $T_{TC\ 2}$ which was warmer than $T_{TC\ 1}$. The only exception to this general pattern (during this period) was observed in the soybean broadcast plot after 1500 hours on July 25 when the three levels were at similar temperatures. The sorghum plots showed that the three levels were at about the same temperature. These results agree with those reported by Teare and Kanemasu (1972).

At night the lower leaves ($T_{TC\ 1}$) were slightly warmer than the upper leaves ($T_{TC\ 3}$) in all crops.

b) Air Temperature

Patterns of air temperature at the highest level measured ($T_{a\ 3}$) and leaf temperature ($T_{TC\ 3}$) are shown in Figure 10b to 15b. In general, $T_{a\ 3}$ is slightly warmer than $T_{TC\ 3}$ at night. However, $T_{a\ 3}$ is

Table 4. Crop cover, leaf area index, plant height and soil water potential in each plot during the three study periods.

Date 1977	Crop	Crop Cover	Leaf Area Index	Soil Water Potential (bars)	Plant Heights cm
July 24-25	Alfalfa	95-100	3.17	- 1.9	50
	Grass	75-80		- 1.6	11
	Soybean Broad.	100	5.85	- 1.4	70
	Soybean Row	75-85	6.74	- 1.2	66
	Sorghum Broad.	85-90	5.21	- 1.0	71
	Sorghum Row	70-80	5.12	- 1.0	73
August 2-3	Alfalfa	80-100		- 5.0	63
	Grass	100		- 8.4	12
	Soybean Broad.	100		- 8.4	84
	Soybean Row	100		- 2.7	90
	Sorghum Broad.	90-100		- 2.3	71
	Sorghum Row	80-90		- 2.7	73
August 17-18	Alfalfa[1]	85		- 3.2	54
	Grass	100		- 8.4	12
	Soybean Broad.[2]	100	4.58	-11.0	72
	Soybean Row	100	4.79	- 8.4	93
	Sorghum Broad.	100	4.97	- 9.4	71
	Sorghum Row	100	5.45	-14.0	73

1 Alfalfa plot used on August 17 is different from that used in the previous periods.

2 Soybean Broadcast was lodged to a considerable degree by August 17.

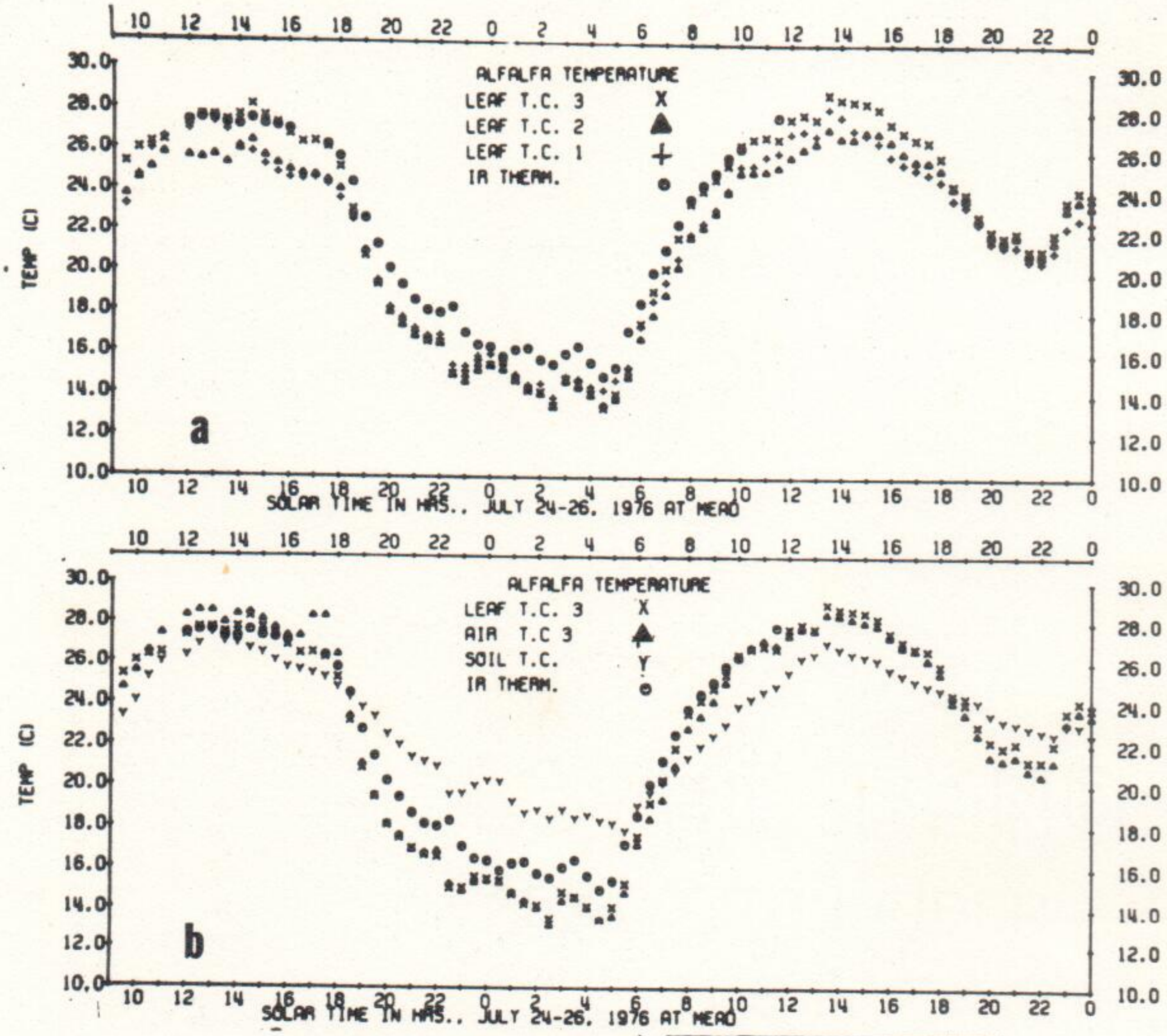


Fig. 10. (a) Daily pattern of alfalfa temperature measured with leaf thermocouples (T_{TC}) at three levels within the canopy and with an IR thermometer (T_{IR}) and (b) relationships between crop, air and soil temperature, July 24-25, 1976.

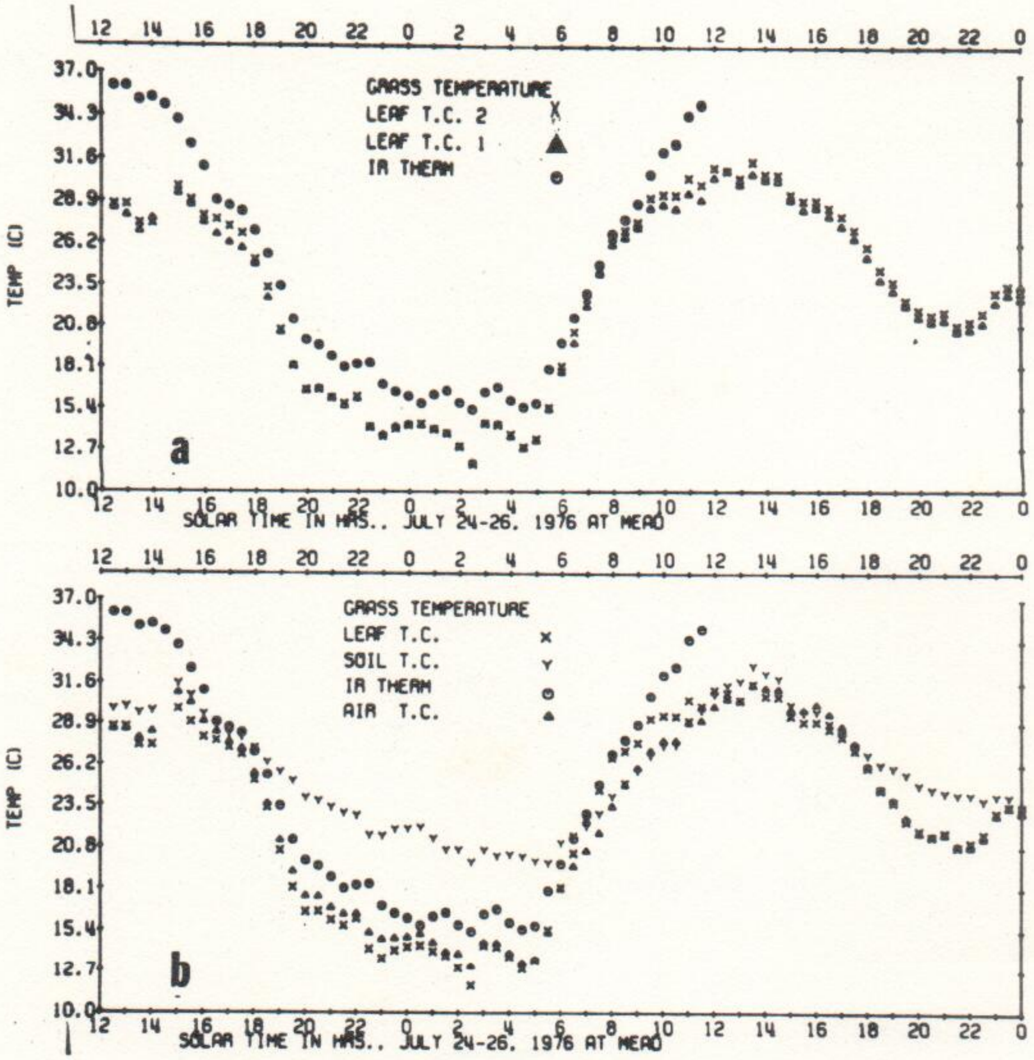
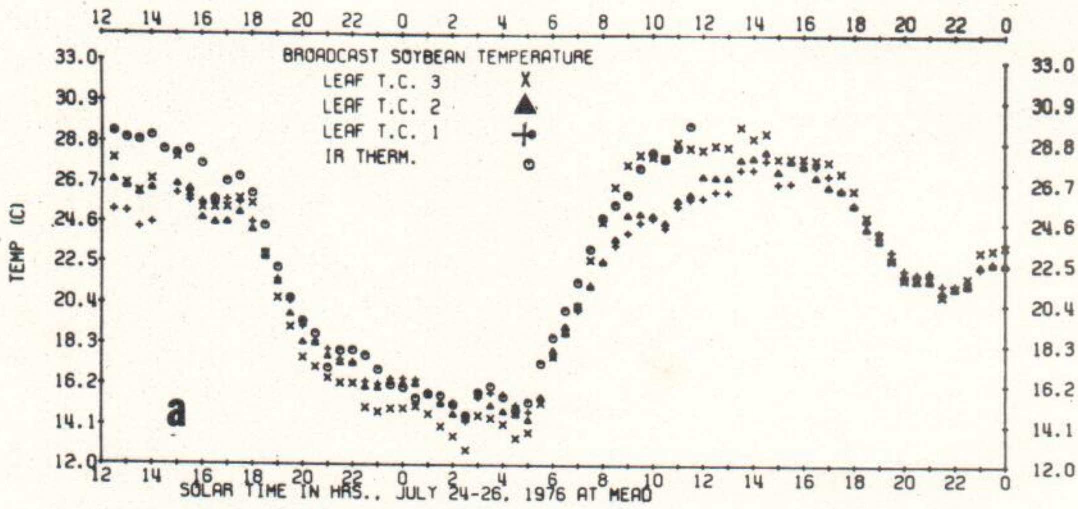


Fig. 11. (a) Daily pattern of grass temperature measured with leaf thermocouples (T_{TC}) and with an IR thermometer (T_{IR}) and (b) relationships between crop, air and soil temperature, July 24-25, 1976.



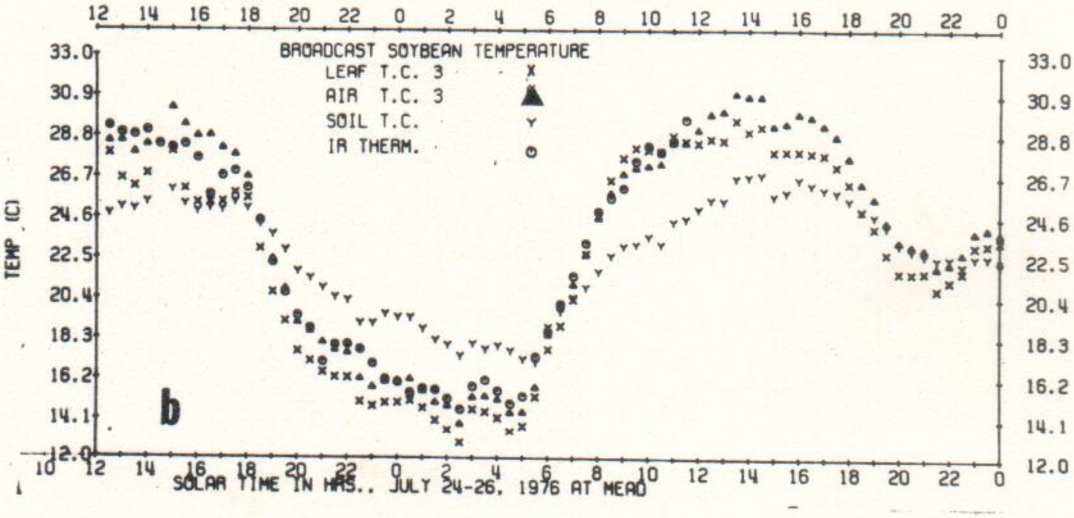


Fig. 12. As in Fig. 10 for soybean broadcast.

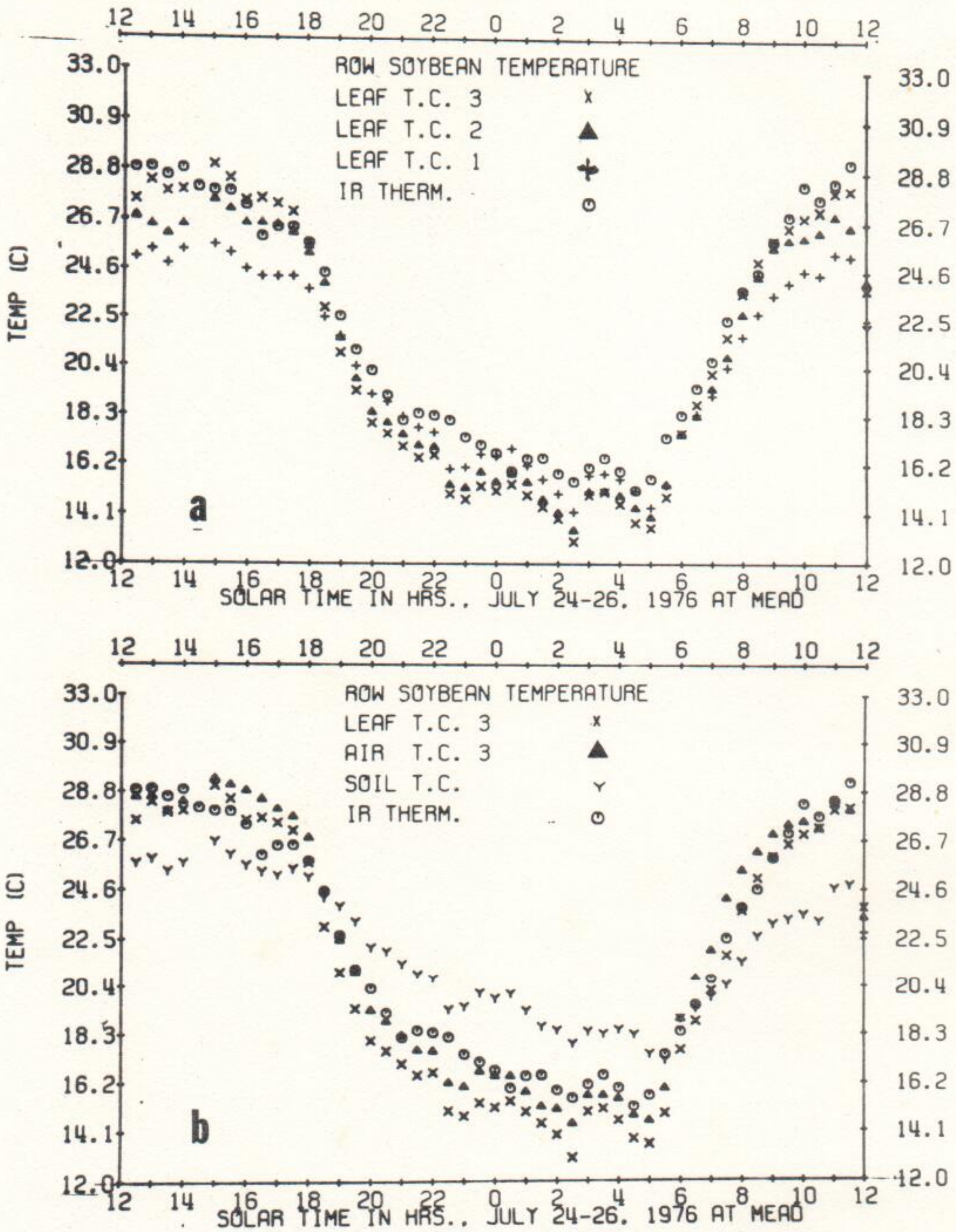


Fig. 13. As in Fig. 10 for soybean row.

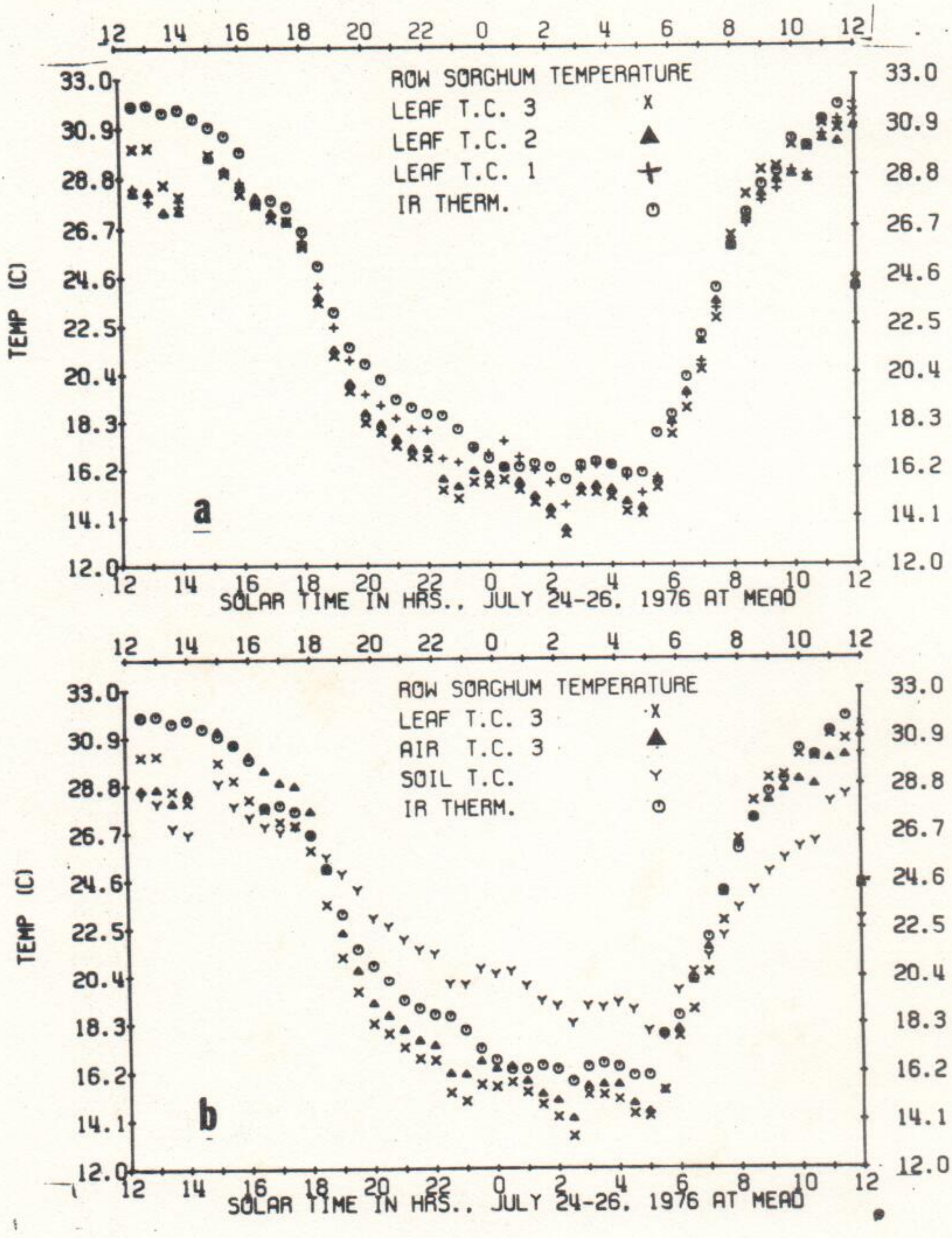


Fig. 14. As in Fig. 10 for sorghum row.

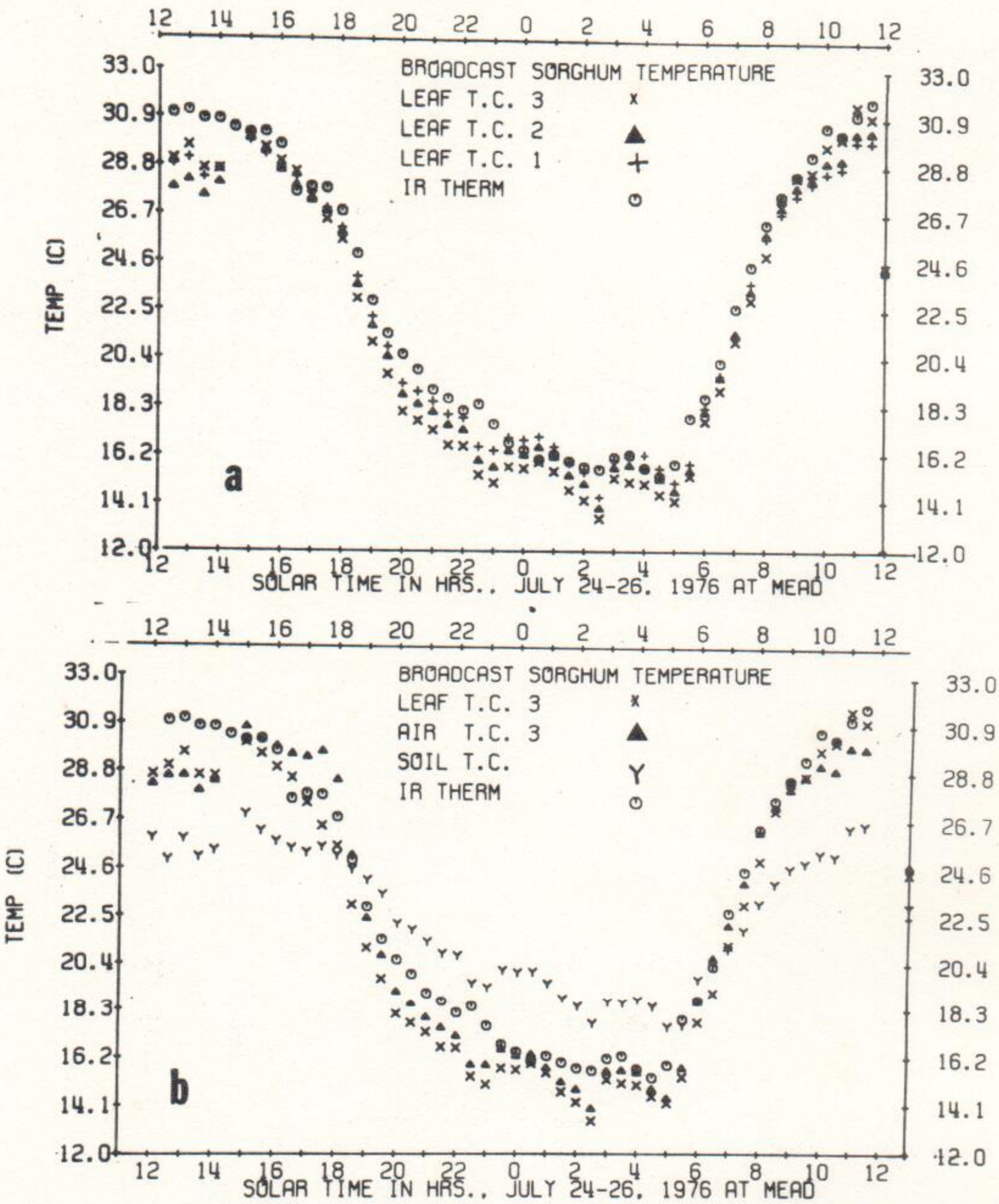


Fig. 15. As in Fig. 10 for sorghum broadcast.

generally closer to $T_{TC\ 3}$ than to T_{IR}. $T_{a\ 3}$ and $T_{TC\ 3}$ tended to show closer agreement at night than during the day. During hours of high transpiration demand (around noon) $T_{a\ 3}$ was generally warmer than $T_{TC\ 3}$.

c) Soil Temperature Patterns

Soil temperature pattern for the six different plots are presented in Fig. 16. The soil was warmest in the grass plot followed by the sorghum row and sorghum broadcast plots. Soil temperature in the alfalfa and both soybean plots were similar and all were 2 to 6 C cooler than the other plots. These data, together with those presented in Fig. 10b to 15b are useful for understanding the agreement of crop temperature as measured with leaf thermocouple and infrared thermometer techniques. Patterns of soil temperature in relation to leaf temperature are presented in Figs. 10b to 15b. The soil has generally about 3 C cooler than the leaves during the day but at night it was 2 - 5 C warmer than the leaves.

d) Comparison of Crop Temperature as Measured with Leaf Thermocouples and an Infrared Thermometer

T_{IR} agreed better with $T_{TC\ 3}$ than with $T_{TC\ 2}$ or $T_{TC\ 1}$ during daytime periods, particularly in the alfalfa and soybean plots. In general, the agreement between T_{IR} and T_{TC} was better (to within about 1 C) during the daytime. At night, T_{IR} was 1 to 3 C warmer than T_{TC}.

Grass presented a completely different pattern. T_{IR} was considerably warmer (as much as 6 C) than T_{TC} in the early afternoon of July 24 and late morning of July 25 (Fig. 11a).

4.3.2 August 2-3, 1976

Patterns of crop, air and soil temperature for the six plots during the August 2-3 period are shown in Figs. 17 to 22.

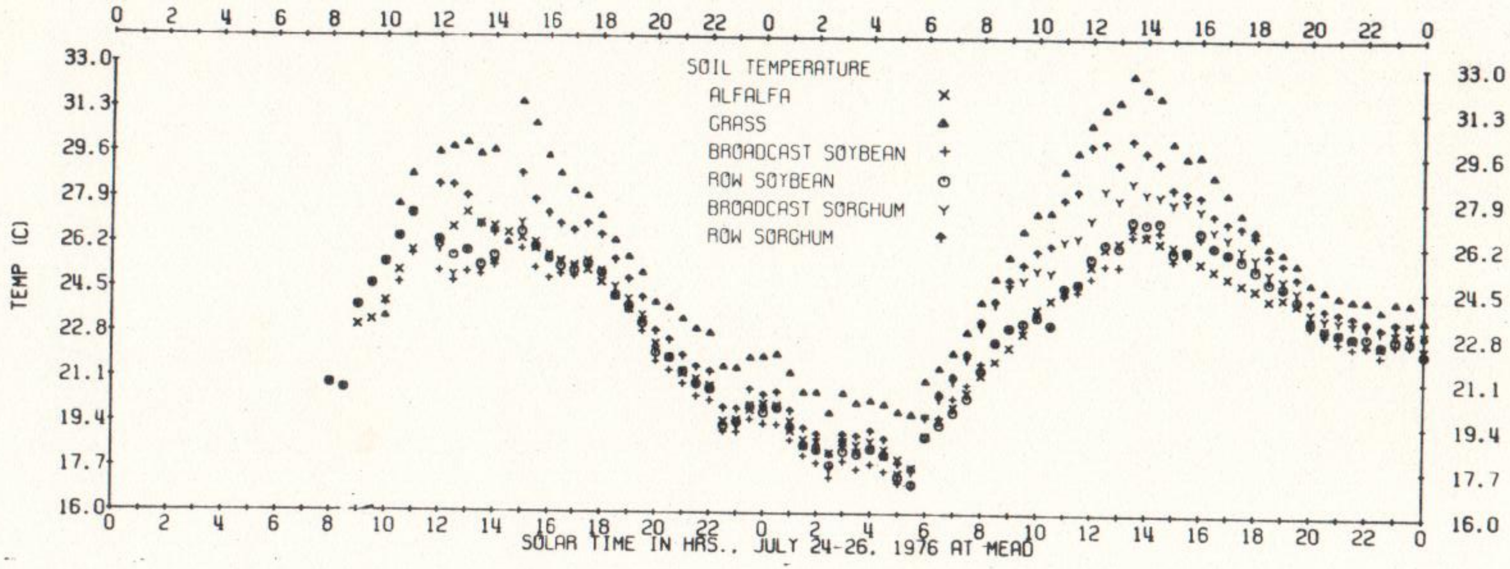


Fig. 16. Soil temperature patterns for the six crops. July 24-25, 1976.

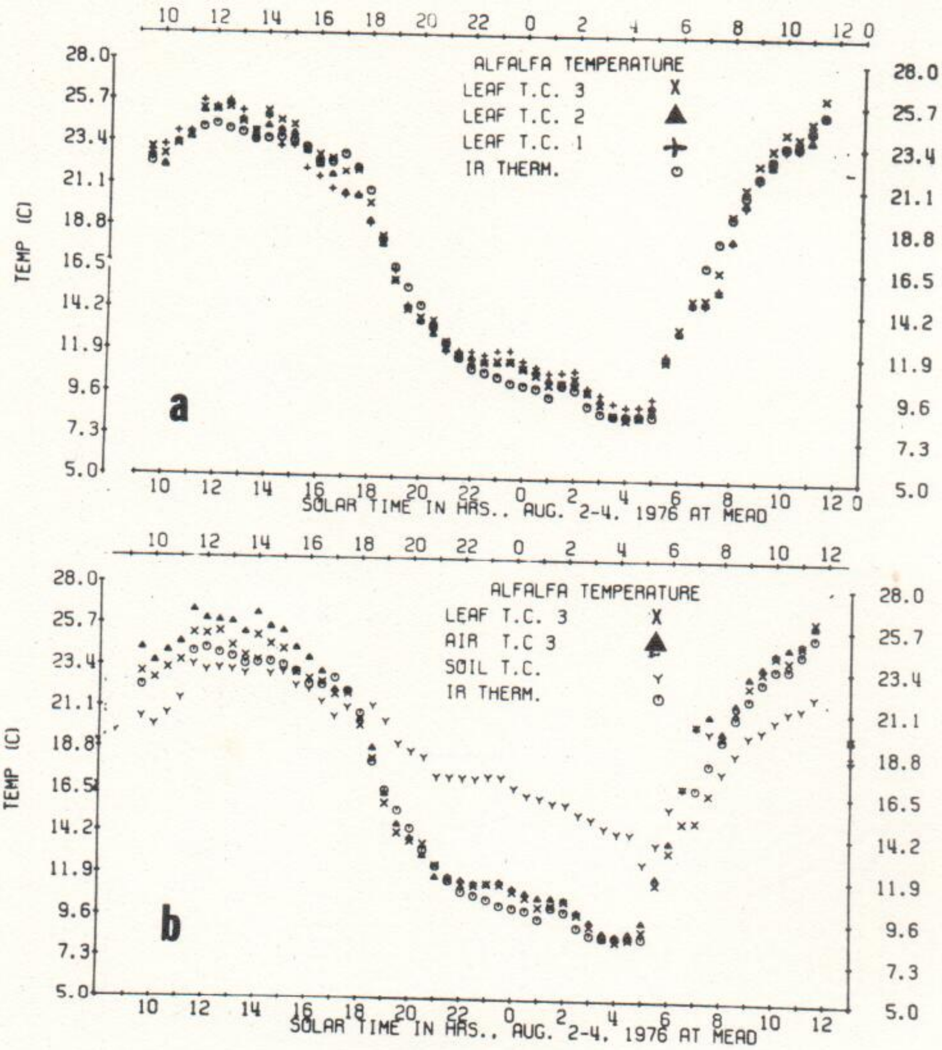


Fig. 17. As in Fig. 10 for August 2-3, 1976.

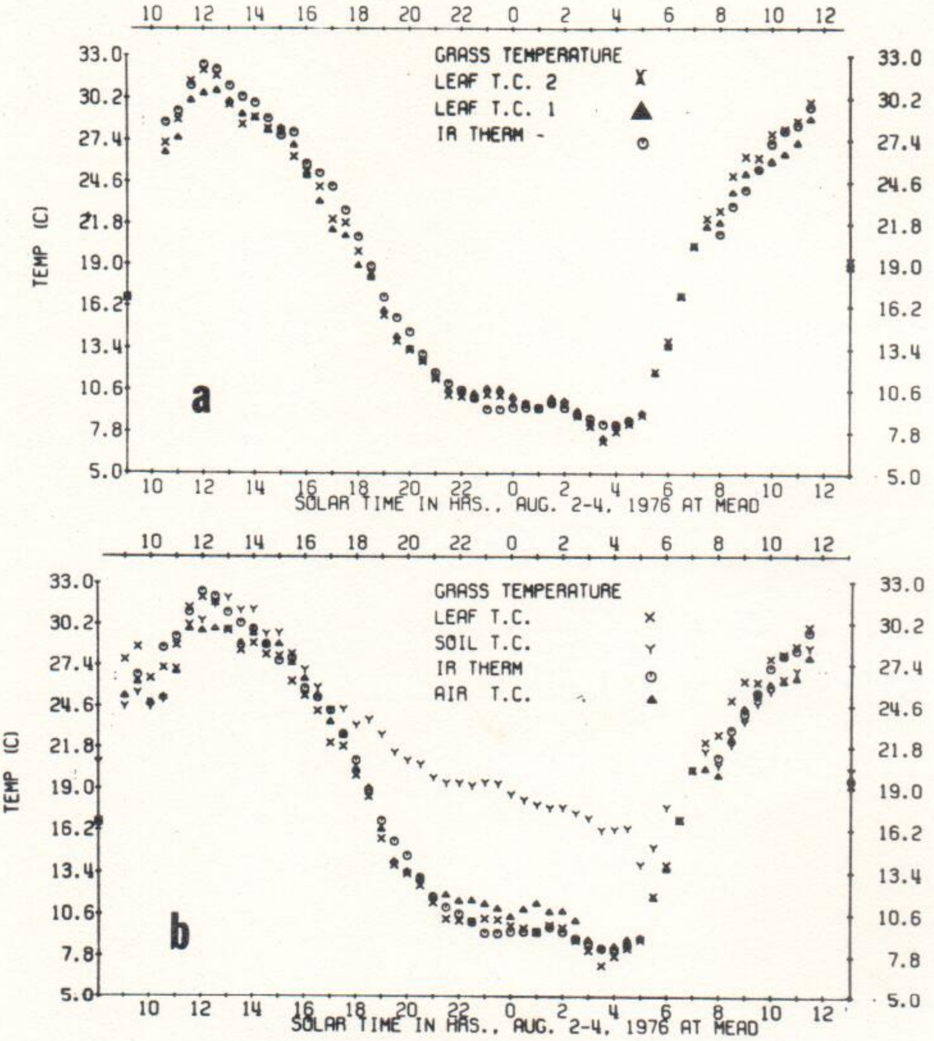


Fig. 18. As in Fig. 11 for August 2-3, 1976.

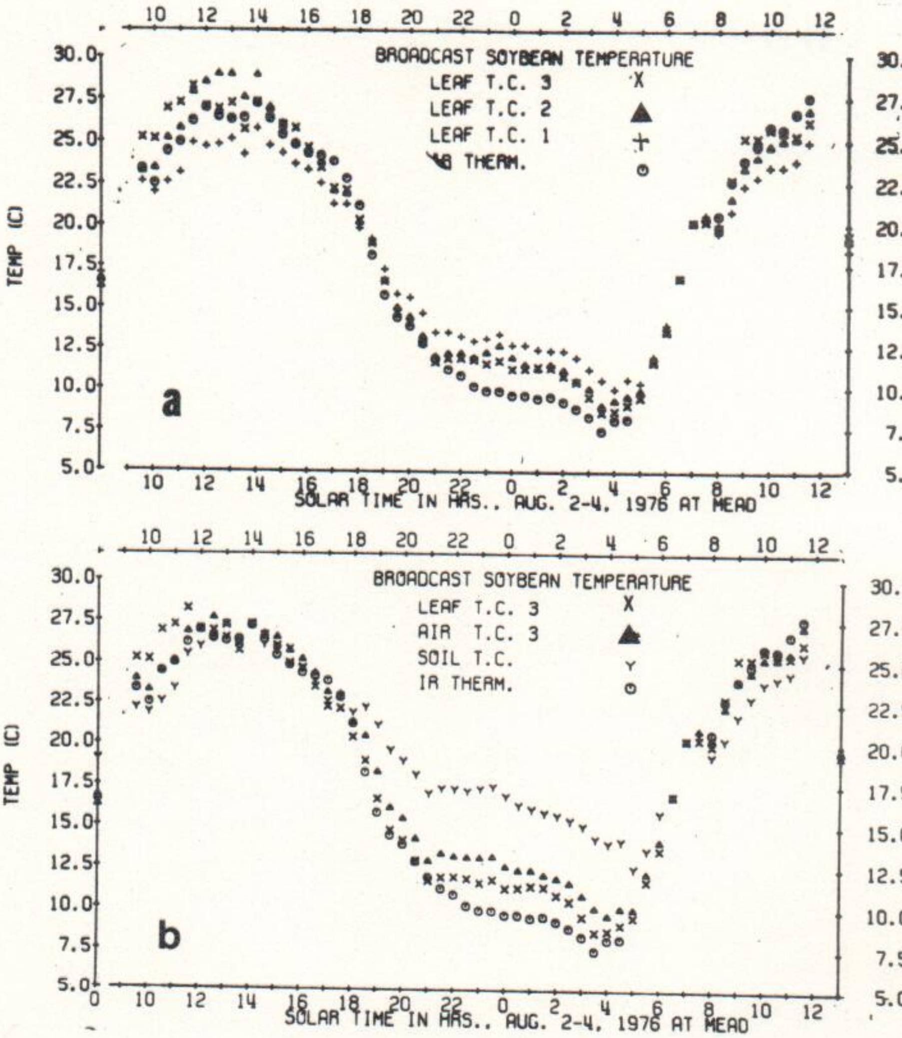


Fig. 19. As in Fig. 12 for August 2-3, 1976.

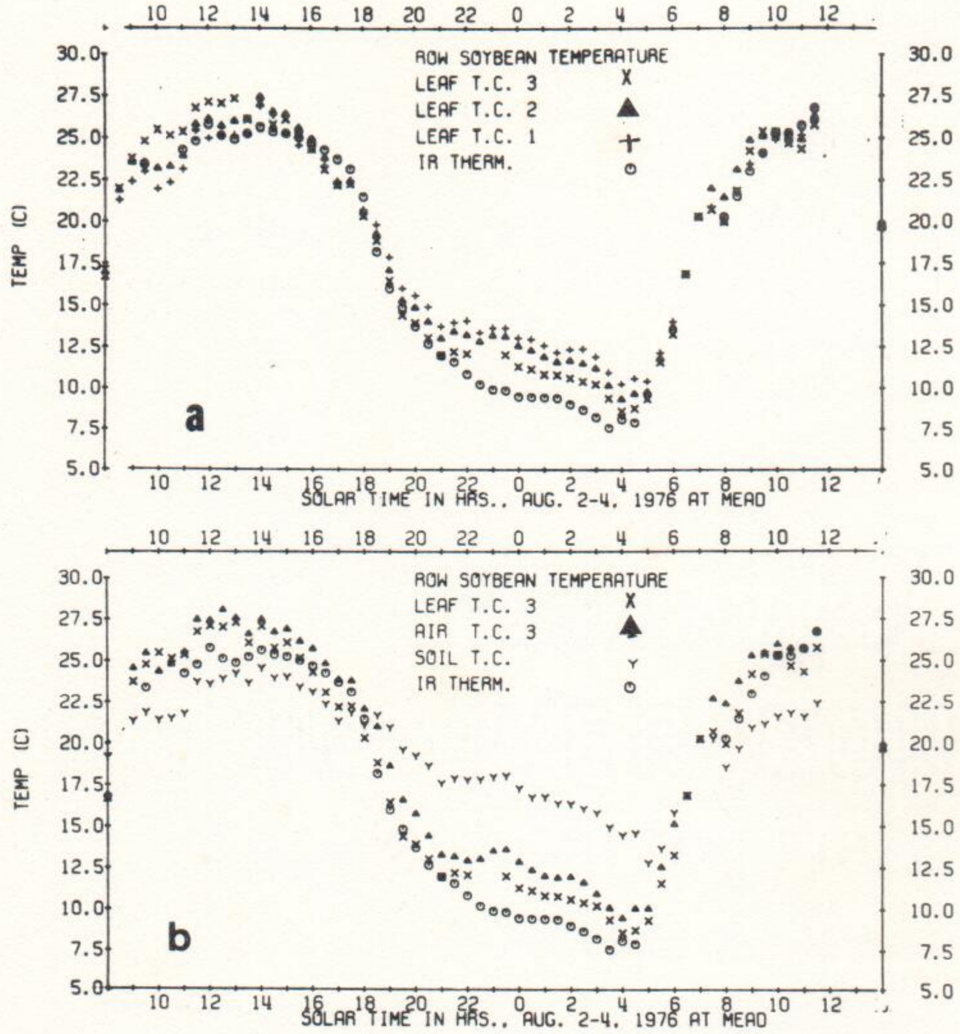


Fig. 20. As in Fig. 13 for August 2-3, 1976.

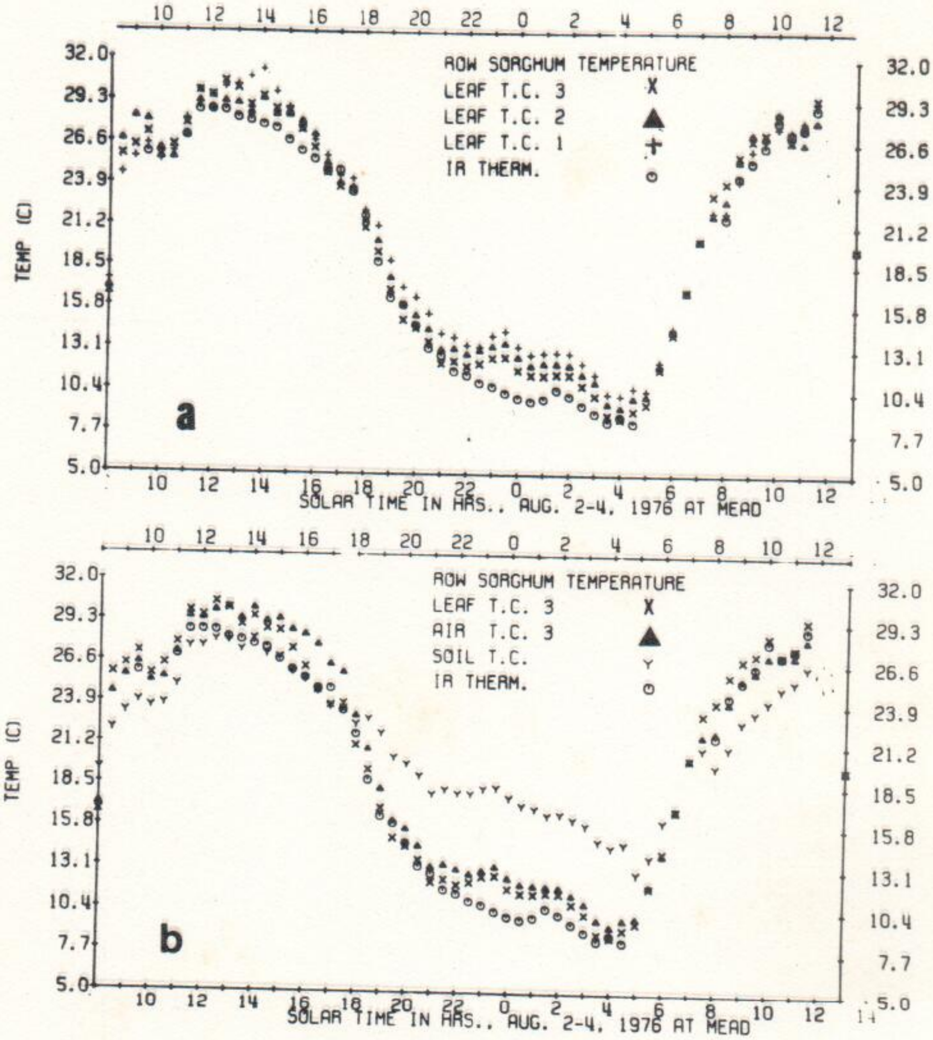
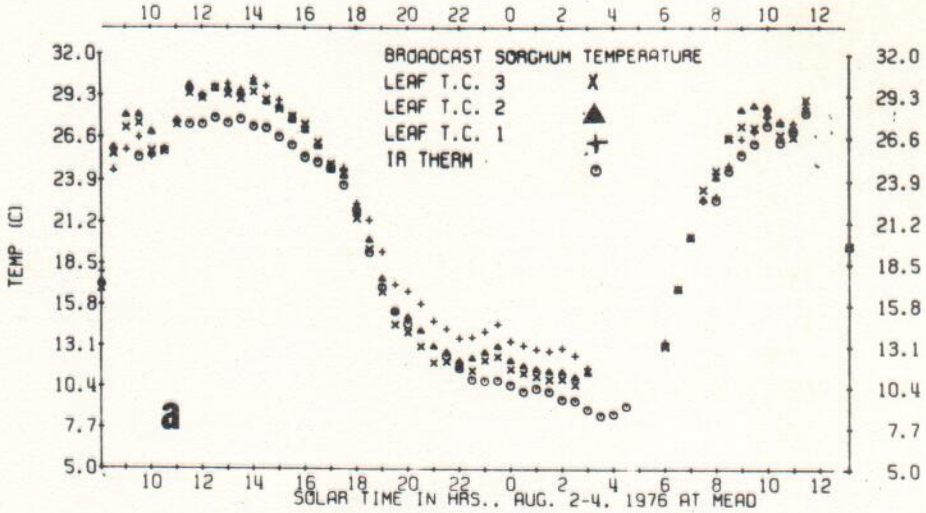


Fig. 21. As in Fig. 14 for August 2-3, 1976.



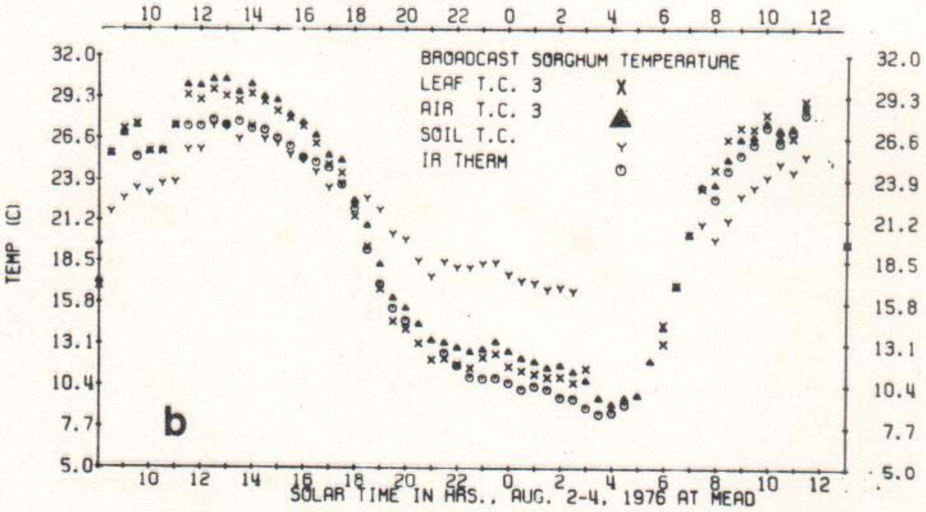


Fig. 22. As in Fig. 15 for August 2-3, 1976.

a) Leaf Temperature Profile

The day and night time patterns in leaf temperature profile were similar to those observed on July 24-25. The main exceptions were in alfalfa and both soybean plots. During the morning and early afternoon of August 2, temperatures of the three levels were similar in the alfalfa plot. In the afternoon, $T_{TC\ 2}$ and $T_{TC\ 1}$ were cooler than $T_{TC\ 3}$. In the morning of the next day differences between the three levels were small although $T_{TC\ 3}$ was consistently higher than the temperatures at the other levels.

The temperature profile of soybean broadcast was different from that of July 24-25 only in respect to $T_{TC\ 2}$. For some unexplained reason $T_{TC\ 2}$ was higher than $T_{TC\ 3}$ from 1200 to 1400 hours on August 2.

In the soybean row plot, there was a clear distinction between the three levels only from 0900 to 1400 hours on August 2. After that the temperature of the three levels was very similar. The same pattern was observed the next morning.

b) Air Temperature

Analysis of the air temperature data indicated that the low level ($T_{a\ 1}$) was slightly cooler than the high level ($T_{a\ 3}$) during the day in all plots. The reverse situation occurred at night. Figs. 17b to 22b show the agreement between $T_{a\ 3}$ and $T_{TC\ 3}$. At night in the grass and both soybean plots $T_{a\ 3}$ was about 1 C warmer than $T_{TC\ 3}$. However, alfalfa and both sorghum plots showed excellent agreement between the two temperatures. During the day $T_{TC\ 3}$ and $T_{a\ 3}$ showed a pattern similar to that on July 24-25.

c) Soil Temperature Patterns

The pattern of soil temperature for the six plots are shown in Fig. 23. Grass was the warmest plot followed by sorghum row and

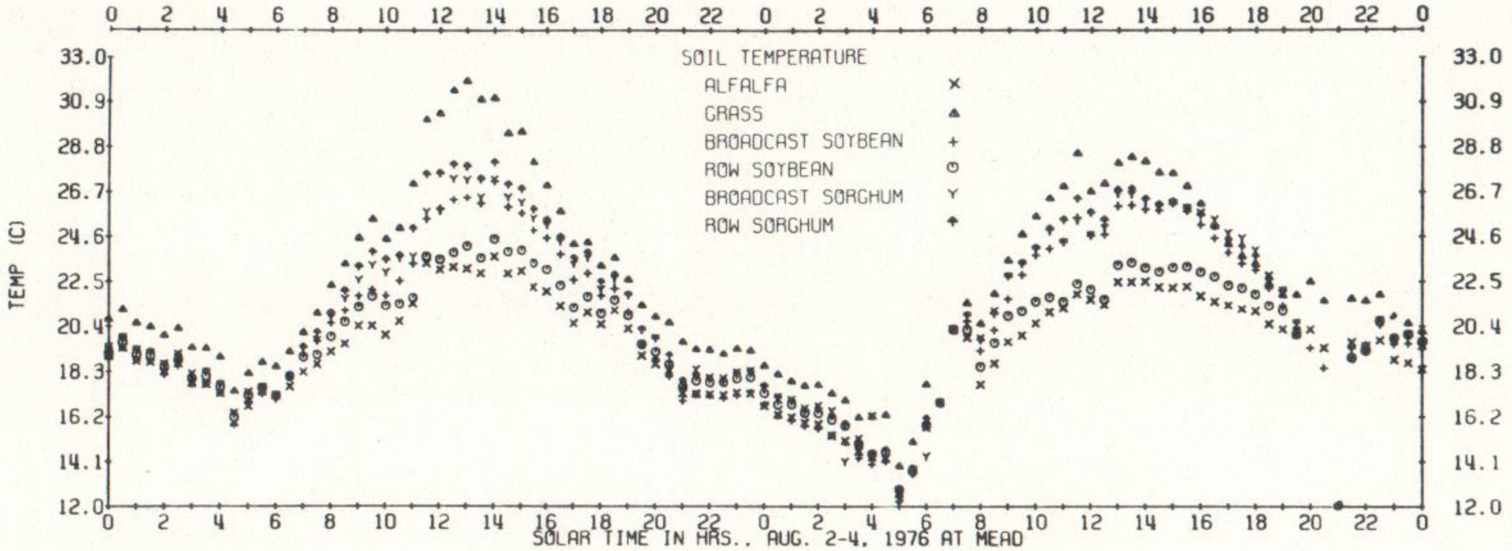


Fig. 23. As in Fig. 16 for August 2-3, 1976.

sorghum broadcast. Soil temperature in the soybean broadcast plot was nearly as warm as the sorghum broadcast plot and was 2 to 3 C warmer than in the soybean row. Soil temperature in the alfalfa plot was consistently lower than any of the other plots. Patterns of soil temperature in relation to leaf temperature are presented in Figs. 17b to 22b. The soil is generally 1 to 3 C cooler than the leaves during the day and as much as 6 C warmer than the leaves at night.

d) Comparison of Crop Temperature as Measured with Leaf Thermocouples and an Infrared Thermometer

The IR thermometer data for this 27 hour period is suspect for reasons previously discussed in section 3. Furthermore, the temperature pattern measured by the IRT during this period does not agree with the T_{IR} patterns during the other two measurement periods. The IR thermometer underestimated the crop temperature, even at night when T_{IR} should have been warmer than T_{TC}.

4.3.3 August 17-18, 1976

The stand of alfalfa in the plot used during this period was not as good as the one used previously. The stand was inferior, growth was less vigorous and crop cover was incomplete. The plot had been irrigated two days before data were collected.

Results of crop, air and soil temperature measurements for all plots are shown from Figs. 24 to 29.

a) Leaf Temperature Profile

Results of leaf temperature measurement in three levels within the canopy are shown in Figs. 24a to 29a. In general, each individual plot presented similar temperature profiles to those obtained in the two previous study periods.

Lower leaves ($T_{TC\ 1}$) in the alfalfa plot, were slightly

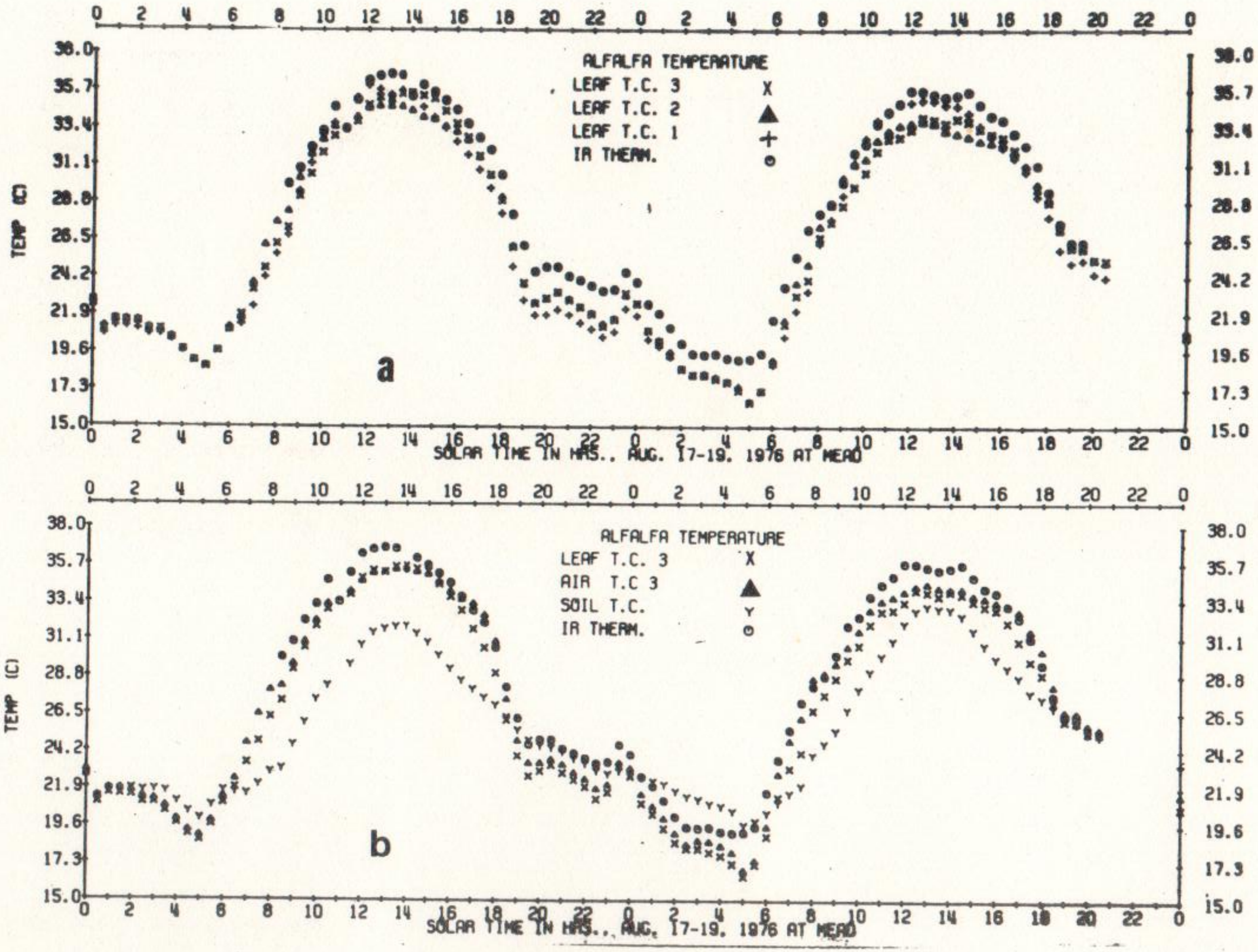


Fig. 24. As in Fig. 10 for August 17-18, 1976.

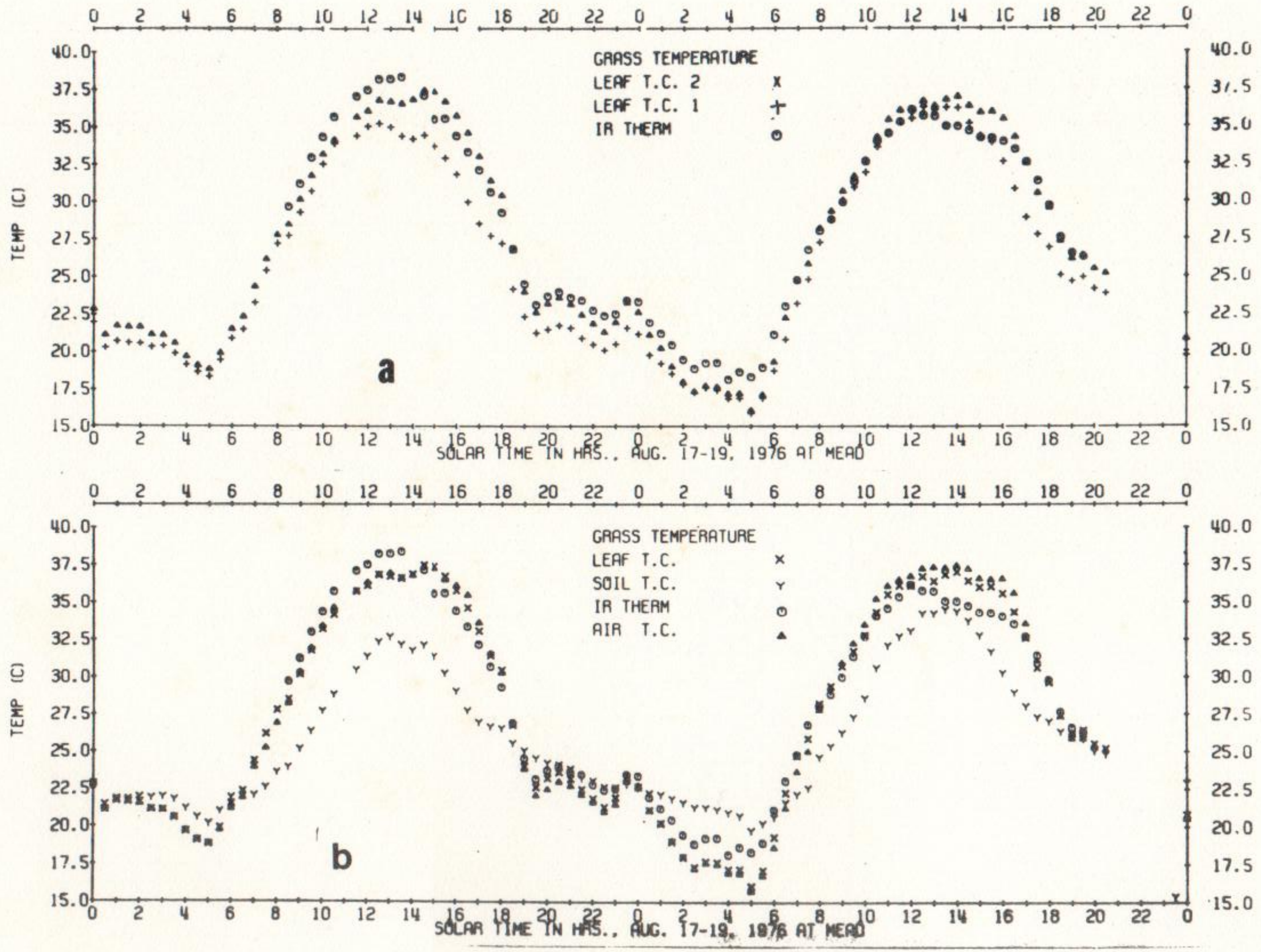


Fig. 25. As in Fig. 11 for August 17-18, 1976.

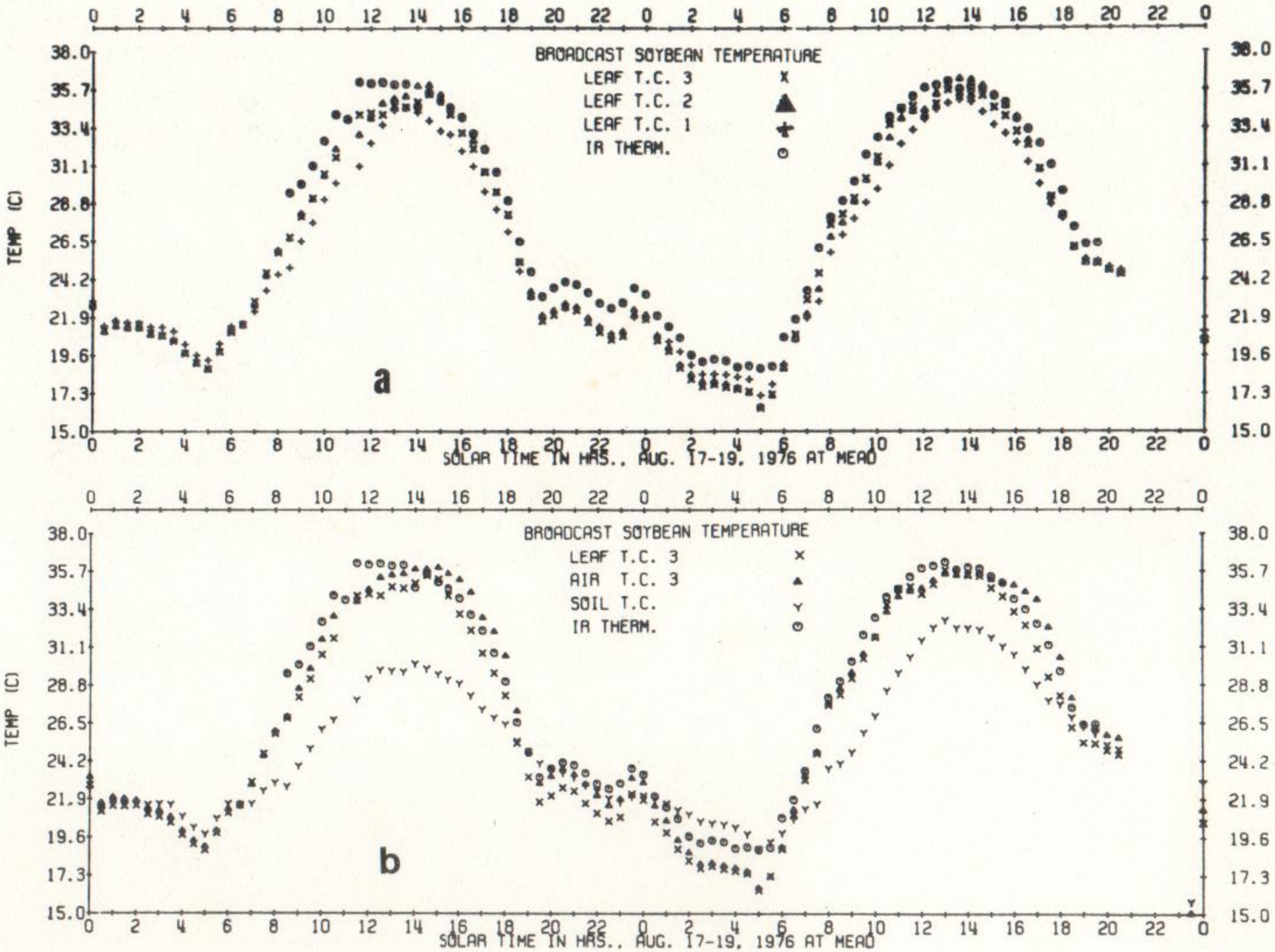


Fig. 26. As in Fig. 12 for August 17-18, 1976.

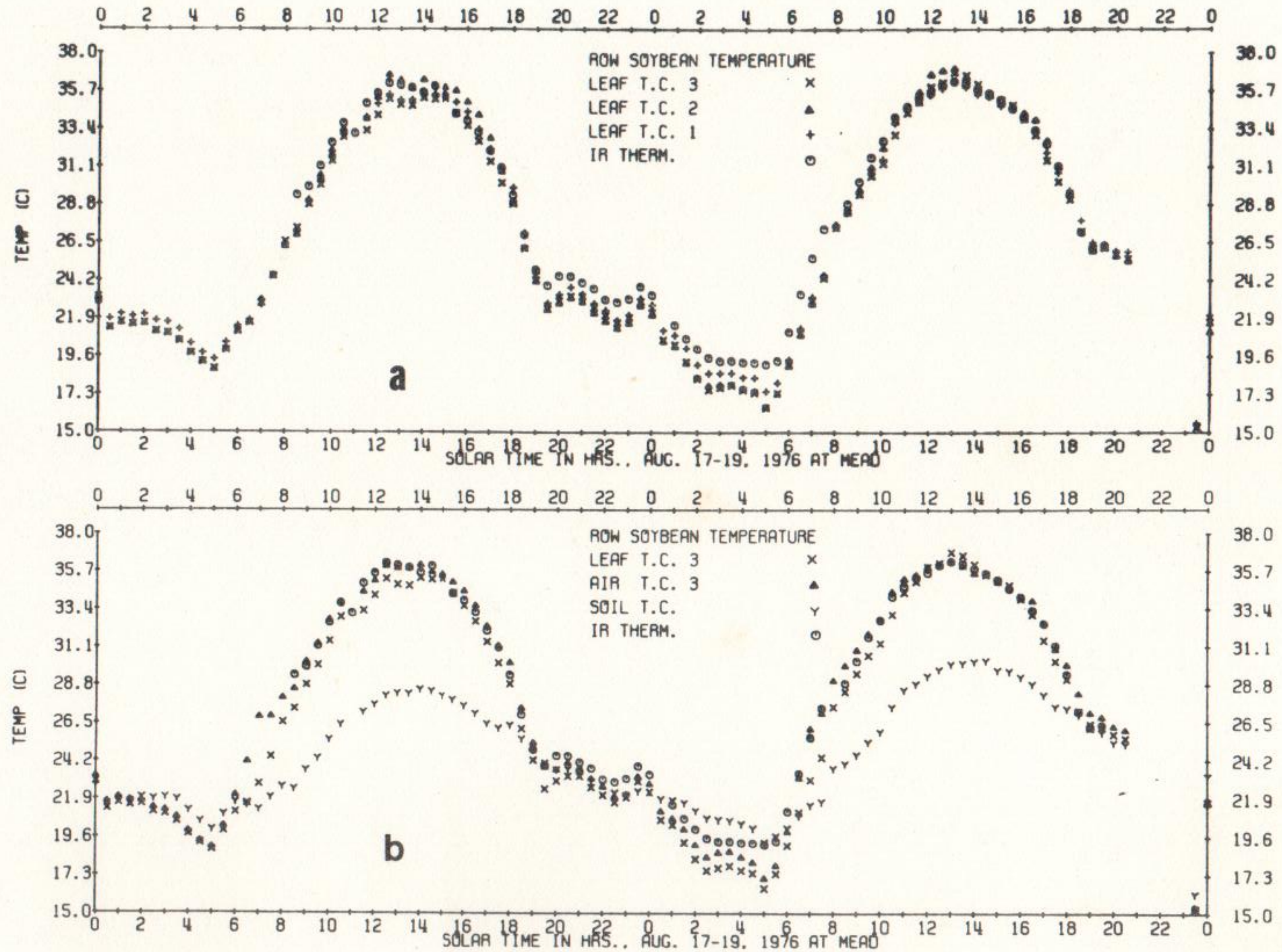


Fig. 27. As in Fig. 13 for August 17-18, 1976.

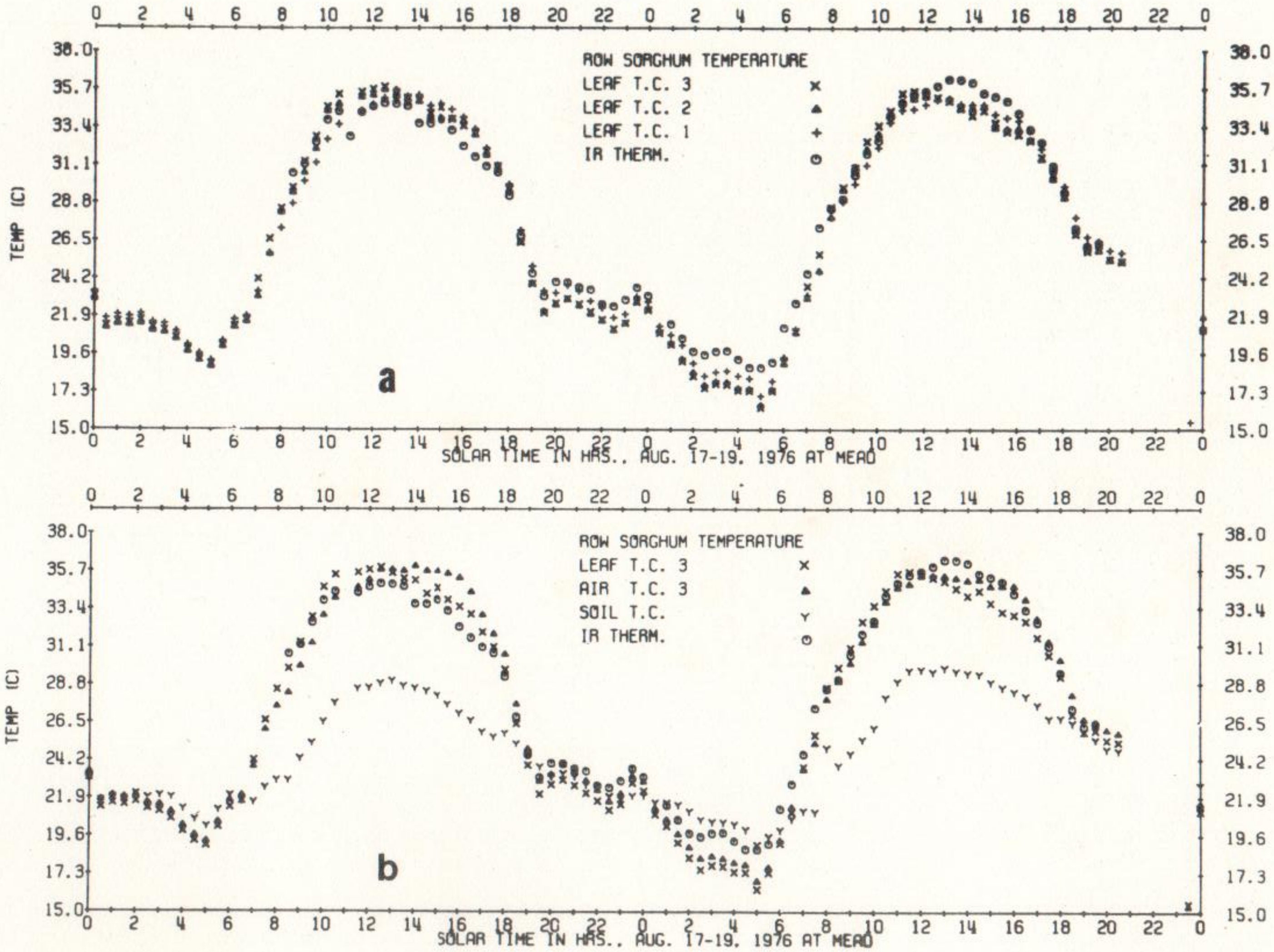


Fig. 28. As in Fig. 14 for August 17-18, 1976.

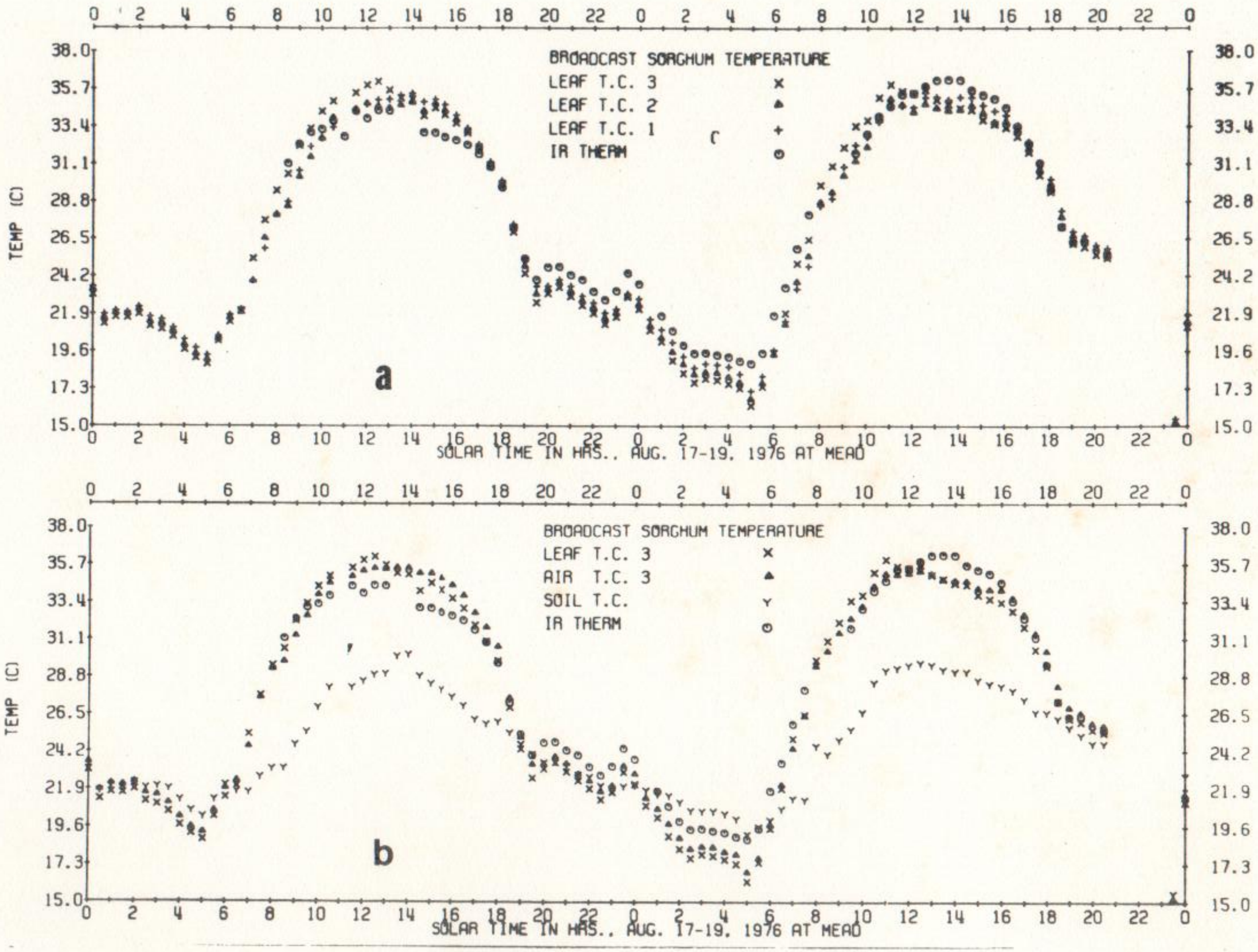


Fig. 29. As in Fig. 15 for August 17-18, 1976.

warmer than the upper ones ($T_{TC\ 3}$) from 1000 to 1400 hours on August 17. After that, the reverse situation was observed. The same pattern was obtained from 0900 to 1500 hours on August 18, except that during this period $T_{TC\ 1}$ was about 1 C higher than $T_{TC\ 3}$ and $T_{TC\ 2}$. Surprisingly, the lower leaves were slightly cooler or at the same temperature as the upper ones before and after midnight. These results differed from those of the first two study periods.

A very unusual pattern of $T_{TC\ 2}$ versus $T_{TC\ 1}$ was observed in the grass plot. Since both sets of thermocouples were attached to similarly exposed leaves they should have indicated similar temperatures. However, $T_{TC\ 1}$ was as much as 3 C lower than $T_{TC\ 2}$ in the afternoon of August 17 (Fig. 25a).

Soybean broadcast presented a profile very similar to that observed in the two previous study periods: $T_{TC\ 3}$ and $T_{TC\ 1}$ were, respectively, the warmest and the coolest layers within the canopy. At night the temperature at all levels was essentially equal until about 0200 hours. After that time, $T_{TC\ 1}$ was slightly higher than the other levels.

Very small differences between leaf temperatures at any of the three levels were observed during the day in the soybean row and both sorghum plots. At night, $T_{TC\ 1}$ was a little higher than $T_{TC\ 2}$ or $T_{TC\ 3}$ in the very early morning hours.

b) <u>Air Temperature</u>

An unusual nocturnal plant and air temperature pattern was observed for all plots on August 17-18. As shown in Figs. 24 to 29, there was a sudden increase in the leaf and air temperature around midnight. During this period a sudden increase in the wind speed occured. The air above was 2 C warmer than the canopy; the wind might have increased turbulent mixing and carried warm air into the canopy thereby increasing canopy temperature.

Comparisons of air temperature within the canopy and at 2 m above the ground, indicated that, in general, the air at 2 m was slightly cooler during the day and 1 to 2 C warmer at night. During the day $T_{a\ 3}$ was, in general, slightly higher than $T_{a\ 1}$. At night, there was practically no difference between these two levels.

Patterns of air and leaf temperature measured in the upper canopy (level 3) are shown in Figs. 34b to 29b. As observed in the previous measurement periods, air and leaf temperatures are similar at night. $T_{a\ 3}$ was slightly warmer than $T_{TC\ 3}$ during the late afternoon.

c) Soil Temperature Patterns

Soil temperature patterns for the six crops are presented in Fig. 30. As in the two previous periods, soil in the grass plot was warmest. Alfalfa and soybean broadcast had the second and third warmest soil surfaces, respectively. Soybean row and both sorghum plots had the coolest soil surfaces.

As mentioned in section 4.1, August 17-18 were the two warmest days (and nights) on which data were collected. A comparison of the soil and leaf temperature indicates that during the day, the soil was 3 to 7 C cooler than the leaves. This difference is much greater than in the two previous periods. A different pattern was also observed at night. Soil was only about 2 C warmer than the leaves until about 0100 hours of August 18. After that the soil became as much as 3 C warmer than the leaves (Figs. 24b to 29b). On the night of August 2-3 (the coolest night) soil temperature was as much as 6 C warmer than the leaves during practically the entire night. The nighttime soil-leaf temperature pattern on August 17-18 differed greatly from that on July 24-25 and August 2-3.

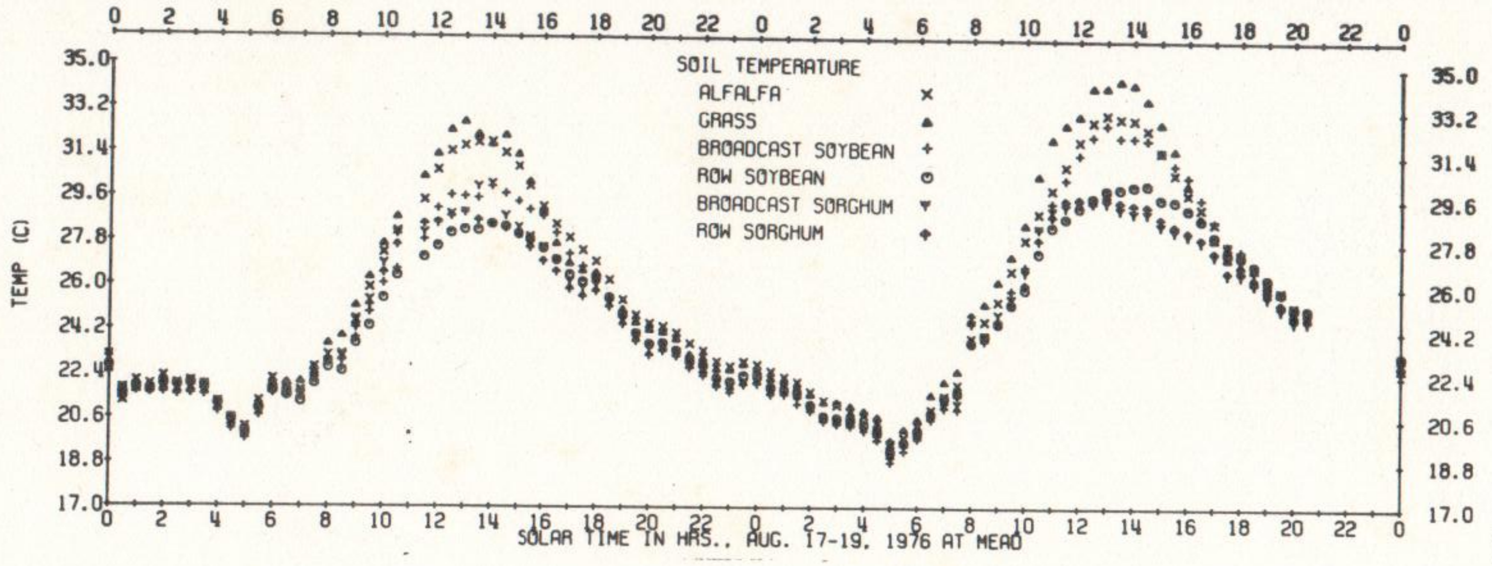


Fig. 30. As in Fig. 16 for August 17-18, 1976.

An explanation for this difference may be that at the earlier times the leaves were radiating to a much colder atmosphere. Since the air temperature was very warm on August 17-18 the leaves may not have lost as much heat by either radiation or convection, and consequently they were only 1 to 3 C cooler than the soil. This effect was observed in each of the plots.

d) Comparison of Crop Temperature as Measured with Leaf Thermocouples and an Infrared Thermometer.

In general, the agreement between T_{TC} and T_{IR} was very good (to within about 1 C) during the day. On the whole, T_{IR} agreed slightly better with the temperature of the sunlit leaves than with the other two levels. At night, in all plots, T_{IR} was closer to $T_{TC\ 1}$ than to $T_{TC\ 3}$.

An unusual pattern was observed in the alfalfa plot from 0900 to 1500 hours of August 18. During this period T_{IR} agreed much closer with $T_{TC\ 1}$ than with the other two levels (Fig. 24a).

Much better agreement between T_{IR} and T_{TC} in grass was observed during this period than on July 24-25. This is particularly true if $T_{TC\ 2}$ is considered to estimate the surface temperature more accurately than $T_{TC\ 1}$.

Except for a short period - 0830 to 1400 hours on August 17 when T_{IR} was almost 2 C warmer than any of the leaf thermocouples, the soybean broadcast showed an excellent (better than 1 C) agreement between $T_{TC\ 3}$ and T_{IR} during the day. At night, as usual, T_{IR} was about 2 C higher than $T_{TC\ 3}$. Excellent agreement between temperatures measured by the two methods during the daytime was observed for the soybean row. At this time, T_{IR} agreed equally well with T_{TC} at all three levels. This pattern is different from that observed in this plot on July 24-25.

T_{IR} and T_{TC} also agreed very well in both sorghum plots during the day. Again T_{IR} agreed about equally well with the thermocouple measured temperatures at any of the levels.

4.3.4 Discussion

4.3.4.1 Leaf Temperature Profile

Data collected during the three measurement periods showed a distinct temperature profile within the canopies of alfalfa and both soybean plots. The primary reason why the upper leaves ($T_{TC\ 3}$) were warmer than the lower ones ($T_{TC\ 1}$) during the day is that the canopy structure of these crops is such that the upper leaves absorb most of the incoming radiation thereby restricting the penetration of solar radiation to the lower leaves. With less absorbed radiation the interior shaded leaves would be cooler than the peripheral sunlit leaves.

The main exceptions to this general pattern were presented by: 1) alfalfa (0900 to 1500 hours of August 18) - during this period the lower leaves ($T_{TC\ 1}$) were often as warm or warmer than the leaves at the other two levels. The crop cover and leaf density were severely reduced from what they had been in the alfalfa plot used during the earlier two study periods. This permitted solar radiation to penetrate to and heat the lower leaves; 2) soybean row (August 17-18) - there was practically no difference in the temperature of the three levels during the daytime of August 17 and 18. A reasonable explanation for this unusual pattern is not known.

Both sorghum plots (row and broadcast) showed no clear distinction between $T_{TC\ 3}$, $T_{TC\ 2}$ and $T_{TC\ 1}$ during the day. Due to its canopy structure, considerable solar radiation penetrated to and was absorbed by the lower sorghum leaves. Teare and Kanemasu (1972) measured a greater stomatal resistance in the lower leaves of sorghum than in the upper ones.

temperature was only about 1 C warmer than the upper leaves (Fig. 24b). After midnight the lower leaves became as warm as the upper ones. The temperature of the lower leaves may have been influenced by the transfer of warmer air from above into the canopy through the greater turbulence caused by the wind speed increase around midnight.

4.3.4.2 Air Temperature

Comparisons of air ($T_{a\ 3}$) and plant temperature ($T_{TC\ 3}$) measured at similar levels in the upper part of the canopy indicates that $T_{a\ 3}$ is in general warmer than $T_{TC\ 3}$ during the afternoon hours, suggesting a transfer of sensible heat from the air to the crop during this period. Comparisons of the nighttime air temperature with the crop temperature, as measured with leaf thermocouples and IR thermometer (T_{IR}) indicates that for most crops, $T_{a\ 3}$ agreed more closely with $T_{TC\ 3}$ than with T_{IR}. In soybeans however, $T_{a\ 3}$ often agreed equally well with T_{IR} and $T_{TC\ 3}$. This may reflect an increased influence of heat coming from the soil on $T_{a\ 3}$ in the dense soybean canopy.

4.3.4.3 Soil Temperature Patterns

On July 24-25, when all plots were at about the same soil moisture content, grass was the warmest plot followed by both sorghum plots (Fig. 16). These data suggest that the percent cover and crop morphology exert a strong influence on soil temperature through their effects on the amount of radiation penetrating to the soil surface.

The soil temperature pattern on August 2-3 was similar to that on July 24-25 except in the soybean plots. Soil temperature of the soybean broadcast plot was 2 to 3 C warmer than that of the soybean row. Temperatures of the soybean plots had been similar in the previous study period (Fig. 16). It seems that soybean broadcast, due to its higher

This suggested a lower transpiration rate and less cooling of the lower leaves. Such an effect could explain why the lower leaves of the sorghum plants were as warm as the upper leaves.

At night all crops presented a very distinct temperature profile within the canopy. The nighttime profile reversed that observed during the days. This was particularly true in alfalfa and soybean. The lower leaves were warmer than the intermediate or upper leaves. At night the upper surfaces of the peripheral leaves radiate to the cold skies while part or all of the radiation from the lower leaves is intercepted by other leaves nearby. In addition the warm soil is a source of heat at night. Those crops with dense canopies trap radiation emitted from the soil and absorb heat convected from it. The reduced wind movement within such canopies is also a factor which can cause a warming of the lower leaves. These factors tend to keep the lower interior leaves warmer than the upper exterior leaves.

The greatest and smallest temperature differences between the upper ($T_{TC\ 3}$) and lower ($T_{TC\ 1}$) leaves were observed on the nights of August 2-3 and August 17-18, respectively. On August 2-3, $T_{TC\ 1}$ was, except for alfalfa, 1 to 2 C cooler than $T_{TC\ 3}$. However, $T_{TC\ 1}$ and $T_{TC\ 3}$ were at similar temperatures on August 17-18. Soil temperature was as much as 6 C warmer than the leaves on August 2-3, a cool night. On August 17-18, a warm night, the soil was only 3 C warmer than the leaves (in the late night, early morning). Reasons for these patterns were discussed previously.

Alfalfa was the only crop to present a different leaf temperature profile on the night of August 17-18 (Fig. 24a). It seems that, at least until midnight, $T_{TC\ 1}$ kept its afternoon pattern (when it was slightly cooler than the other two levels). During this period, the soil plant population, had used more water than had the soybean row plot. Probably because of this, soybean broadcast had the driest soil among all crops (Table 4). Consequently, radiant energy reaching the soil surface would be used primarily to heat the soil and to generate sensible heat rather than to evaporate water.

The soil temperature data of August 17-18 (Fig. 30) indicate that the alfalfa and soybean broadcast plots were slightly cooler than grass, the warmest crop. It seems that, due to the poor alfalfa stand, solar radiation penetrated readily through the canopy to warm the soil surface, even though the soil moisture level was relatively high (Table 4). Soybean broadcast had one of the driest soil surfaces among all crops (Table 4). We also observed that, in some areas, plants were moderately lodged. Because of this, more solar radiation could have penetrated through the canopy to warm the dry soil.

4.3.4.4 Comparison of Crop Temperature as Measured with Leaf Thermocouples and an Infrared Thermometer

During the day, in the soybean row, soybean broadcast and the alfalfa plots, surface temperature measured with the IR thermometer gave better agreement with the thermocouple temperature of the sunlit leaves than with temperatures at the other two levels. This pattern was verified during the three study periods. Due to the canopy structure of these crops, the IR thermometer viewed mainly the upper peripheral leaves. An exception to this pattern was observed on the alfalfa plot on August 18 when T_{IR} agreed best with $T_{TC\ 1}$.

A different pattern of agreement between IR thermometer and leaf thermocouple temperatures, was observed in the sorghum row and sorghum broadcast plots. For these crops T_{IR} agreed about equally well with $T_{TC\ 3}$, $T_{TC\ 2}$ and $T_{TC\ 1}$. Since the temperature at all three levels, as observed during each study period, was so similar it appears that placement of thermocouples in canopies with structures similar to sorghum is less crucial for determining crop temperature than it is for crops with canopies structures similar to soybean or alfalfa.

The worst agreement between the two methods was observed in the grass plot on July 24-25. The poor agreement between T_{TC} and T_{IR} during the day may be explained as follows: green blades of grass were rather sparcely distributed and permitted a significant amount of solar radiation to penetrate the grass canopy. This caused the soil temperature to be slightly higher than that of the leaves (T_{TC}). This may explain, partially, the much higher temperature sensed by the IR thermometer. However, T_{IR} was still 3 to 5 C warmer than soil temperature (Fig. 11b). Probably the layer of senescent leaves covering the ground had a "mulching" effect. This non-transpiring material absorbed solar radiation and became much warmer than either the soil or the green blades. Consequently, the strong radiative flux from this hot, dead material sensed by the IR thermometer caused T_{IR} to be as much as 6 C warmer than T_{TC} under conditions of high radiative flux densities.

The agreement in crop surface temperature as measured with the two techniques was much better during the day than at night. During the day T_{IR} and T_{TC} agreed, in general, to within about 1 C (except in the case of grass). It seems that the soil temperature, which was usually 2 to 6 C cooler than the leaves, did not exert a major influence on the temperature sensed by the infrared thermometer, at least at the levels of crop cover in this study. At night, however, T_{IR} was usually 1 to 3 C warmer than $T_{TC\ 3}$. This suggests that, even though the crop cover was high, significant amounts of radiation from the warm soil were sensed by the IR thermometer. These results agree with and help to explain the findings of Blad et al. (1975) and of Blad and Rosenberg (1976).

At night, with no shortwave radiant heat load, the crop temperature should be nearly identical with the air temperature at the same levels. Comparisons of $T_{a\ 3}$ with T_{TC} and T_{IR} show that, for alfalfa, sorghum row and sorghum broadcast, $T_{a\ 3}$ was closer to $T_{TC\ 3}$ than to T_{IR}. This suggests that, at least at night, leaf thermocouples provided a better estimate of the plant temperature than did the IR thermometer. This was also true for the grass where air and leaf temperatures were measured at only one level. Blad et al. (1975) reported similar results for millet and sorghum.

Soybean row and soybean broadcast showed a different pattern than the other crops. In soybean, $T_{a\ 3}$ agreed better with T_{IR} than with $T_{TC\ 3}$. The reasons for such a pattern are discussed in section 4.3.4.2.

4.4 Comparison of the Temperature of alfalfa, grass, soybean (rows) and sorghum (rows)

4.4.1 July 24-25, 1976

Crop temperature differences measured with leaf thermocouples are shown in Fig. 31a. The temperature of each crop represents the average of thermocouples attached to six sunlit leaves. No great temperature difference existed among the crops on July 24th, but on July 25th a distinct pattern was observed. Sorghum and grass were the two warmest crops followed by soybean and alfalfa. Sorghum was as much as 3 C warmer than alfalfa. In general, grass and sorghum were about 2 C warmer than soybean and alfalfa. That was true for the entire morning and the early afternoon of July 25. As the afternoon progressed, soybean seems to have experienced some stomatal closure since its temperature became as warm as grass.

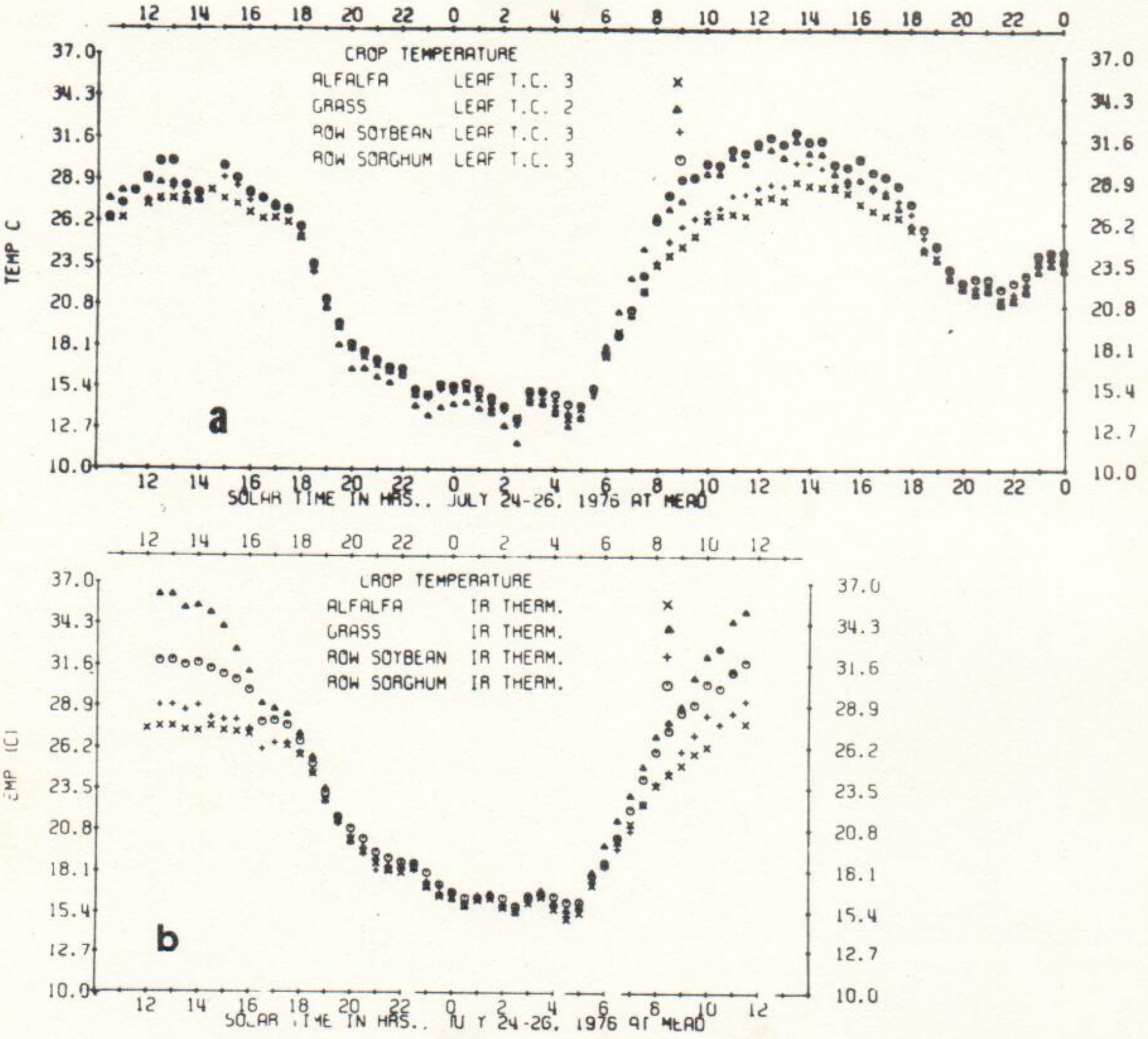


Fig. 31. Temperature patterns of alfalfa, grass, soybean (rows) and sorghum (rows) as measured with (a) leaf thermocouples and (b) IR thermometer, July 24-25, 1976.

Crop temperature differences, as measured with the infrared thermometer, are presented in Fig. 31b. In general, the patterns are similar to those measured with leaf thermocouples. The magnitudes of the values, however, are slightly different. For the afternoon of July 24, grass, the warmest crop, was as much as 8 C warmer than alfalfa. The probable reason for this, as previously discussed, is related to the effects of the hot dead grass covering the soil.

4.4.2 August 2-3, 1976

Temperature patterns of alfalfa, grass, soybean rows and sorghum rows, as measured with leaf thermocouples, are shown in Fig. 32a. As in the previous period, grass and sorghum were the two warmest crops. Their temperatures were very similar and no one crop was consistently warmer than the other. Alfalfa was the coolest of all crops. During the morning and afternoon hours of August 2, grass and sorghum were consistantly 2 to 3 C warmer than soybean. Soybean was about 1 C warmer than alfalfa. A similar pattern was observed on the morning of August 3.

As mentioned in section 4.3.2, the infrared thermometer was unstable during this period of measurements. However, since we are interested in relative temperature differences, the IRT data are presented for these dates (Fig. 32b). The infrared thermometer temperature patterns are very similar to those given by leaf thermocouples.

Technical problems in the data acquisition systems prevented taking some data from 0300 to 0800 hours of August 3.

4.4.3 August 17-18, 1976

Surface temperature of alfalfa, grass, soybean and sorghum, measured with leaf thermocouples and infrared thermometer, are shown in Fig. 33a and b. Temperature measured with leaf thermocouples indicated

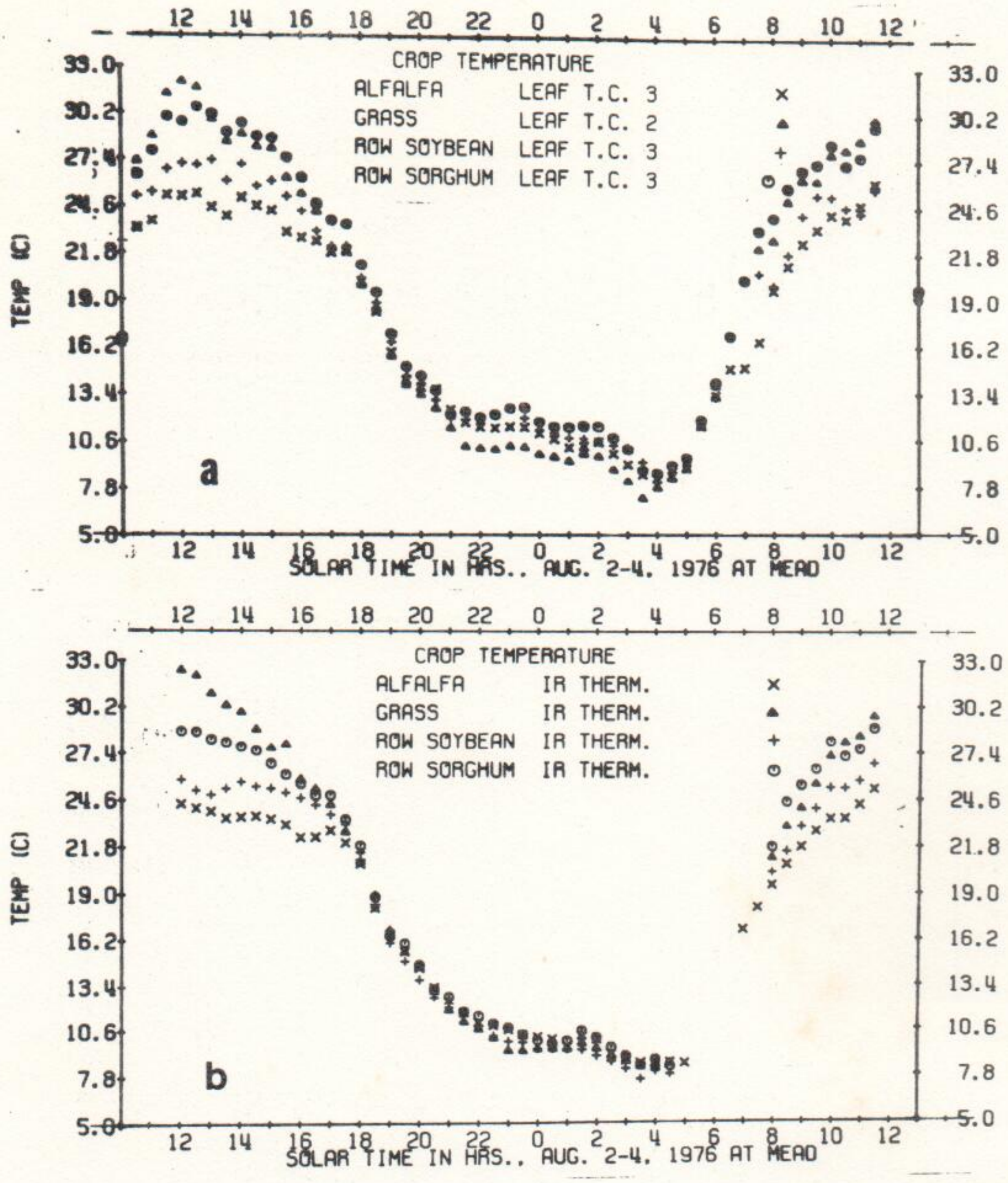


Fig. 32. As in Fig. 31 for August 2-3, 1976.

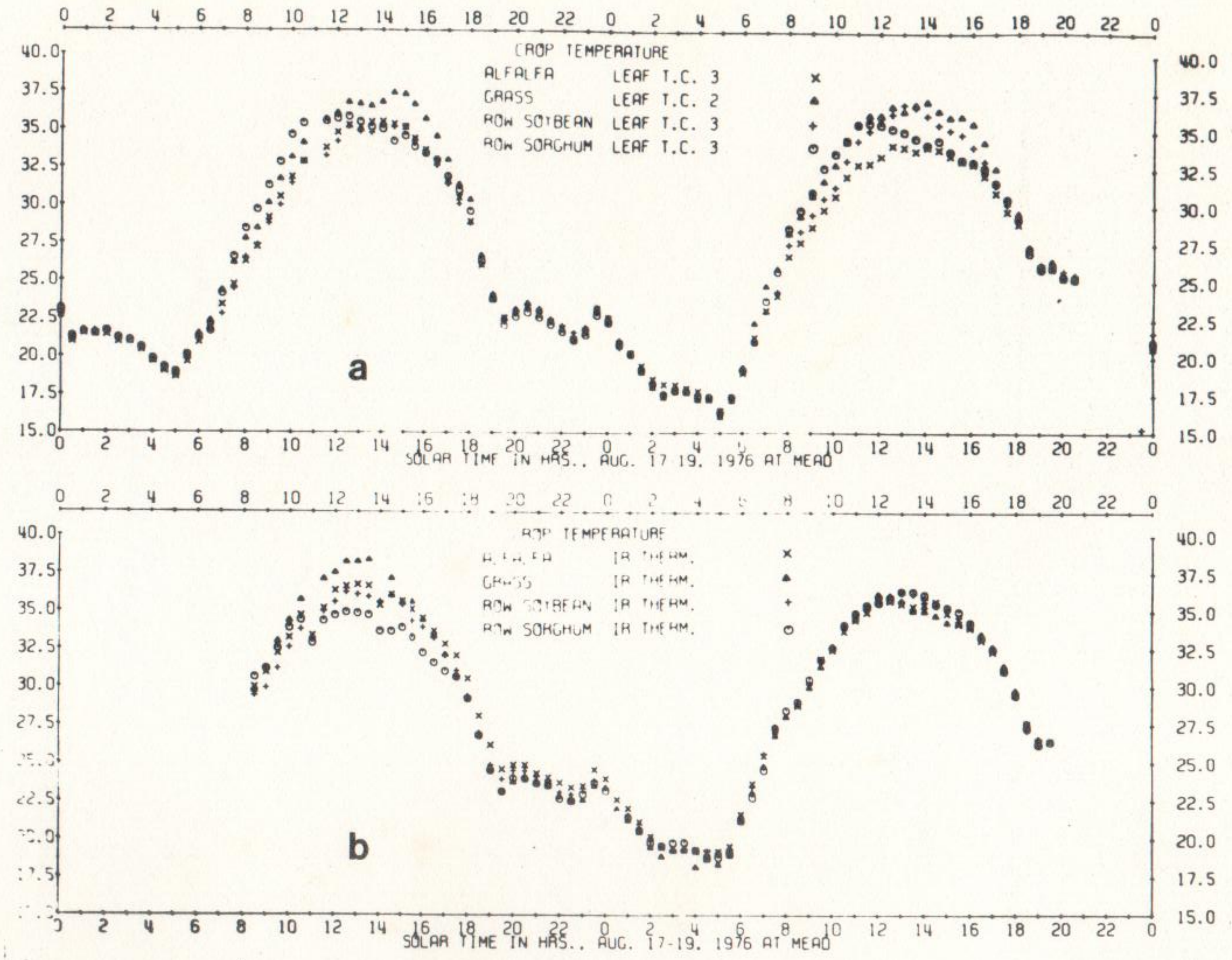


Fig. 33. As in Fig. 31 for August 17-18, 1976.

grass to be the warmest crop (Fig. 33a). Sorghum, which in the previous two study periods had been as warm as grass and warmer than soybean and alfalfa, presented a different pattern on these days. Sorghum was slightly warmer than grass until about 1100 hours of August 17. After that, sorghum temperature decreased while the grass temperature continued to increase until about 1500 hours. Very similar patterns were obtained on August 18. These differences are probably a function of the relative transpiration rates of the two crops.

The temperature difference between soybean and alfalfa was distinct on both days. On August 17, these crops were at about the same temperature. On August 18, however, soybean was much warmer than alfalfa and sorghum and only slightly cooler than grass, the warmest crop. It seems that soybean, which had maintained fairly high transpiration rates during the previous periods, was experiencing some degree of water stress. Under such circumstances, transpiration would decrease and the crop would become warmer than if there were no stress.

The location of the alfalfa plot had been changed and the new plot irrigated two days prior to the measurements. Thus, the alfalfa should not have been under water stress. As before, alfalfa remained the coolest crop.

Results obtained with the infrared thermometer are shown in Fig. 33b. T_{IR} data on August 17 indicated that grass was as much as 3.5 C warmer than sorghum (the coolest crop). Soybean and alfalfa were 1 to 2 C warmer than sorghum and 1 to 2 C cooler than grass. On August 18, the IR thermometer measurements indicated that all crops were at essentially the same temperature. Reasons for this apparent agreement are unclear, especially since the T_{TC} data did not support these findings and the crops were not irrigated or treated in any way that would cause a departure from the pattern of the previous day.

4.4.4 Discussion

In general, plant temperature is inversely related to its transpiration rates. Based on this premise, we estimate that the water use for the crops studied on the first two measurement periods (July 24-25; August 2-3) was: alfalfa > soybean > sorghum > grass. On these days none of the crops were under water stress since all plots had just been irrigated and had adequate soil moisture. During the final period of measurement (August 17-18) the crops presented a different temperature and water use pattern. Evapotranspiration rates were estimated to be in the following order: alfalfa > sorghum > soybean > grass.

Soybean, which had been the second coolest crop during the first two study periods, was the second warmest crop on August 17-18. It seems likely that because the crop had maintained fairly high transpiration rates on the earlier days of the experiment it was experiencing some water stress on August 17-18. It is also possible that by this time the soybean plants were approaching maturity. It is apparent from the decrease in LAI (Table 4) that many senescent leaves had fallen from the soybeans and it is likely that several other leaves were approaching this stage. This senescent or nearly senescent tissue would reduce the transpiring ability of the soybeans.

Sorghum, one of the warmest crops on July 24-25 and August 2-3, was the second coolest crop on August 17-18. It appears that sorghum, even though it had the driest soil, was able to maintain relatively high transpiration rates during hours of high transpiration demand.

4.5 Effect of the Planting Pattern on the Temperature of Soybean and Sorghum

4.5.1 July 24-25, 1976

Temperature patterns for soybean and sorghum in the two different planting systems are shown in Fig. 34. Comparisons of the temperatures measured with leaf thermocouples and with the IR thermometer are shown in Fig. 34a and 34b, respectively.

There were only minor differences between the crop temperatures of the broadcast and row sorghum plants during either the night or the day. This was true for the crop temperatures measured by either leaf thermocouples or IR thermometer. Surface temperatures of the soybean plots measured with the IR thermometer were almost identical throughout both days (Fig. 34b). However, the temperature in the soybean row plot as measured with leaf thermocouples was warmer than that in the soybean braodcast plot during the afternoon of both days. The greatest difference was observed from 1500 to 1700 hours on July 24. The soybean broadcast temperature appears suspiciously low during this period. The small temperature difference between the two soybean plots on July 25 was perhaps due to differences in the exposure of the instrumented leaves in the two plots to solar radiation.

The crop temperature data during this period (July 24-25) suggest that the planting pattern had little effect on the crop temperature. This was especially true for the temperature measured with the IR thermometer. The primary exception to this general pattern was observed with the leaf thermocouple data of the soybean plots during the day.

4.5.2 August 2-3, 1976

Temperature patterns given by leaf thermocouples and IR thermometer are presented in Fig. 35a and 35b, respectively. Leaf thermocouples indicated that there was practically no difference between the temperature

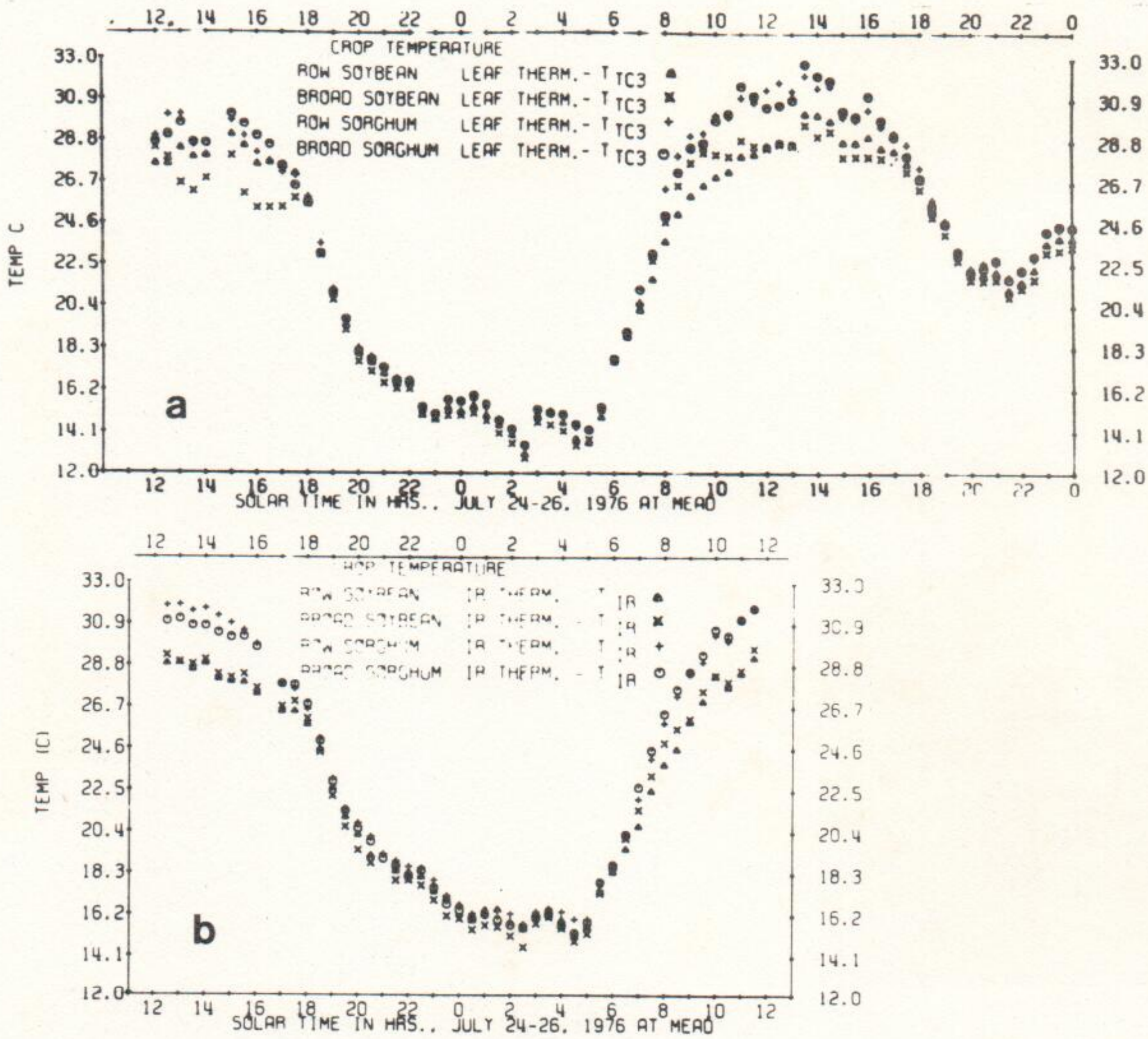


Fig. 34. Temperature patterns of soybean rows, soybean broadcast, sorghum rows and sorghum broadcast as measured with (a) leaf thermocouples and (b) IR thermometer, July 24-25, 1976.

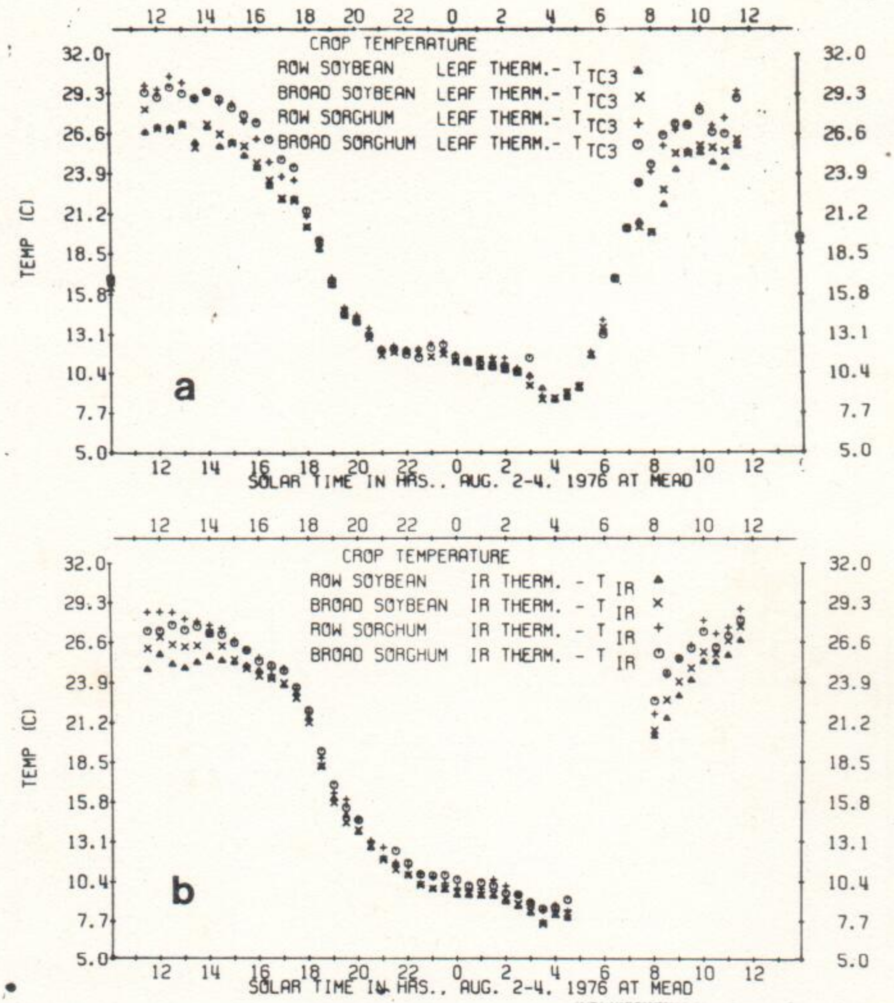


Fig. 35. As in Fig. 34 for August 2-3, 1976.

of the two sorghum plots nor the two soybean plots.

Greater differences were noted in both crops for the IR thermometer data, but even then the agreement was generally better than 1 C. Temperature of the soybean row plot was generally slightly cooler than that of the soybean broadcast plot but the sorghum row plot tended to be warmer than the sorghum broadcast plot. Even though the IR thermometer was apparently malfunctioning due to a shift in calibration, the patterns, but not the absolute values, should still be valid. The IR thermometer data suggest that the planting patterns do have a slight effect on the crop temperature sensed by the IR thermometer. These findings however, are not confirmed by the thermocouple data. At this time the percent cover of all plots was almost complete and the soil temperature was slightly cooler than the leaves. Thus, it is unlikely that the planting pattern influenced the IR thermometer temperatures. Furthermore, the temperature differences observed are less than 1 C which is within the accuracy of the IR thermometer.

4.5.3 August 17-18, 1976

Temperatures given by leaf thermocouples are shown in Fig. 36a. During the morning of both days sorghum broadcast was slightly warmer than sorghum row. During the rest of the periods however, both plots were at similar temperatures.

Soybean row and soybean broadcast presented very similar temperatures during both days. However, from 1200 to 1400 hours of August 18, soybean row was about 1 C warmer than soybean broadcast, perhaps due to differences in the exposure to solar radiation of the instrumented leaves in the two plots.

The temperature patterns given by the IR thermometer can be seen

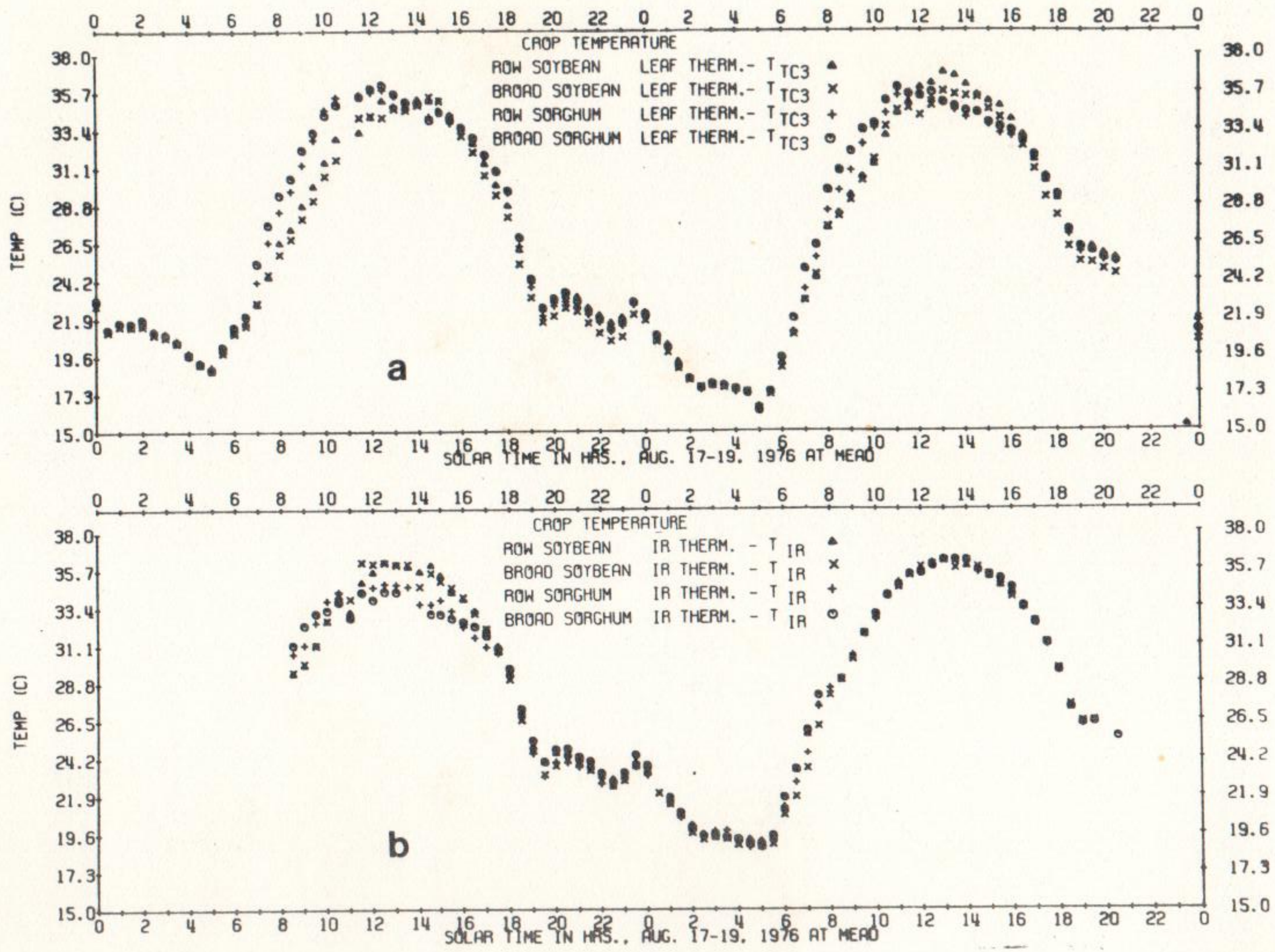


Fig. 36. As in Fig. 34 for August 17-18, 1976.

in Fig. 36b. Very good agreement between the temperatures of the row and broadcast crops was observed for both sorghum and soybean plots.

V. SUMMARY, CONCLUSIONS AND FUTURE RESEARCH

5.1 Summary and Conclusions

Leaf temperature measured with evanohm-constantan thermocouples at three levels within the canopy indicated that the temperature profile was influenced by plant morphology and soil temperature. During the day in the alfalfa and soybean plots the sunlit leaves ($T_{TC\ 3}$) were warmer than leaves at the other two levels. However, in the sorghum plots only minor variation between temperatures were observed at the three levels of measurement. At night in all crops the lower leaves were slightly warmer than the upper ones. The lower leaves were warmer because of the radiation and convection to them from the relatively warm soil and because they received radiation from nearby leaves. Therefore these lower leaves lost less radiative energy to the cold sky than did the upper leaves.

The soil temperature was lower than the leaf temperature during the day and higher at night. On July 24-25 the soil temperature was 1 to 3 C lower than the leaves during the day and as much as 6 C higher than the leaves at night. However, on August 17-18, a very hot period, soil was up to 7 C cooler than the leaves during the day and only 1 to 3 C warmer than the leaves at night.

The agreement of crop surface temperature as measured with leaf thermocouples (T_{TC}) and an IR thermometer (T_{IR}) was much better (about 1 C) during the day than during the night (1 to 3 C). In the alfalfa and both the soybean row and soybean broadcast plots the best agreement was observed between T_{IR} and $T_{TC\ 3}$. For sorghum T_{IR} agreed about equally well with any of the three levels. At night T_{IR} was 1 to 3 C higher than T_{TC} indicating that the infrared thermometer was sensing a significant amount of radiation from the warm soil.

Air temperature measurements within the canopy were generally closer to T_{TC} than to T_{IR}. This suggests, at least at night, that leaf thermocouples gave a better estimate of the crop temperature than did the infrared thermometer.

The worst agreement between T_{TC} and T_{IR} methods was obtained in the grass plot on July 24-25 when T_{IR} was as much as 6 C warmer than T_{TC} during the day. Radiation from the hot layer of senescent leaves covering the ground surface, which was sensed by the infrared thermometer was probably the major cause of this disagreement.

The good daytime agreement (about 1^{o}C) between T_{IR} and T_{TC} obtained in this study indicates that crop surface temperature can be estimated by either IR thermometer or thermocouples which are attached to sunlit leaves, when the crop cover is 75% or greater. Due to the apparent strong influence at night, of soil temperature on the temperature sensed by the IR thermometer some adjustments in T_{IR} would be required if the goal of the measurement was plant temperature and not the overall field temperature. It appears that, at night, a better estimate of plant temperature is obtained with leaf thermocouples than with instruments which sense radiation coming from the crop surface.

Grass was the warmest crop during the three study periods. It was as much as 6 C warmer than alfalfa on August 2. Grass and sorghum constituted one group which was generally 2 to 3 C warmer than a group formed by soybeans and alfalfa. These groupings held for the first two study periods but a slightly different pattern emerged with the August 17-18 data. Soybeans were much warmer (compared to the other crops) than they had been on the previous dates. By this time it seems that soybeans were subject to some water stress, probably as result of the depletion of soil moisture from relatively high transpiration rates on days preceeding the final study period. Sorghum on the other hand, exhibited just the opposite behavior. It was as cool as alfalfa during hours of high transpiration demand and much cooler, relative to the other crops, than it had been earlier. In general, the leaf thermocouples and the IR thermometer gave similar estimates of the temperature difference between the crops.

Based on the temperature patterns of July 24-25 and August 2-3, relative water use rates were estimated to be: alfalfa > soybean > sorghum > grass. For August 17-18 they were estimated to be: alfalfa > sorghum > soybean > grass.

There was practically no temperature difference between broadcast and row soybean and sorghum plots. However, it should be emphasized that the percent cover of all crops in this experiment was greater than 75. Obviously greater temperature differences would be expected, particularly from the IR thermometer data, if the crops had less crop cover.

5.2 Future Research

Further research is needed to evaluate the influence of crop cover on the agreement of crop temperature as measured with leaf thermocouples and IR thermometer. Temperature measurements should be made when the crop percent cover increases from no cover to the 75% level. Corresponding LAI values should also be determined. It would also be advisable to vary the viewing angle of the IR thermometer from vertical to nearly horizontal. Alteration of the viewing angle may provide one way to reduce the effects of soil temperature on the plant canopy temperature sensed by the IR thermometer.

In further experiments careful attention should be given to the measurement of soil and plant water potential. The influence of ET rates on temperatures of different crops likewise merits further investigation.

It was established in this study that different crops exhibit different temperature responses when subject to similar environmental conditions. The temperature responses of other agronomic and horticultural crops, rangeland and forest vegetation should be investigated. These responses should be studied at different locations under a wide range of climatic conditions.

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Appendix I. Symbols Used

B*	Flux Density of the Incoming Longwave Radiation (8-14 μ m)
C	Celsium Degree
cm	Centimeter
IR	Infrared Radiation (8-14 μ m)
IRT	Infrared Thermometer
mm	Millimeter
m.s.l.	Mean Sea Level
R_{bc}	Radiative Flux Density (8-14 μ m) from the Crop Surface
R_{bp}	Radiative Flux Density from the Aluminum Plate
R_{LW}	Total Outgoing Radiative Flux Density (8-14 μ m)
$T_{a\ 1,2,3*}$	Air Temperature (^{o}C)
T_{IR}	Crop Surface Temperature (^{o}C) Measured with the IR Thermometer
T_p	Absolute Temperature (^{o}K) of the Aluminum Plate
T_s	Soil Temperature (^{o}C)
$T_{TC\ 1,2,3*}$	Leaf Temperature (^{o}C) Measured with Leaf Thermocouple
ε_c	IR Emissivity of the Crop Surface
ε_p	IR Emissivity of the Aluminum Plate
σ	Stefan-Boltzmann Constant, $8 . 117 \times 10^{-11}$ $Lymin^{-1}$ K^{-4}
μ	Micron

*Subscripted numbers refer to level of placement.

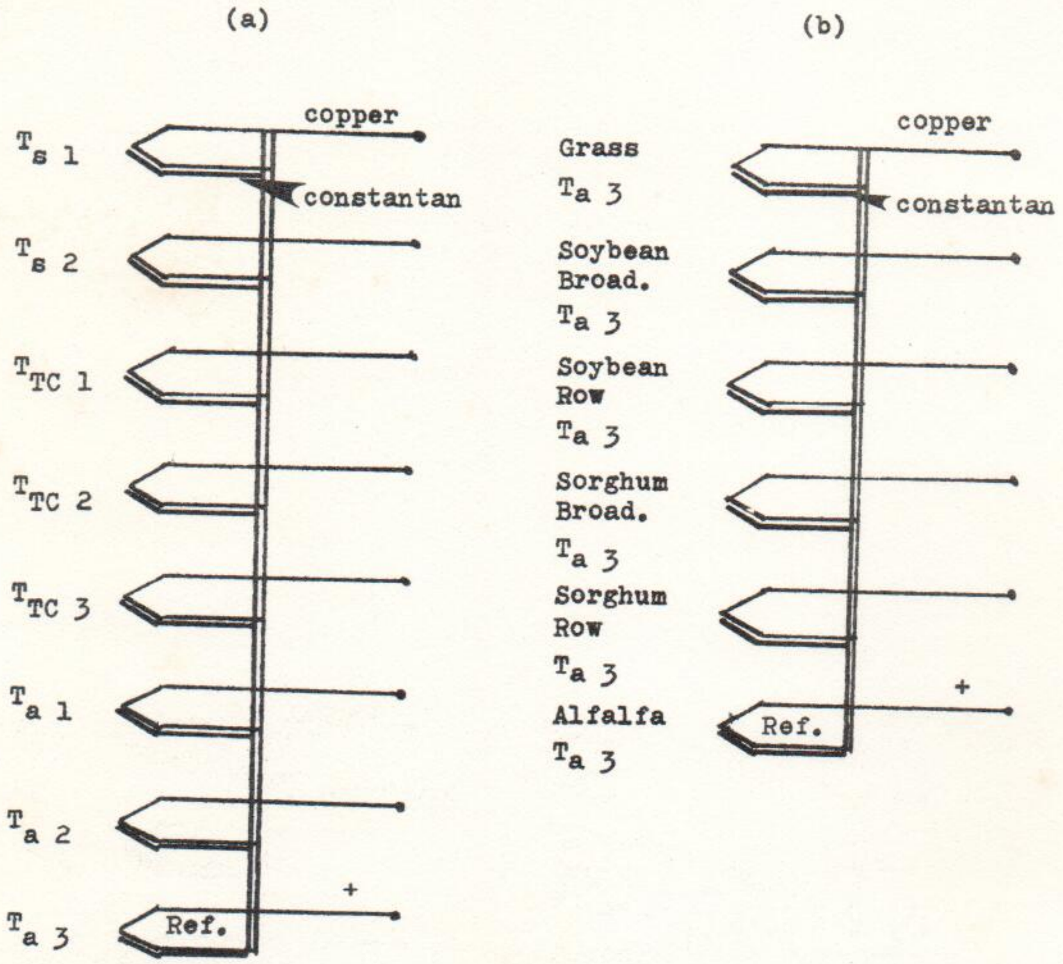

Fig. A-1. Electrical wiring diagram for thermocouples (a) within each plot and (b) between the plots.

Legend: $T_{s\ 1,2*}$ is soil temperature

$T_{TC\ 1,2,3*}$ is crop temperature measured with leaf thermocouples

$T_{a\ 1,2,3*}$ is air temperature

*Subscripted numbers refer to level of placement