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APPLICATION OF REMOTE SENSING IN ESTIMATING EVAPOTRANSPIRATION IN THE PLATTE RIVER BASIN

Final Report for the Period May 1, 1972 - April 30, 1976

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Project Title:

Application of Remote Sensing in Estimating Evapotranspiration in the Platte River Basin

Investigators:

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Purpose of Investigation:

The primary objectives of this study were: (1) to develop and test evapotranspiration models based on crop temperatures and (2) to determine the feasibility of using remotely sensed thermal imagery to supply data on crop temperature for use with these models.

Results:

A summary of results obtained in this study is presented in this report. The findings related to the achievement of objective 1 are given in the section entitled "Evaluation of Resistance and Mass Transport Evapotranspiration Models Requiring Canopy Temperature Data" and those pertaining to objective 2 are reported in "Measurement of Crop Temperature by Leaf Thermocouple, Infra-Red Thermometry and Remotely Sensed Thermal Imagery". The results presented will soon appear in the scientific literautre and reprints will be submitted at that time.

EVALUATION OF RESISTANCE AND MASS TRANSPORT EVAPOTRANSPIRATION MODELS REQUIRING CANOPY TEMPERATURE DATA

ABSTRACT

The increasing use of thermal scanners on aircraft and satellites makes it likely that data on surface temperature for large areas will become routinely available. If reliable evapotranspiration methods which incorporate surface temperature data can be developed an important tool for research and application in hydrology, in irrigation scheduling and in other water management procedures will result.

A 'resistance model' which stems from the work of Brown and Rosenberg and a mass transport (Daltonian) model for estimating evapotranspiration (ET) were tested on large fields of naturally subirrigated alfalfa (Medicago sativa L.). Both models make use of crop canopy temperature data. Temperature data were obtained with an IR thermometer and with leaf thermocouples. A Bowen ratio-energy balance (BREB) model, adjusted to account for underestimation of ET during periods of strong sensible heat advection, was used as the standard against which the resistance and mass transport models were compared.

Daily estimates by the resistance model were within 10% of estimates made by the BREB model. Daily estimates by the mass transport model did not agree quite as well. Performance was good on clear and cloudy days and also during periods of non-advection and strong advection of sensible heat.

The performance of the mass transport and resistance models was less satisfactory for estimation of fluxes of latent heat for short

term (15 minute) periods. Both models tended to overestimate at low LE fluxes.

The increasing use of airborne thermal scanners provides an opportunity for mapping ground and crop surface temperature over large areas (Wiegand and Bartholic, 1970 and Bartholic, Namken and Wiegand, 1972). This sensing capability may provide crop temperature data which can be applied in evapotranspiration (ET) models. Reliable estimates of ET over large areas can provide valuable input for hydrologic studies, for irrigation scheduling, and for the management of water resources in general.

Stone and Horton (1974) evaluated the performance of two ET estimation methods which utilize crop temperature on grain sorghum (Sorghum bicolor (L.) Moench). They compared ET estimates made by the Penman (1948) and Bowen ratio-energy balance (BREB) techniques with those of a method suggested by Bartholic, Namken and Wiegand (hereafter B-N-W) (1970), and with a model which they referred to as Brown and Rosenberg's (1973) 'resistance model'. Compared to the BREB estimates the B-N-W method underestimated ET by 17%. Brown and Rosenberg's method overestimated ET by about 22%. We have reason to question their results because of the effects of advected sensible heat.

Our objective was to evaluate a 'resistance model' based upon Brown and Rosenberg (1973) as well as a mass transfer (Daltonian) model for their ability to provide estimates of ET. The tests were made on large fields of alfalfa (Medicago sativa L.) under climatic conditions characteristic of the central Great Plains. Both of these models utilize crop temperature as one of their major input parameters.

MATERIALS AND METHODS

Sites and Measurements

Data to test the ET estimation methods were collected during June and July 1972 at a site located midway between Schuyler and Columbus, Nebraska (lat 41° 24' N, long 97° 13' W, elevation above m.s.l. 425 m) and during August and September 1973 at a site near Cozad, Nebraska (lat 40° 53' N, long 100° 00' W, elevation above m.s.l. 800 m). At both sites measurements were made over naturally subirrigated alfalfa. The field at the Schuyler-Columbus site was about 200 x 200 meters in size; the field at Cozad was much larger. Instruments were located near the center of the field at Schuyler-Columbus; at Cozad they were located so that minimum fetch to the south and west was at least 300 m, 125 m to the east and 500 m to the north.

After harvest of the alfalfa fields measurements were begun when plants had recovered to a height of about 35 cm and crop cover was about 75% and continued until the subsequent cutting when the alfalfa reached about 80 cm and cover was complete. Instantaneous wind speed was measured with a 3-cup wind speed transmitter [3] modified to generate signals in the millivolt range. The instrument was calibrated over a wide range of wind speeds by reference to a Sheppard-type Casella anemometer. Starting speed of the transmitter was about 70 cm sec^{-1}.

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[3] Science Associates Catalog No. 406-1.

Crop canopy temperature was measured with a Barnes IR thermometer (Model IT-3 S/3°). Six copper-constantan thermocouples wired in parallel and attached to plant leaves were also used to measure canopy temperature. Air temperature was measured with radiation shielded thermocouples. Temperature and vapor pressure gradients were obtained with thermocouple psychrometer assemblies of the type described by Rosenberg and Brown (1974). Vapor pressure of the air was also measured with a Honeywell "Dew Probe" (Model 5 SP129).

Net radiation measurements were made with Middleton (Model CN6) miniature net radiometers and with a Swissteco type S-1 net radiometer (used only in 1973). Soil heat flux was measured with Middleton flux plates. Except for the soil heat flux plates and thermocouples in the crop canopy, measurements were made at a height of 200 cm above the ground. Gradients of air temperature and vapor pressure were also obtained. Measurements were taken at a reference level about 15-25 cm above the crop and at 25, 50, and 100 cm heights above the reference.

Meteorological measurements were recorded by an automatic data logging system with each channel being sampled twice during a 4-minute recording cycle on the quarter hour. Data were converted into parametric and graphic forms through a series of computer programs.

<u>Mass Transfer Model</u>

The mass transfer model for estimating evaporative (latent heat) flux (LE) may be described by:

$$LE = C(e_s - e_a) \quad (1)$$

where C is a theoretically or empirically derived constant usually involving a windspeed term, e_s is the saturation vapor pressure (a function of surface temperature) of the evaporating surface, and e_a is the actual vapor pressure at a specified height above the surface. Modifications of this formula, the original derivation of which is generally attributed to Dalton (ca. 1800), have been made by Rohwer (1931), Penman (1948), Slatyer and McIlroy (1961), Harbeck (1962), Pruitt (1963) and others.

Using surface temperature data measured from airborne platforms, the method has been successfully applied to estimating evaporation from the Great Lakes (Richards and Irbe, 1969). The model has also been used to estimate ET from bare soils (Conaway and Van Bavel, 1967 and Ripple, Rubin and Van Hylckama, 1970) and from vegetation (Pruitt and Aston, 1963) with temperature measurements made near the surface.

Penman (1948), using pan evaporation data of Rohwer (1931), developed the following expression:

$$LE = (2.17 \times 10^{-2} + 7.6 \times 10^{-5} u_2)(e_s - e_a) \quad (2)$$

where u_2 is the wind speed in cm sec^{-1} at 2 m and vapor pressure is in millibars. This equation suggests a linear relationship between wind speed and evaporative flux.

Pruitt and Aston (1963) developed another modification of the Daltonian equation:

$$LE = f(u)(e_s - e_{100}) \quad (3)$$

where e_{100} is the vapor pressure at 100 cm and f(u) is a proportionality factor obtained graphically from a plot of wind speed at 100 cm vs $LE/(e_s - e_{100})$. In this case LE was measured with a lysimeter.

The approach taken in our study is similar to that of Pruitt and Aston (1963) except that, as a standard for comparison, we measured LE with an adjusted BREB method. The adjusted method accounts for an underestimation of LE by about 20% when the BREB model is used under conditions of strong sensible heat advection (Blad and Rosenberg, 1974). Vapor pressure of the air was measured at 200 cm. Thus the model takes the form:

$$LE = f(u)(e_s - e_{200}) \quad (4)$$

Resistance Model

The energy balance at the earth's surface is described by:

$$Rn + S + H + LE = 0 \quad (5)$$

where Rn is net radiation, S is soil heat flux, H is sensible heat flux to or from the air and LE is latent heat flux. The sensible heat flux can be expressed as:

$$H = \rho \, C_p \left(\frac{T_a - T_s}{r_a}\right) \quad (6)$$

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 and r_a is the boundary layer resistance. Increasing wind speed or turbulence will decrease r_a and increase the sensible heat flux.

Substitution of expression (6) into (5) and rearrangement of terms yields:

$$-LE = \rho\ C_p\ (T_a - T_s)/r_a + Rn + S\ . \qquad (7)$$

All terms in equation (7), the 'resistance model', can be easily measured except r_a which must be estimated from a functional relationship with windspeed.

Before the resistance model can be applied, experimental data are required to establish the relation between r_a and windspeed. We evaluated r_a by solving equation (7) to give:

$$r_a = \frac{\rho\ C_p (T_s - T_a)}{Rn + S + LE} \qquad (8)$$

Values of LE used in eq. (8) were obtained from concurrent BREB estimates of LE. Crop temperature, T_s, was measured with the IR thermometer. The r_a values thus obtained were matched with simultaneous windspeed data to develop a relationship $r_a = f(u)$. Data from relatively cloud free periods between the hours of 0900-1500 in 1972 and 1973 were selected for this analysis. Alternative methods for calculation of r_a have been proposed by Szeicz, Endrodi and Tajchman (1969) and Wiegand and Bartholic (1970). These methods require very accurate measurements of the wind profile. Such data were unavailable in this study.

RESULTS AND DISCUSSION

Mass Transfer

Plots of $LE/(e_s - e_{200})$ vs windspeed are given in Figs. 1 and 2 for 1972 and 1973, respectively. The lines shown were derived by fitting the data with linear regression equations. The equations based on leaf thermocouple data agree more closely with the Penman expression than do the equations based on IR thermometer measurements.

Some variation in our f(u) relationships between years may have arisen from differences in the aerodynamic roughness of the two alfalfa fields. We are uncertain as to which expression (that based upon the IR thermometer or that based upon leaf thermocouple data) is the more accurate. (For comparison and discussion of temperatures measured by leaf thermocouples and IR thermometry, see Blad and Rosenberg, 1976). The thermocouple expression is in closer agreement with Penman's expression. However, f(u), an empirical expression, is compared with an expression which Penman derived for a different location and for a different type of evaporating surface.

Although Pruitt and Aston (1963) found the relationship between u and $LE/(e_s - e_a)$ to be curvilinear, most such relations reported in the literature are linear. Our data were fitted with both linear and quadratic coefficients. Very little improvement in the correlation coefficient accrued to the data fitted with quadratic expressions. Thus f(u) can be adequately described by linear expressions.

The linear f(u) expressions based on the IR thermometer data were used to estimate LE rates on days other than those used to establish the relationship $LE/(e_s - e_{200})$ vs u_{200}. These LE rates are compared for several days during 1972 and 1973 with rates calculated by the BREB method. Daily LE rates calculated by the mass transfer method were 2.4% higher, 9.9% lower, and 8.6% lower than the BREB calculated rates on the relatively clear days of June 29, July 8, 1972 and September 3, 1973, respectively. On the partly cloudy days July 4, July 7, 1972 and August 30, 1973 the mass transfer method yielded daily values that were 17.7% higher, 3.1% higher and 1.8% lower, respectively, than the BREB calculated rates. The good agreement of the BREB and mass transfer estimates of LE on both cloudy and clear days is encouraging.

Daily LE patterns on a clear and a partially cloudy day are shown in Figs. 3, 4. The mass transfer method appears to work during afternoon periods when advective conditions (LE > Rn) generally occur (see for example the 1200-1600 hr period in Fig. 4) and also during periods when sensible heat is generated at the crop surface (Rn > LE). Agreement between BREB and mass transfer LE is generally best from about 0900 to 1500 hours.

A plot of 15-minute estimates of BREB versus mass transfer LE for the 0600-1800 hour period on the six study days is presented in Fig. 5. The standard error for the regression coefficient was 0.032. The average mass transfer LE was 0.59 ly min^{-1} and the average BREB LE was 0.55 ly min^{-1}. Most of this difference was caused by the overestimation by the mass transfer model at low LE rates.

There was a strong tendency, when BREB estimates of LE were < 0.3 ly min^{-1}, for the mass transfer model to overestimate LE. These rates were common during periods near sunrise and sunset (Figs. 3, 4). At such times BREB estimates of LE are subject to large errors (Fuchs and Tanner, 1970). The mass transfer model may likewise become unreliable at these times, especially if rapid radiational cooling of the canopy compared to the air, occurs at the low light intensities.

At LE > 0.3 ly min^{-1} there was no strong tendency for the mass transfer model to under-estimate or over-estimate LE rates. The scatter of data suggests that 15 minutes may be too short to obtain reliable estimates of LE.

Resistance Model

Plots of r_a vs windspeed are presented in Fig. 6. The data are widely scattered with r = .44 in 1972 and r = .38 in 1973. The 'best-fit' expressions are, however, quite similar to those given by other researchers. Some of this scatter may be due to the fact that the data were taken over a period of several days - long enough for the actively growing alfalfa to have changed its aerodynamic roughness. In 1972 the relationship of r_a vs u_{200} was:

$$r_a = 9.99(u_{200})^{-0.72} \tag{9}$$

and in 1973 the equation was:

$$r_a = 102.0(u_{200})^{-1.11} \tag{10}$$

where u_{200} is in cm sec^{-1}.

In the windspeed range from 200-700 cm sec^{-1} these two expressions yield similar r_a values (see Fig. 6).

Equation (9) was used in combination with IR thermometer data to compute LE rates over 15 minute intervals for several days in 1972 and equation (10) was used in 1973. These were days other than those from which data was taken to develop the $r_a = f(u)$ expressions. Resistance model LE values were compared with estimates obtained from the adjusted BREB model. Data for six days were chosen for study - four in 1972 and two in 1973. On each of these six days the agreement in daily LE values ranged from 1-10%. Daily LE patterns on two of these days are shown in Figs. 7, 8.

Comparison of all 15-minute estimates of LE by the resistance model and the BREB method during the 0600-1800 hour period on the six days is shown in Fig. 9. The resistance model, as with the mass transfer model, exhibited a strong tendency to overestimate LE when BREB calculated LE was < 0.3 ly min^{-1}. A slight tendency towards underestimation at high LE was also observed. The regression equations for both methods are similar, however a better fit of the resistance data is indicated by the higher correlation coefficient and the lower standard error of the regression coefficient (0.025).

Clear and cloudy weather and periods of sensible heat advection and non-advection occurred during the days studied. The performance of the resistance model appears equally good under all of these climatic conditions.

Stone and Horton (1974) reported that the resistance model overestimated ET by about 22% when resistance model estimates were compared to BREB estimates. We did not observe this tendency, except at LE fluxes < 0.3 ly min^{-1}. We think that Stone and Horton's study was conducted under conditions of significant sensible heat advection. With advection the BREB model has been shown to underestimate ET by about 20% (Blad and Rosenberg, 1974). Thus the resistance model may have given Stone and Horton the best estimates of ET of any method they tested.

Stone and Horton tested the model over sorghum. We used alfalfa. The difference in crops may have contributed to the different results. The crop factor is one that should be evaluated.

CONCLUSIONS

Our results suggest that the mass transfer and resistance models provide reliable estimates of ET, especially daily values, for vegetation well supplied with water. For the most part, LE rates calculated with the resistance model agree more closely with BREB estimates than those obtained with the mass transfer model. Estimates of ET with the resistance model should improve if r_a is estimated from accurate wind profile data instead of the method used in this study.

The mass transfer model will give increasingly worse estimates of LE as moisture available to the crop becomes less and less available. Under moisture stress conditions crop temperature is elevated; e_s, since it is based on the crop temperature, will increase resulting in LE estimates that are excessively high. The resistance model accounts for increased temperature through an increased generation of sensible heat flux from the crop. Therefore, it should provide reliable estimates of ET even under moisture limiting conditions. It remains to be tested under such conditions, however.

Micrometeorological methods such as the BREB model require detailed measurements, especially of temperature and vapor pressure profiles, to be made in individual fields. To estimate LE over large regions with such micrometeorological methods would require an impractically large number of instrument locations in each region. ET estimates over a large region could be supplied, without the need for such detailed measurements in so many different fields, by the mass transfer or resistance model using crop temperature data obtained from remotely sensed thermal imagery.

ACKNOWLEDGMENTS

Support for this project came from the Conservation and Survey Division of the University of Nebraska-Lincoln and from the Office of University Affairs, NASA Grant NGL 28-004-020. Helpful suggestions from Dr. Shashi Verma, Dr. Raoul Lemeur and Dr. Maximo Baradas are appreciated. Messrs. Dale Sandin, Russel Suverkrubbe and James Hines provided technical support. Roberta Sandhorst, Linda Larsen and Linda Shealy helped in preparation of the manuscript.

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LIST OF FIGURES

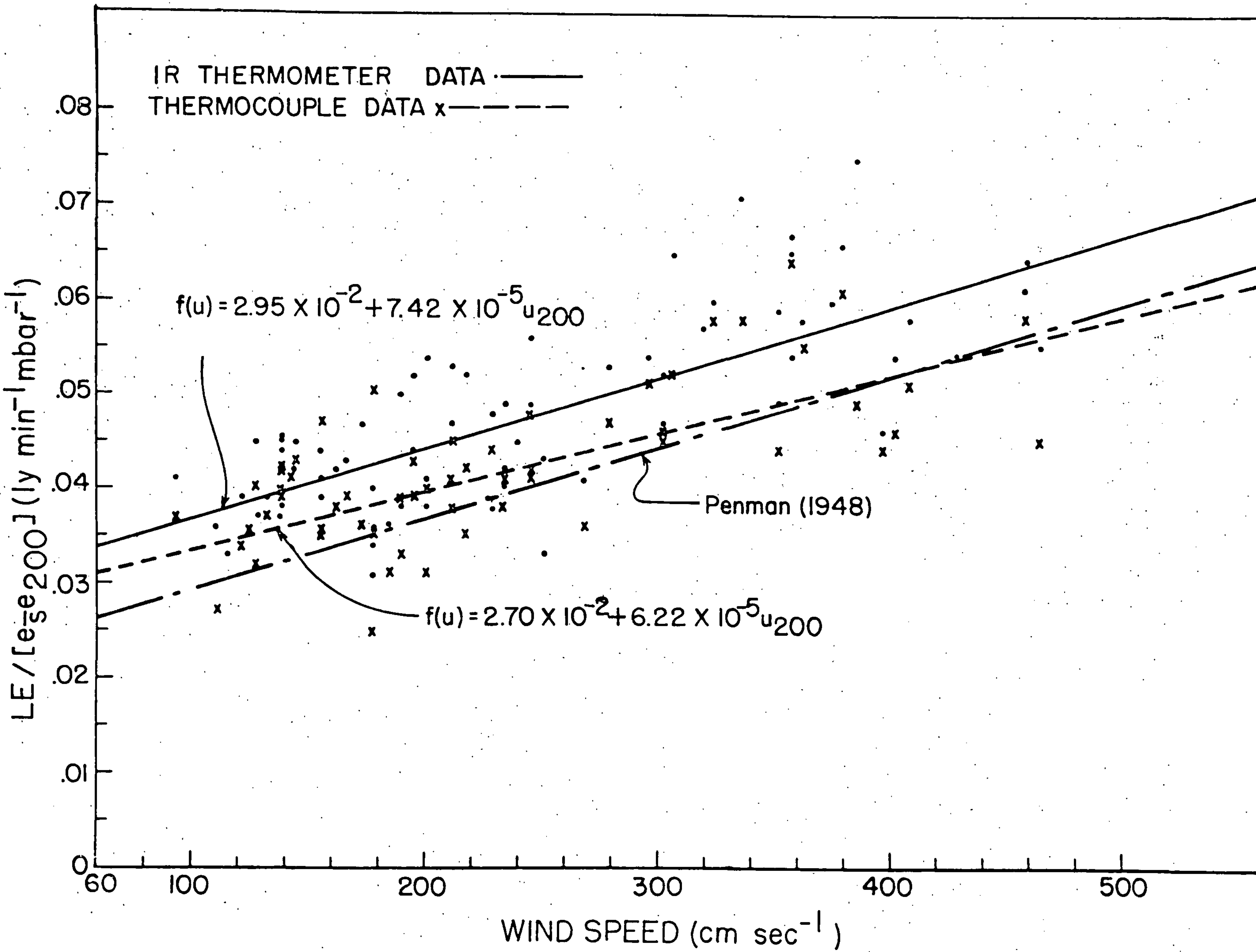

Fig. 1. Dependency of the ratio $LE/(e_s - e_{200})$ on wind speed at the 200 cm elevation. The f(u) expressions are based on IR thermometer and leaf thermocouple estimates of canopy temperature. Observations were made over alfalfa at the Schuyler-Columbus site in 1972.

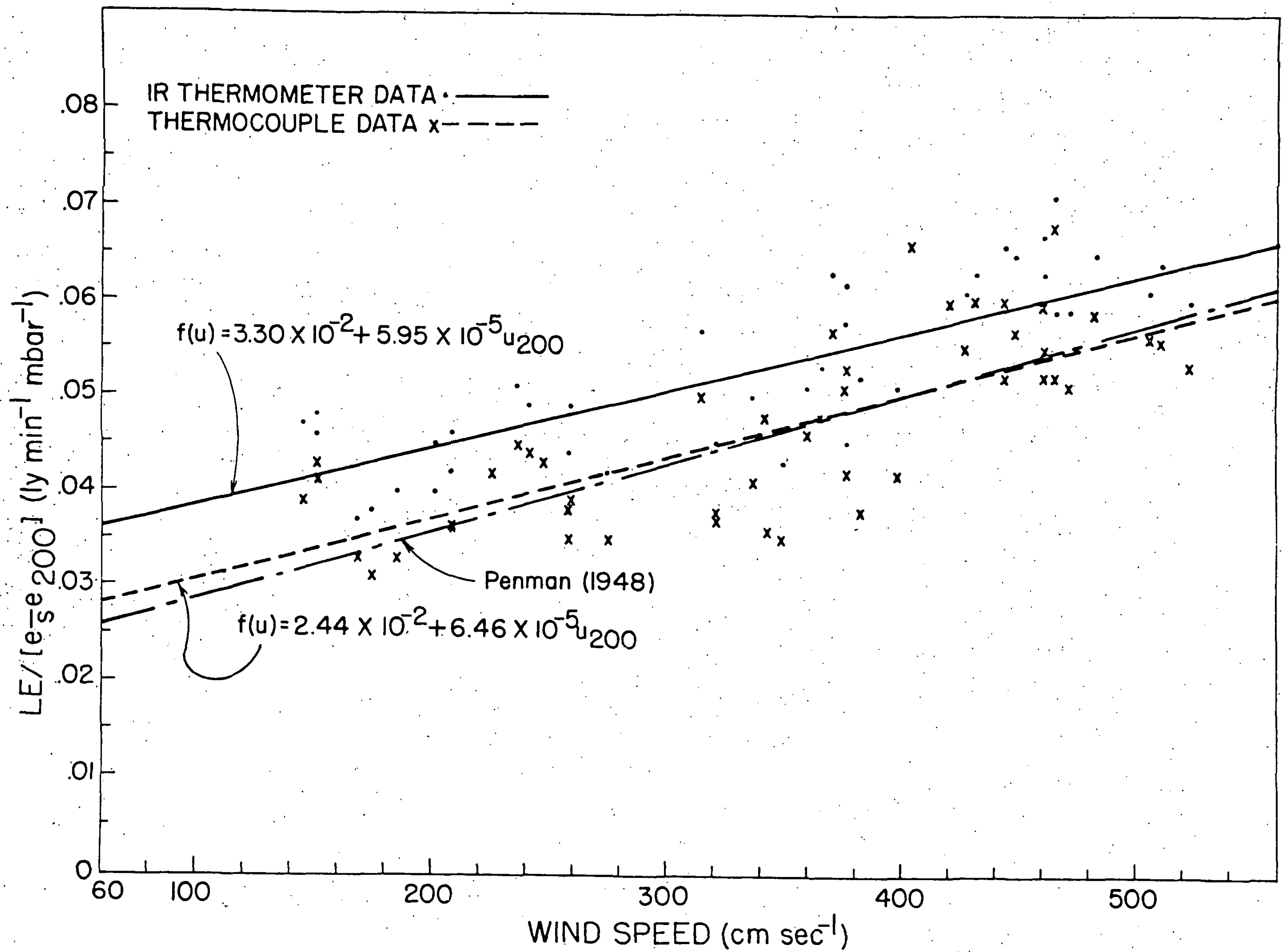

Fig. 2. As in Fig. 1 for observations made over alfalfa at the Cozad site in 1973.

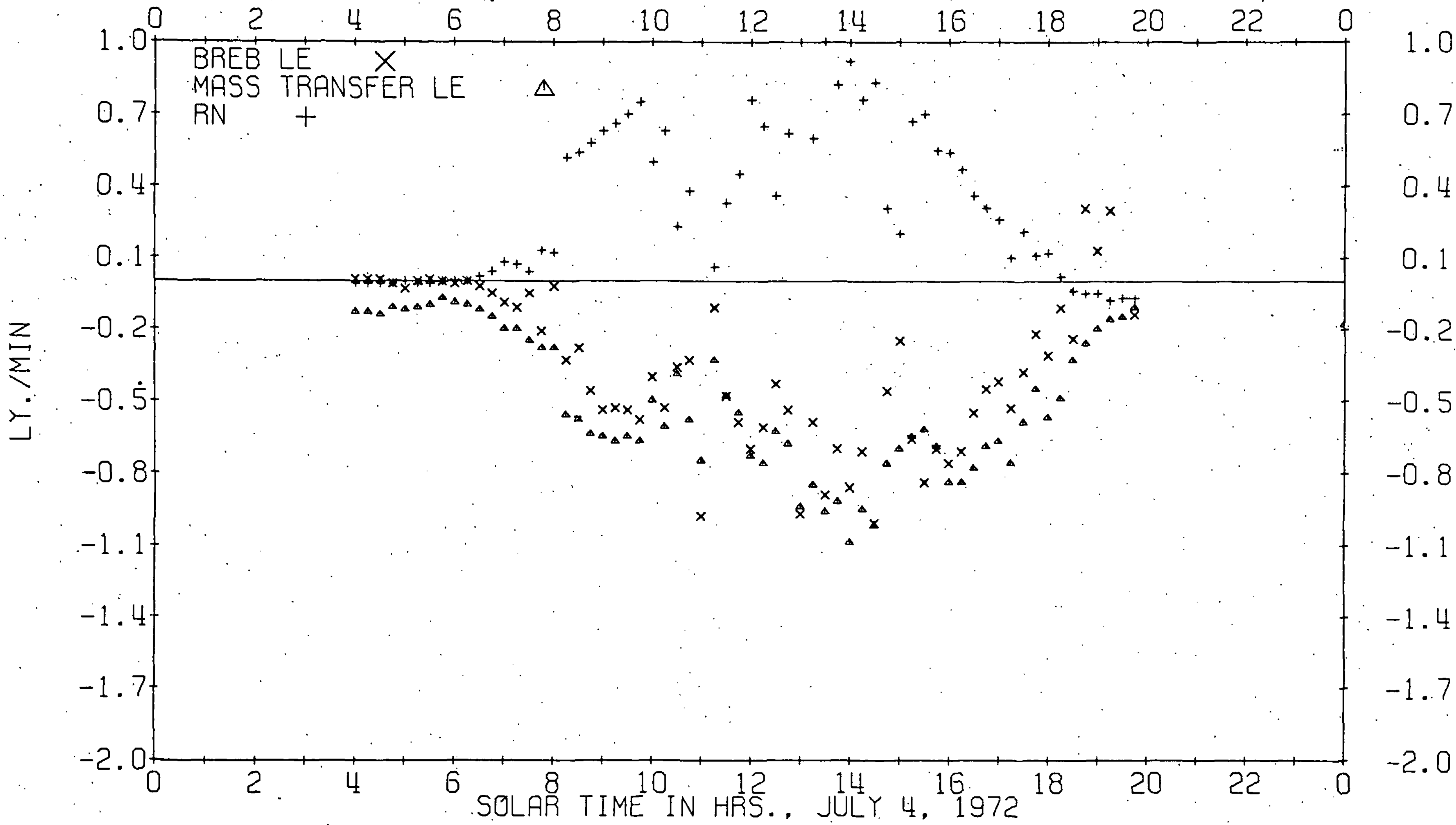

Fig. 3. Patterns of LE flux over alfalfa estimated by the BREB and the mass transfer methods on July 4, 1972 at the Schuyler-Columbus site. Net radiation is also shown.

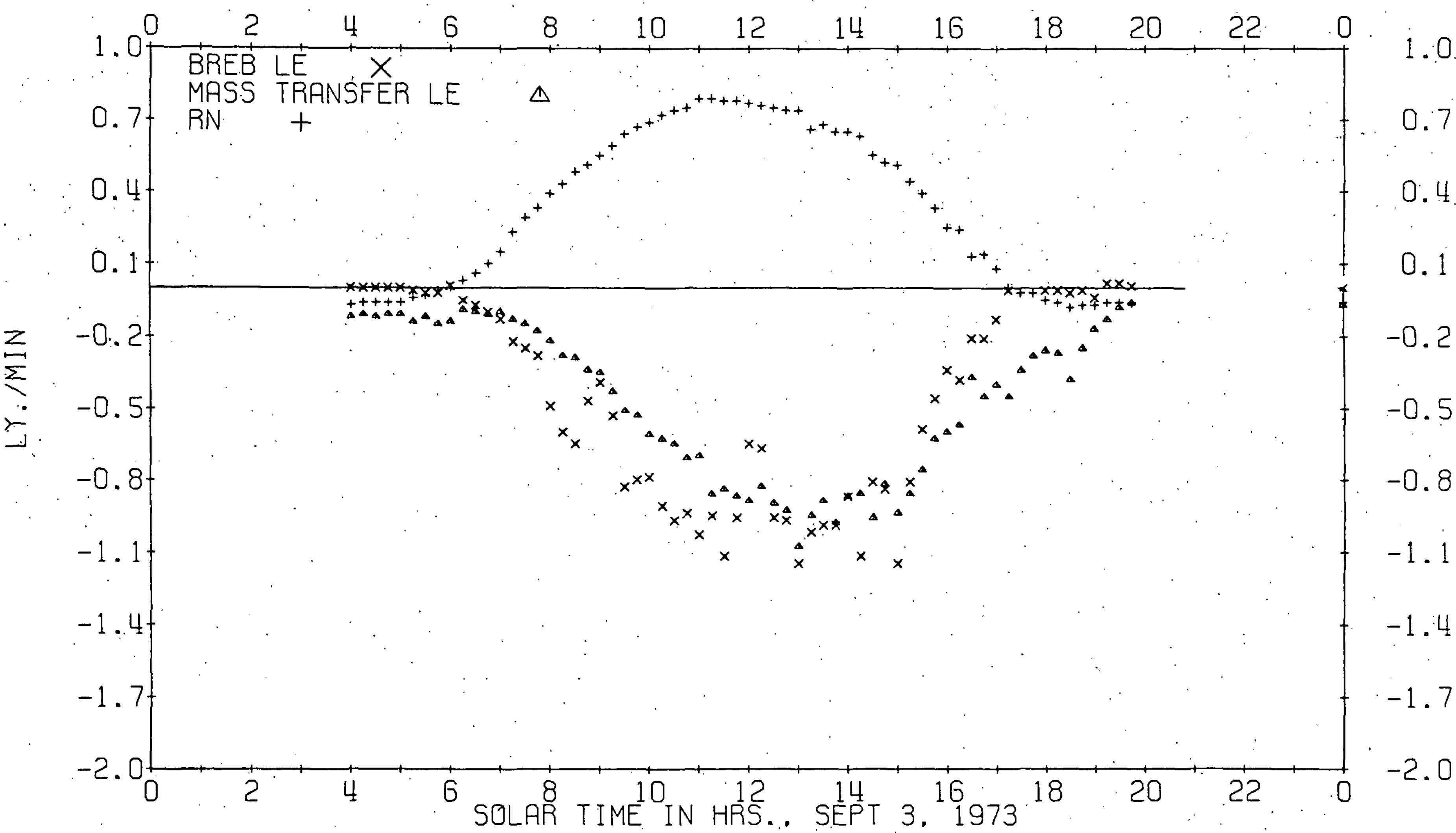

Fig. 4. As in Fig. 3 except on September 3, 1973 at the Cozad site.

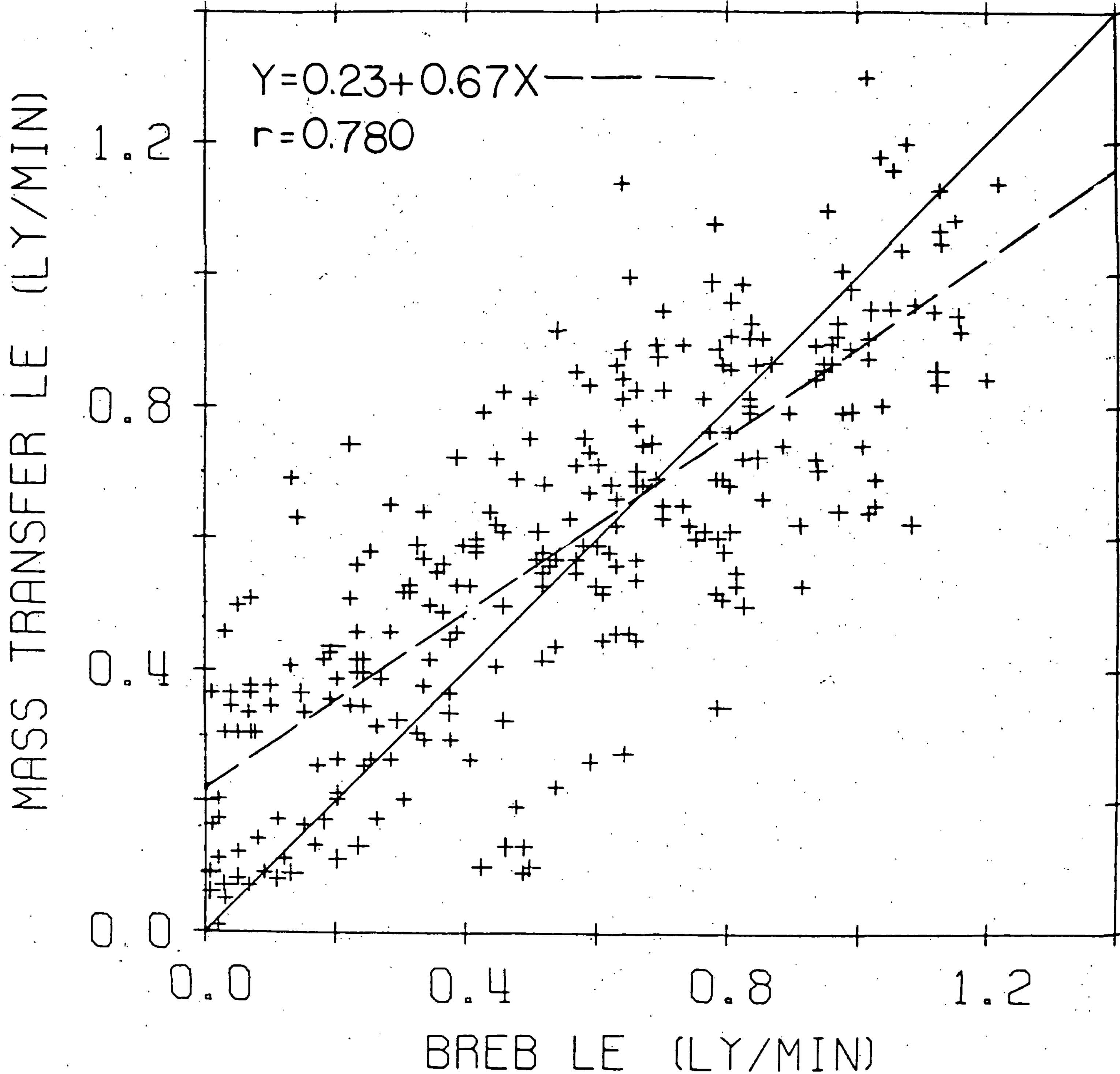

Fig. 5. Mass transfer-estimated LE compared with BREB-estimated LE. Values are for the 15-minute periods on June 29, July 4, 7 and 8, 1972 and on August 30 and September 3, 1973.

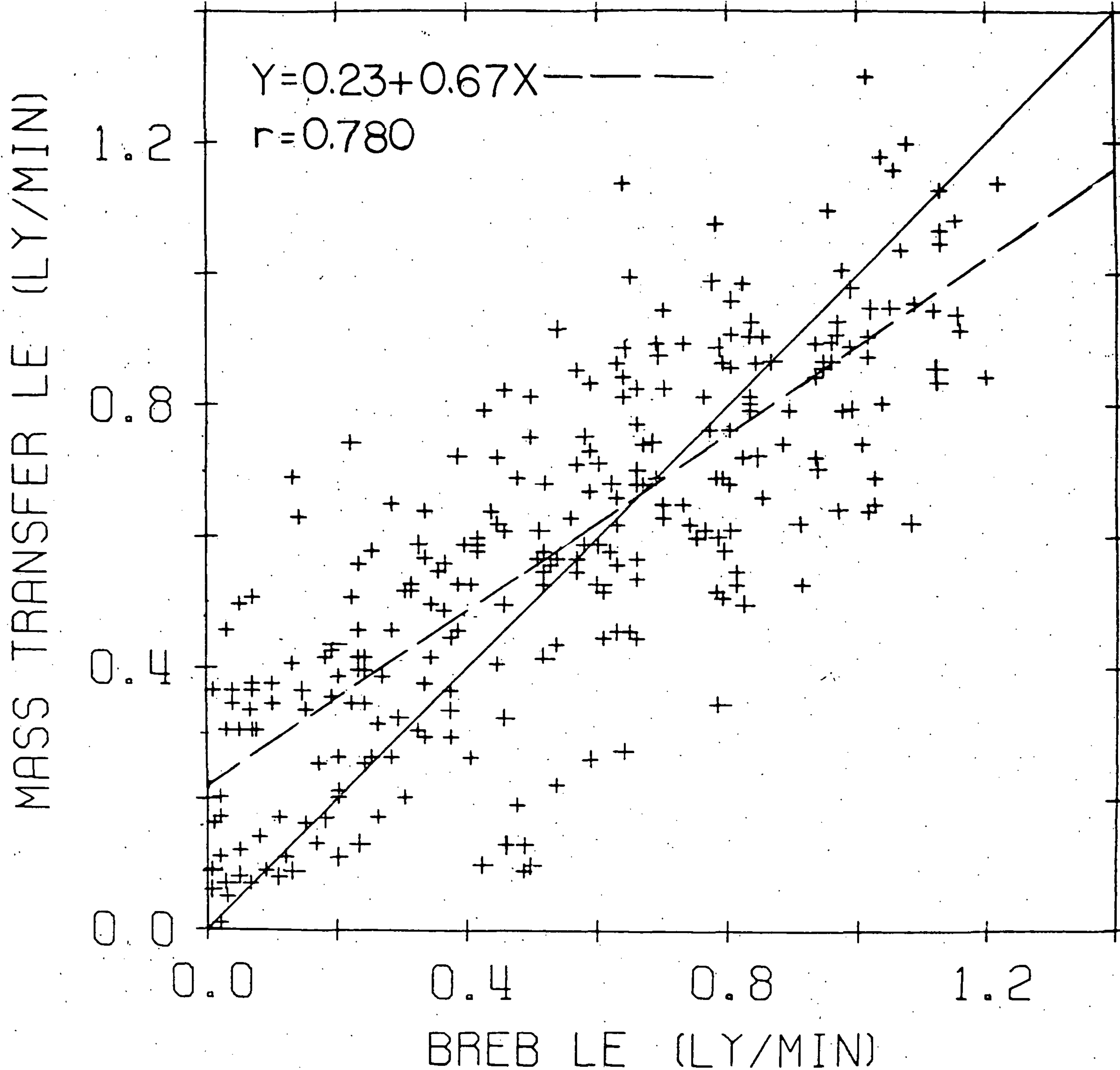

Fig. 5. Mass transfer-estimated LE compared with BREB-estimated LE. Values are for the 15-minute periods on June 29, July 4, 7 and 8, 1972 and on August 30 and September 3, 1973.

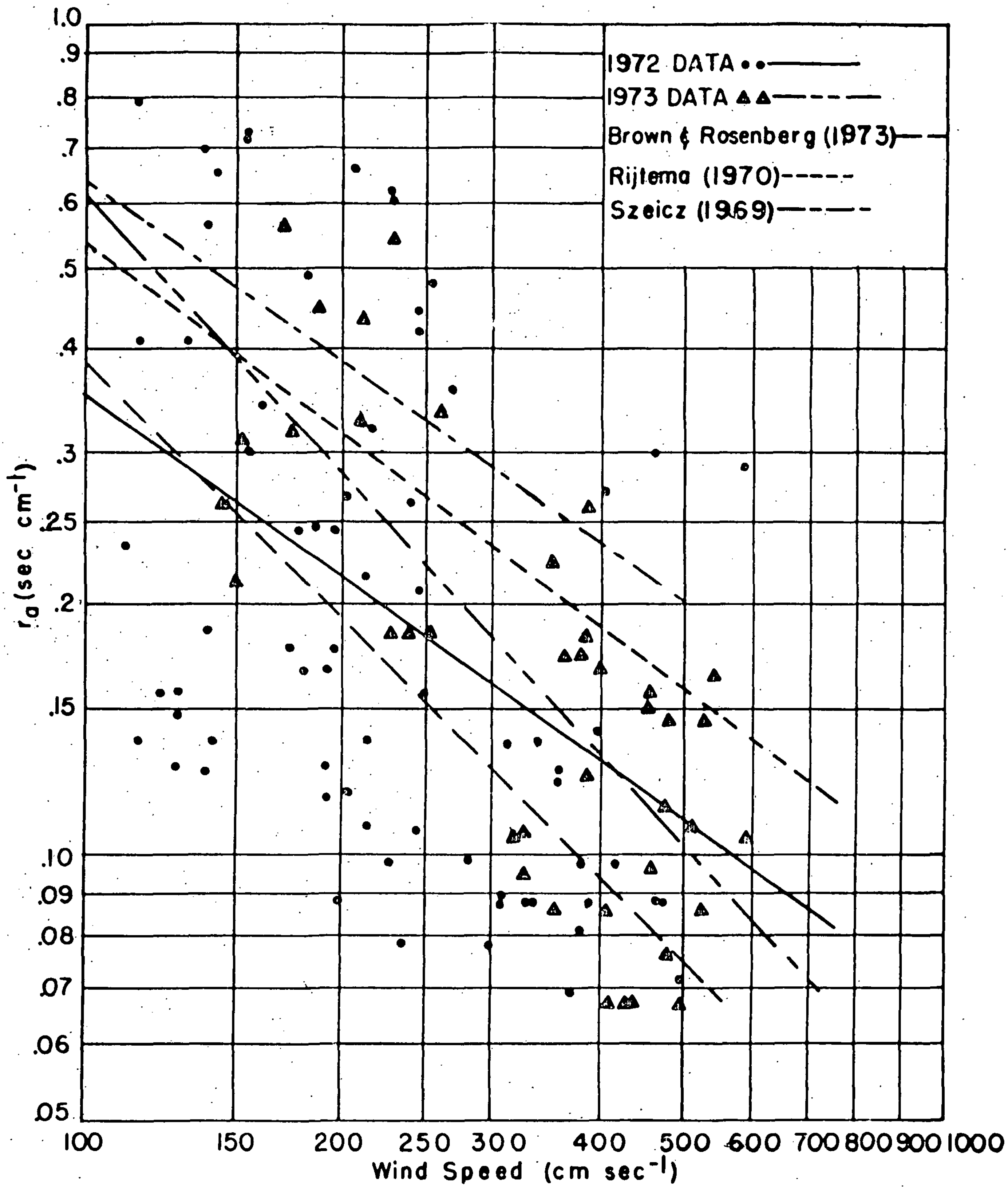

Fig. 6. The relationship $r_a = f(u)$ over an alfalfa surface. Windspeed was measured at 200 cm above the surface. Observations were made in 1972 at the Schuyler-Columbus site and in 1973 at the Cozad site. Comparative data are included.

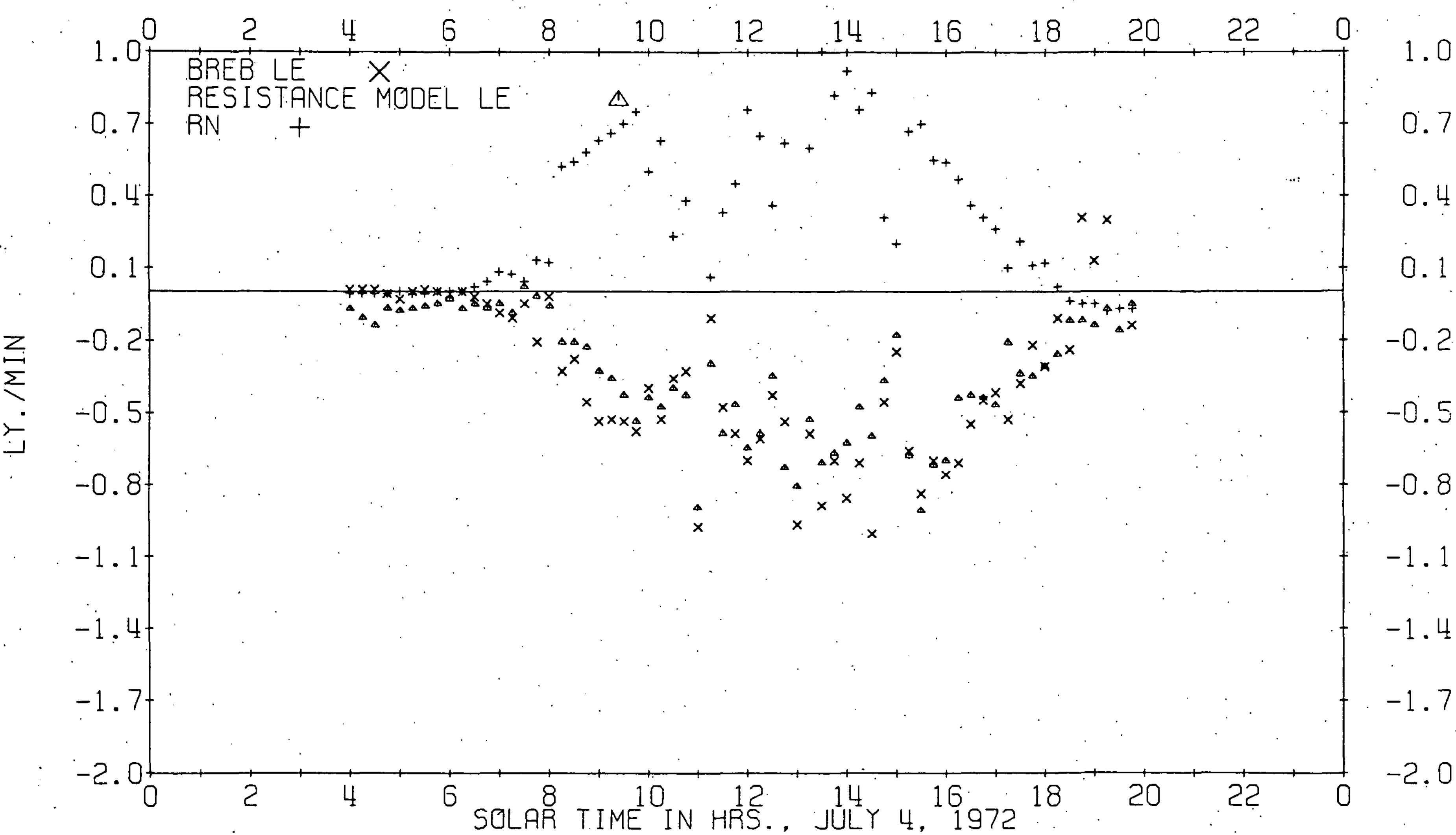

Fig. 7. Daily patterns of LE fluxes estimated with the BREB and resistance methods on July 4, 1972 at the Schuyler-Columbus site.

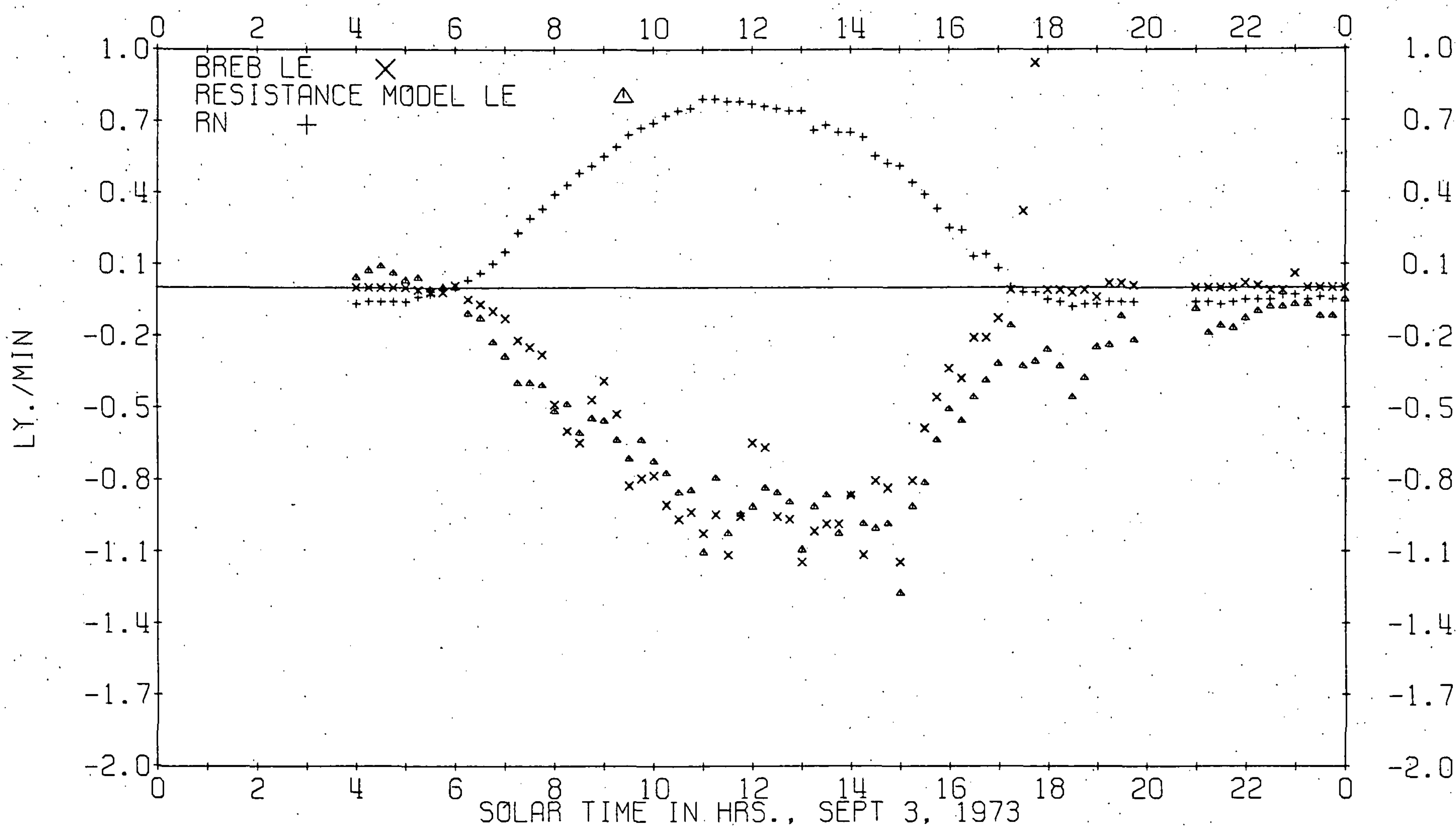

Fig. 8. As in Fig. 7 except on September 3, 1973 at the Cozad site.

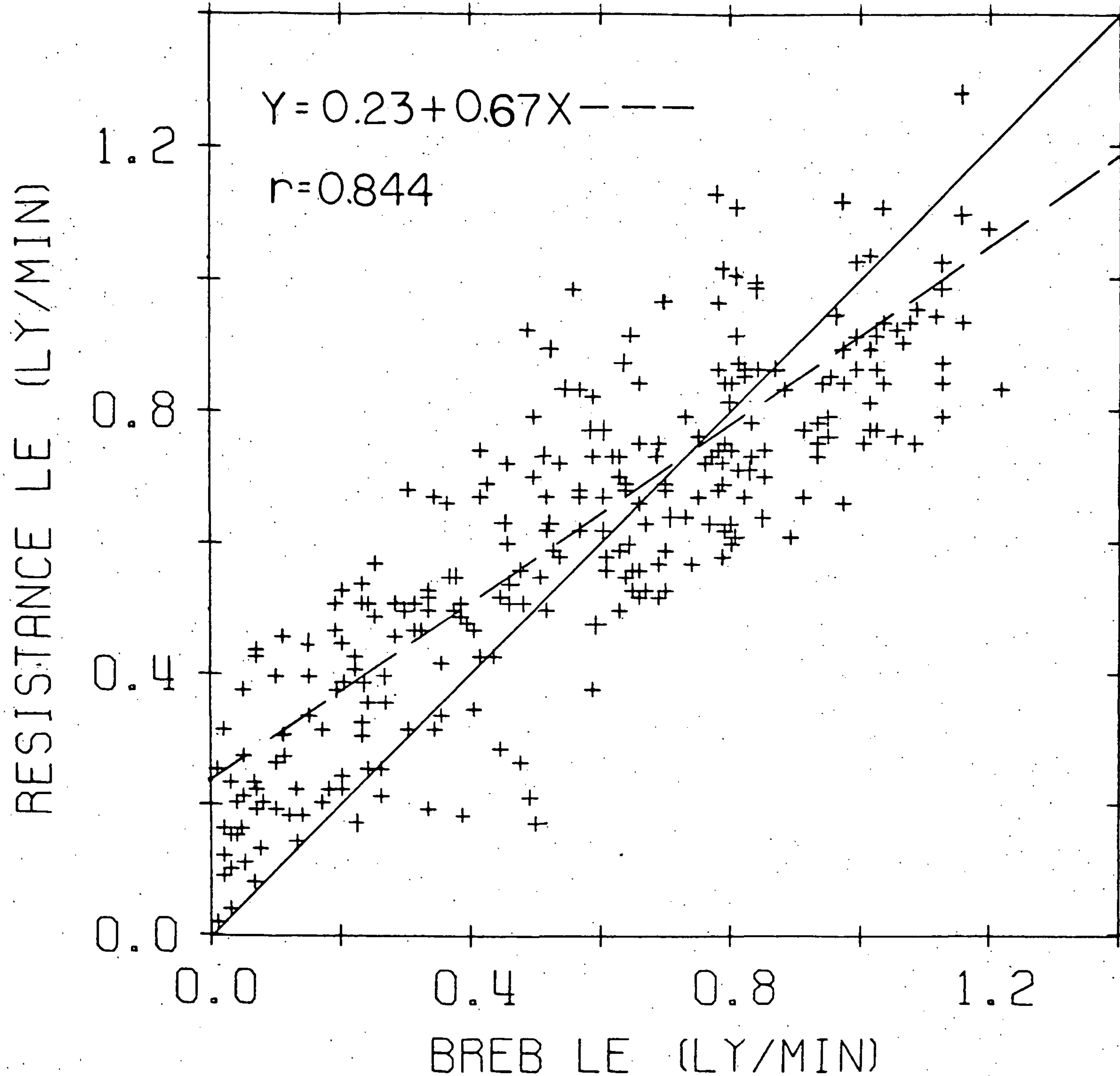

Fig. 9. Resistance model-estimated LE compared with BREB-estimated LE. Values are for 15-minute periods on June 29, July 4, 7 and 8, 1972 and on Aug. 30 and September 3, 1973.

MEASUREMENT OF CROP TEMPERATURES BY LEAF THERMOCOUPLES, INFRA-RED THERMOMETRY AND REMOTELY SENSED THERMAL IMAGERY

ABSTRACT

Crop temperature of alfalfa (*Medicago sativa* L.) was measured with an IR thermometer (T_{IR}) and with leaf thermocouples (T_{TC}). T_{TC} of corn (*Zea mays* L.) was also measured. Thermal imagery of the alfalfa research sites and neighboring fields was also obtained. The study was undertaken to determine daily patterns of crop temperature, to compare crop and air temperature, to determine whether or not alfalfa and corn are consumers or generators of sensible heat in the climate of the central Great Plains and to determine the utility of using remotely sensed thermal imagery to measure crop temperature.

T_{TC} and T_{IR} were often closer than 0.5 C but the agreement was not consistently better than 1-2 C. Measurements indicated that daytime thermal inversions existed over alfalfa fields during several hours on the days studied. Alfalfa was often 5-7 C cooler than air at the 200 cm level in mid and late afternoon. The intensity and duration of the daytime inversions observed in this study indicate that significant quantities of advected sensible heat are supplied to the alfalfa for consumption in evapotranspiration (ET). This finding supports ET studies reported by Rosenberg (1972) and Blad and Rosenberg (1974).

The temperature of corn, alfalfa and air were compared late in the growing season. Even though the corn was irrigated it exhibited a temperature that was consistently higher than that of a nearby alfalfa field. It was also warmer than the air except for short periods in the late afternoon. Unlike alfalfa, corn generated sensible heat

and therefore, probably used significantly less water than did the alfalfa.

Quantitative interpretation of the thermal imagery was not possible but imagery obtained in late spring indicated that wheat and alfalfa were at approximately the same temperature and both were cooler than pasture. If the net radiation and crop boundary layer resistance terms are similar for these three crops then the imagery suggests that wheat and alfalfa used water at about the same rate and that pasture used less water than either.

Surface temperature data can be useful to physical and biological scientists in the study of many natural processes, for example, to: indicate possible sites of volcanic erruption (Lange and Avent, 1973); detect heat islands over land (Rao, 1972); locate geothermal power sources (Friedman, 1970); detect vegetation under stress (Karschon and Pinchas, 1971; Aston and Van Bavel, 1972; Bartholic, Namken and Wiegand, 1972; Carlson, Yarger and Shaw, 1972); estimate evaporative losses from large bodies of water (Richards and Irbe, 1969, and Webb, 1970), bare soil (Conaway and Van Bavel, 1966, 1967) and vegetation (Stone and Horton, 1974; Blad and Rosenberg, 1975).

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

$$R = \varepsilon\sigma T^4 \qquad (1)$$

where ε is the emissivity, σ is the Stefan-Boltzmann constant, and T is the temperature of the radiating surface in degrees K. The total radiative flux from any object includes reflected radiation if the object does not behave as a 'black body'. The total outgoing longwave radiative flux, R_{LW}, may thus be stated as:

$$R_{LW} = \varepsilon\sigma T^4 + (1 - \varepsilon)B^* \qquad (2)$$

where B^* is the flux of incoming longwave radiation. With R_{LW} measured, the emissivity of the surface and the flux density of B^* known, the temperature of an object can be readily calculated.

Tanner (1963), Conaway and Van Bavel (1966), Fuchs and Tanner

(1966, 1968), Fuchs, et al. (1967) and McGinnes and Aronson (1971) discuss theory, techniques and problems associated with measurement of the temperature of vegetation and soil by infra-red (IR) thermometers (sometimes called thermal radiometers). Measurement of crop temperature with IR thermometry constitutes an improvement over the use of contact sensors, such as thermocouples, which must be attached to or inserted in a plant leaf and which can, thus, cause changes in the condition of the leaf.

In most cases the use of ground based IR thermometers for measurement of surface temperature has been restricted to rather small areas. In recent years IR thermometers and thermal scanners have been operated from airborne platforms to measure surface temperatures over large areas.

To accurately measure surface temperature with thermal imagery from airborne platforms the emissivity of the surface, the flux density of B*, and the attenuation of longwave radiation caused by atmospheric absorption between the surface and the aircraft must be known. Fuchs and Tanner (1966), Conaway and Van Bavel (1966) and Davies, Robinson and Nunez (1971) give techniques for determination of B* and ε. Weiss (1971) and Maul (1973) describe methods to account for the atmospheric attenuation of IR radiation. Weiss (1970) and Richards and Irbe (1969) made measurements over large bodies of water. Bartholic et al. (1972) used a thermal scanner to measure soil and crop temperature in Texas and concluded that the thermal imagery obtained was adequate to delineate crops showing moisture stress from those unstressed, to evaluate the uniformity of irrigation and to evaluate the moisture status of the surface soils.

The objectives of our study were to: 1) observe daily patterns of crop temperature as measured with leaf thermocouples and with IR thermometers; 2) compare crop temperature with air temperature to determine whether or not the crop was a consumer or generator of sensible heat and 3) determine the utility of using remotely sensed thermal imagery to measure crop temperature.

EXPERIMENTAL METHODS

Sites and Instrumentation

Studies were conducted at two sites: one located midway between Schuyler and Columbus, Nebraska (lat 41° 25' N, long 97° 13' W, m.s.l. 425 m) in 1972 and the other near Cozad, Nebraska (lat 40° 53' N, long 100° 00' W, m.s.l. 800 m) in 1973.

During each study leaf temperature of alfalfa and corn was determined with six thermocouples wired in parallel and attached to six different leaves. Crop temperature of alfalfa was measured with a Barnes IR thermometer (Model IT-3 S/3°) mounted 2 meters above the crop on a boom that traveled along a trolley for a distance of 4 meters. Four to eight recordings were made at various points along the transect during a recording cycle. Cycles began on the quarter hour.

Thermal imagery from airborne sensors was obtained on three days in 1972 and one day in 1973. In 1972 thermal scans were made at the Schuyler-Columbus site by U.S. Geological Survey aircraft using a Texas Instrument model RS-9 thermal scanner operating in the 8-14 μm waveband range. To aid in interpretation of the imagery the aircraft also carried a Barnes precision radiation thermometer (PRT-5) which measured the surface temperature. In 1973 the thermal scan was made at the Cozad site by a Nebraska Air National Guard aircraft with a Texas Instrument model AN/AAS-18 thermal scanner operating in the 10-14 μm waveband range.

Net radiation was measured with Middleton (model CN6) miniature net radiometers and with a Swissteco type S-1 net radiometer (used only in 1973). Soil heat flux was measured with Middleton flux plates. Temperature, vapor pressure and relative humidity values were obtained from measurements made with thermocouple psychrometer assemblies of the type described by Rosenberg and Brown (1974). Wind speed was measured with a 3-cup wind speed transmitter[3] modified to generate signals in the millivolt range.

IR Thermometer Calibrations

The IR thermometer was calibrated before and after each season's work using a procedure similar to that of Conaway and Van Bavel (1966). The 'black body' radiation source was immersed in a water bath and the temperature of the water bath was raised, gradually, from 0-50 C. Calibration expressions were developed by 'best fitting' data with linear and quadratic expressions. The quadratic expressions provided a small, but significant, improvement to the 'best fit'.

Emissivity of the Aluminum Plate

Conaway and Van Bavel (1966) describe a method for determining the emissivity of an aluminum plate. In their technique a heated or cooled alumninum plate is placed inside a black painted styrofoam box and allowed to change temperature gradually. We found, using their technique, that the calculated plate emissivity often varied depending upon whether a heating or cooling cycle was employed. This was due

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3/ Science Associates, Catalog No. 406-1.

to a continuous change in temperature of the styrofoam box walls because of absorption of radiation emitted by the aluminum plate.

We have developed a modified and somewhat simplified method for determining the emissivity of the aluminum plate which is described in Appendix A. For a newly painted aluminum[4] plate the emissivity was found to be 0.52, in agreement with results reported by Bartholic et al. (1972).

Emissivity of the Plant Canopy

Fuchs and Tanner (1966) provide a method for obtaining the emissivity of vegetation which requires measurement of R_{LW}, B^* and the temperature of the vegetation. Fuchs and Tanner measured the temperature of plants enclosed in an aluminum pop-tent. Our procedure is similar to that of Fuchs and Tanner, except that the temperature of the vegetation was measured with leaf thermocouples at night under clear skies.

From observations made on August 28 and September 3, 1973, the emissivity of the alfalfa was found to be 0.976 and 0.971. These values are in very good agreement with the 0.976 reported by Fuchs and Tanner (1966).

Calculations

In actual field use the flux density of incoming longwave radia-

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4/Plate painted with alunimum paint manufactured by Moore Paint Co., St. Louis, for National Paint Distributors.

tion, B*, is determined from measurements made while the IR thermometer sensing head views the aluminum plate. B* is calculated from the following equation:

$$B^* = \frac{R_{bp} - \varepsilon_p \sigma T_p^{\,4}}{1 - \varepsilon_p} \qquad (3)$$

where R_{bp} is the longwave flux from the aluminum plate (measured with the IR thermometer), ε_p is the emissivity of the aluminum plate and T_p is the plate temperature.

The plant canopy temperature, T_c, is calculated as follows:

$$T_c = \left[\frac{R_{bc} - (1-\varepsilon_c)B^*}{\varepsilon_c \sigma}\right]^{\frac{1}{4}} \qquad (4)$$

where R_{bc} is the radiative flux of the crop (measured with the IR thermometer) and ε_c is the crop emissivity.

The latent heat fluxes were calculated with the Bowen ratio-energy balance technique. Sensible heat fluxes were calculated as the residual in the energy balance equation (see eq. 5).

RESULTS AND DISCUSSION

In the discussion that follows the term 'crop surface temperature' (T_{IR}) refers to the temperature measured with an IR thermometer. 'Plant temperature' (T_{TC}) refers to that measured with leaf thermocouples. The surface viewed by the IR thermometer includes exterior sunlit leaves, interior shaded leaves and exposed soil surface. The plant temperature is the average temperature of six peripheral leaves.

Temperature Measurement of Air and Alfalfa - Results from the Schuyler-Columbus Site, 1972

Daily patterns of air and alfalfa temperature under varying weather conditions on May 31 and June 1, 2 are presented in Figs. 1-3. Data on energy balance and climatological parameters on the above days are provided in Table 1. The energy balance at the surface of the earth may be written as:

$$Rn + LE + H + S = 0 \qquad (5)$$

where Rn is net radiation, LE is evaporative (latent heat) flux, H is sensible heat and S is soil heat flux. The sign convention is that fluxes to the surface are positive and fluxes from the surface are negative. Whenever the energy consumed in LE exceeds that available from (Rn + S) the additional energy is supplied from advective sensible heat and H in equation (5) will be positive.

The temperature patterns under the changing weather conditions of the May 31 - June 2 period provide several interesting contrasts. May

31 was clear and relatively cool. Daily Rn exceeded daily evapotranspiration (ET) indicating that on this day the crop was a generator, rather than a consumer of sensible heat. This observation is supported by the fact that air temperature at 200 cm was lower than the crop temperature until about 1600 hours (solar time).

T_{TC} was significantly higher than T_{IR} until about 1500 hours. Differences were as great as 3 C and were likely due to a significant contribution of energy radiated from the cool moist soil and shaded interior leaves to the radiant flux density sensed by the IR thermometer. Agreement between T_{IR} and T_{TC} improved significantly when the crop to air temperature gradient changed from lapse to inversion (the ambient air temperature became warmer than the crop).

In contrast to the previous day, June 1 was warm, clear and ET flux was strong. After about 1200 hours air temperature was greater than crop temperature and sensible heat was consumed in ET by the alfalfa. A total of 262 cal cm^{-2} of energy was computed to have been supplied by sensible heat advection.

A cool moist soil surface may have been the cause for the lower T_{IR} observed before 1000 hours. Later, temperature measured by the two methods agreed very well although T_{IR} was slightly higher than T_{TC} in the mid and late afternoon. This effect was probably due to an increased contribution of thermal radiation from the soil surface which had dried and was warm relative to the surrounding plant material.

June 2 began cool, but by mid-morning the air was warm. Some cirrus clouds were present during mid-day. Advective conditions existed after about 1100 hours but the rate of sensible heat consumption was lower than on the previous day. Agreement between T_{IR} and T_{TC} was good except during late afternoon when T_{IR} was higher.

On all 3 days shown by these figures the night-time inversion was disrupted at about 0600-0700 hours. The onset of the day-time thermal imversion, which indicates sensible heat advection, varied from mid-morning to late afternoon.

Temperature Measurement of Air, Alfalfa and Corn - Results from the Cozad Site, 1973

Temperature patterns for air, alfalfa and corn on August 28 and September 5, 1973 are presented in Figs. 4 and 5. Energy balance and climatic conditions on these days are given in Table 1.

August 28 was clear and warm. It was a day of strong sensible heat advection. Advective conditions, as indicated by the persistent temperature inversion, existed throughout the day. Advection supplied about 31% of the energy consumed by ET.

Corn, on the other hand, was warmer than the air, except in late afternoon. Thus, sensible heat was generated by the corn during most of the day and consumed only during a small portion of the afternoon. This suggests that the ET rate of the corn was considerably lower than that of the nearby alfalfa. The corn was irrigated, but had tasseled and the ears were almost full size by this time. Water use by the corn, may, therefore, have been less than if the corn had been in a more active stage of growth.

Until mid-afternoon and except for a brief period around solar noon the alfalfa temperature measured with thermocouples was consistently about 1 C higher than that measured with the IR thermometer. Late in the afternoon temperature measured by both methods agreed closely.

September 5 was clear. Temperatures were low in the morning but warmed rapidly. A distinct temperature inversion did not develop over the alfalfa until about 1400 hours and advected sensible heat contributed only about 50 cal cm^{-2} of energy. T_{TC} was generally 1-2 C higher than T_{IR}. Again the temperature of the corn remained above air temperature until late afternoon.

The 1972 and 1973 data together suggest that radiation from the interior leaves and soil surface contributes a measurable portion of the energy sensed by the IR thermometer. The IR thermometer provides good estimates of canopy temperature if crop cover is complete or nearly so. If not, radiation from the soil will strongly influence the 'apparent' canopy temperature. Thermocouple measurements are inadequate since it is very difficult to place a sufficient number of thermocouples to obtain an accurate average of the crop temperature.

Measurement of Crop Temperature by Airborne Thermal Scanners

Several attempts were made to obtain thermal imagery of the research site and surrounding fields during these studies. Because of inclement weather and instrument malfunction, thermal imagery was obtained only on May 31, June 1, August 16, 1972 and August 28, 1973. Quantitative interpretation of the imagery was not possible because the thermal scanners had no internal calibration sources and data obtained with the PRT-5 thermal radiometers were unacceptable.

Despite these limitations, several observations of a qualitative nature can be made from the thermal scans shown in Fig. 6. The photographs are positive prints of scanner produced negatives. The darker the area, the lower its temperature.

From the first series of flights [Fig. 6(a,b)] we observed that the experimental alfalfa field (A) was relatively cool as was the wheat field (B) just north of it. The pasture (C) was warmer than alfalfa and the bare fields (D,E) were the warmest of any in the area. The tree windbreak near the farm buildings (F) was cool.

Crop temperature can be related to the evaporation rate of the crop. A method to estimate evaporative latent heat flux from crop temperature is discussed by Brown and Rosenberg (1973), Stone and Horton (1974) and Blad and Rosenberg (1975). One appropriate equation is:

$$-LE = Rn + S + C_p \rho \frac{(T_a - T_c)}{r_a} \qquad (6)$$

where C_p is the specific heat of air at constant pressure, ρ is the density of air, T_a is air temperature, T_c is crop temperature, and r_a is the crop boundary layer resistance.

Equation 6 indicates that, with all other factors equal, the cooler the crop - the greater the LE flux. Net radiation and soil heat flux should have been nearly identical for alfalfa, wheat and pasture. All the crops were of about the same height. Therefore, the values of r_a may be approximately equal (Brown and Rosenberg, 1973 and Blad and Rosenberg, 1975) although the different plant morphologies may affect the aerodynamic roughness of the various crops. The thermal imagery suggests that evapotranspiration occurred at about the same rate for wheat and alfalfa but at a lower rate in the pasture We reported, on the basis of Bowen ratio-energy balance measurements, that evapotranspiration rate in a pasture was lower than that in adjoining alfalfa (Blad and Rosenberg, 1974). The thermal imagery shown here supports our earlier finding.

Fig. 6c is a thermal scan made on August 16, 1972. The fields of alfalfa (A), soybean (D) and corn (E) were all at approximately the same temperature. The wheat field (B) had been harvested and was very warm as was the strip of bare soil (G) between two corn fields. The pasture (C) was slightly warmer than the alfalfa and other agricultural crops in the area.

The only thermal imagery obtained in 1973 is shown in Fig. 6d. On this thermal scan the corn field (B) appears slightly lighter grey than the alfalfa field (A). Thermocouple measurements indicated that the corn was about 2 C warmer than the alfalfa during the time of the overflight.

Several light areas appear in the fields. Note, in particular, the two areas near the center of field (A). These were two large haystacks. Other light colored spots are small bare areas or areas where soil conditions led to severe moisture stress on the crop. No significant rainfall had occurred for several weeks prior to the flight.

CONCLUSIONS

T_{IR} and T_{TC} for alfalfa did not agree any better than 1-2 C, consistently. There were, however, periods of several hours in which the agreement was closer than 0.5 C. Agreement was generally best during mid and late afternoon and worst in the early morning.

Rosenberg (1969) and Blad and Rosenberg (1974) reported that ET rates of alfalfa in the east central Great Plains are often very high due to consumption of advected sensible heat. Sensible heat will be consumed in ET only when the air is warmer than the crop, that is, when a temperature inversion exists. Measurements of crop and air temperature made in this study do indeed show that daytime thermal inversions, often lasting for several hours in the mid and late afternoon, occur over the alfalfa fields. On some days these inversions are observed for all or most of the day. Particularly in the late afternoon, the inversion can be very intense. It is common to find that the temperature of alfalfa is 5-7 C lower than air temperature measured at the 200 cm level.

Comparison of corn and alfalfa temperature late in the growing season revealed that corn, although irrigated, was consistently warmer than a nearby alfalfa field. Corn was also warmer than the air except during the late afternoon. These data suggest that, unlike alfalfa, the corn field generated sensible heat. It follows, then, that more water was consumed by alfalfa than by corn during that portion of the growing season in which the studies were conducted.

Linacre (1964) and Priestly and Taylor (1972) observed that at about 33 C the temperature of air and crop were equal. Below 33 C leaves were warmer than air and above they were cooler. According to Linacre, the leaf temperature will generally exceed the air temperature in a sunny moist climate with low windiness. For alfalfa, under the advective conditions which often prevail in the central Great Plains, the air and leaf temperature relationship observed by Linacre and Priestly and Taylor does not appear to hold. For the days presented in this study the cross over point (air temperature becomes warmer than leaf temperature) occurred in a temperature range from about 23-30 C. On many days the air temperature from that point continued to increase while the crop temperature either decreased or remained nearly constant. Although the air temperature data reported here were measured at 200 cm above ground a similar pattern was observed for air temperature measured within 25 cm of the crop.

The thermal imagery obtained in this study was of sufficiently good quality to permit qualitative, but not quantitative, interpretation. This imagery showed that pastures were warmer than alfalfa fields indicating lower ET rates in pasture. This agrees with results of direct micrometeorological measurements made by Blad and Rosenberg (1974) in the same region.

The thermal imagery obtained in the late spring of 1972 showed that wheat and alfalfa, under conditions of minimal moisture stress, were at approximately the same temperature. It appears that differences in water use by the alfalfa and wheat were insufficient to produce temperature differences that could be discriminated from the imagery. Unless the r_a or Rn values for the two crops were very different, alfalfa and wheat should have consumed water at approximately the same rate. This conclusion does not agree with results reported by Fritschen (1966) who found, in an Arizona experiment, that wheat used water at a slightly lower rate than did alfalfa. Reasons for the disagreement are uncertain.

It is difficult to obtain satisfactory quantitative interpretation of thermal imagery when the only reference temperature data is that obtained with precision radiation thermometers. This is especially true in areas where agricultural fields are relatively small (10-20 acres). We feel that the quantitative interpretation of thermal imagery can be improved by the use of thermal scanners with internal calibration sources and by the use of several ground stations for measurements of surface 'truth' temperature.

ACKNOWLEDGMENTS

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APPENDIX A

Method for Determining Emissivity of the Aluminum Plate

1) A 35 cm x 35 cm x 0.95 cm aluminum plate, with 4 thermocouples embedded in the surface near the center of the plate, was coated with aluminum paint. The plate was placed over a 30 cm deep styrofoam box, in which a 100 watt light bulb was mounted.
2) The plate and box were placed in a room where background radiation during the emissivity measurements was nearly constant. The IR thermometer was mounted about 1 meter above the floor and aimed at the center of the plate.
3) The aluminum plate was refrigerated and cooled to about 5 C and placed on the styrofoam box. The light bulb was turned on and produced heat sufficient to raise the plate temperature, gradually, to above 60 C.
4) The longwave radiative flux from the plate, calculated from the plate thermocouple temperature was plotted on the x-axis and the radiation sensed by the IR thermometer was plotted on the y-axis. The slope of the line so plotted is the plate emissivity, ε_p.

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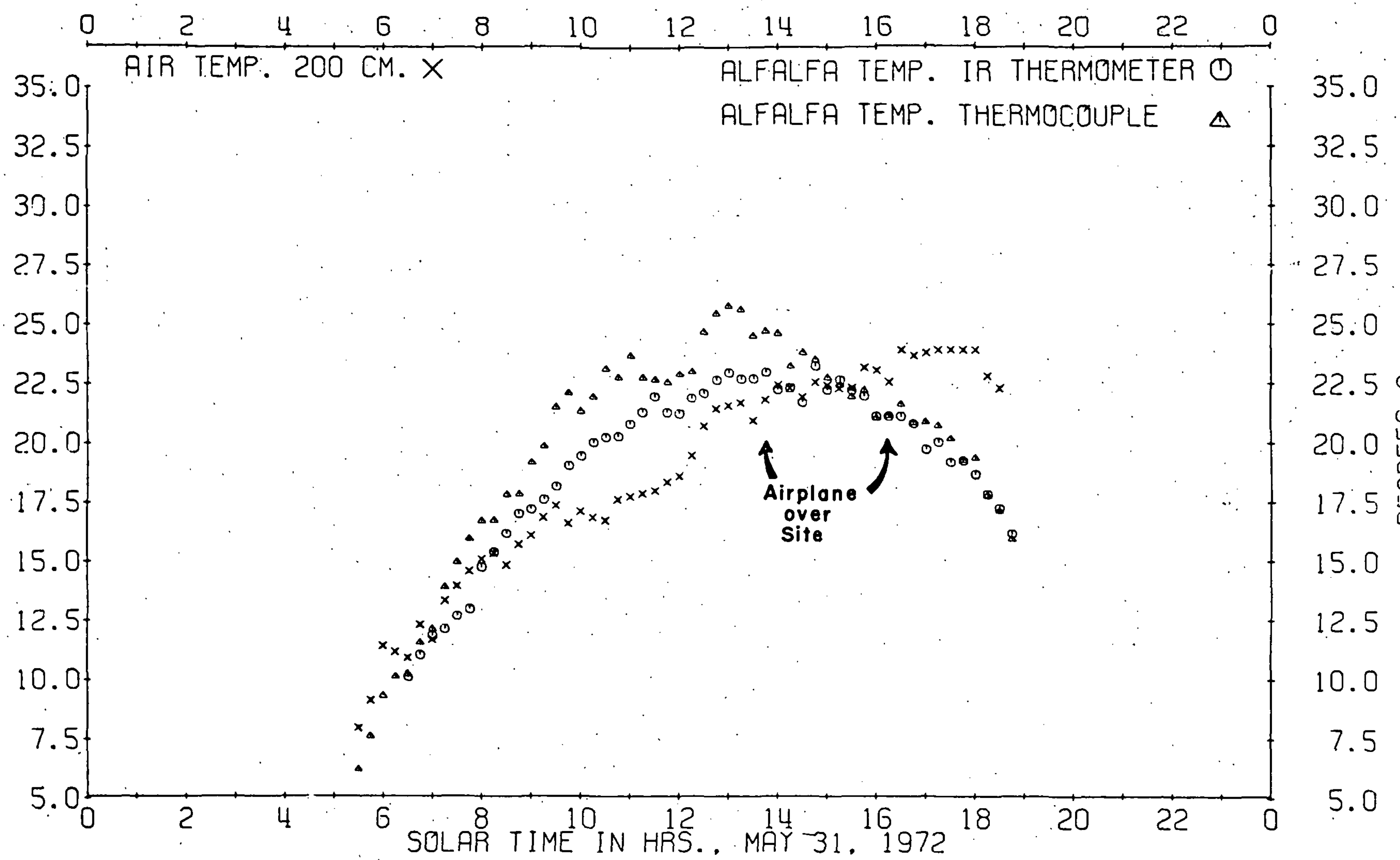

Fig. 1. Daily pattern of air temperature measured at 200 cm above ground and alfalfa temperature measured with an IR thermometer and with thermocouples. May 31, 1972 at the Schuyler-Columbus site.

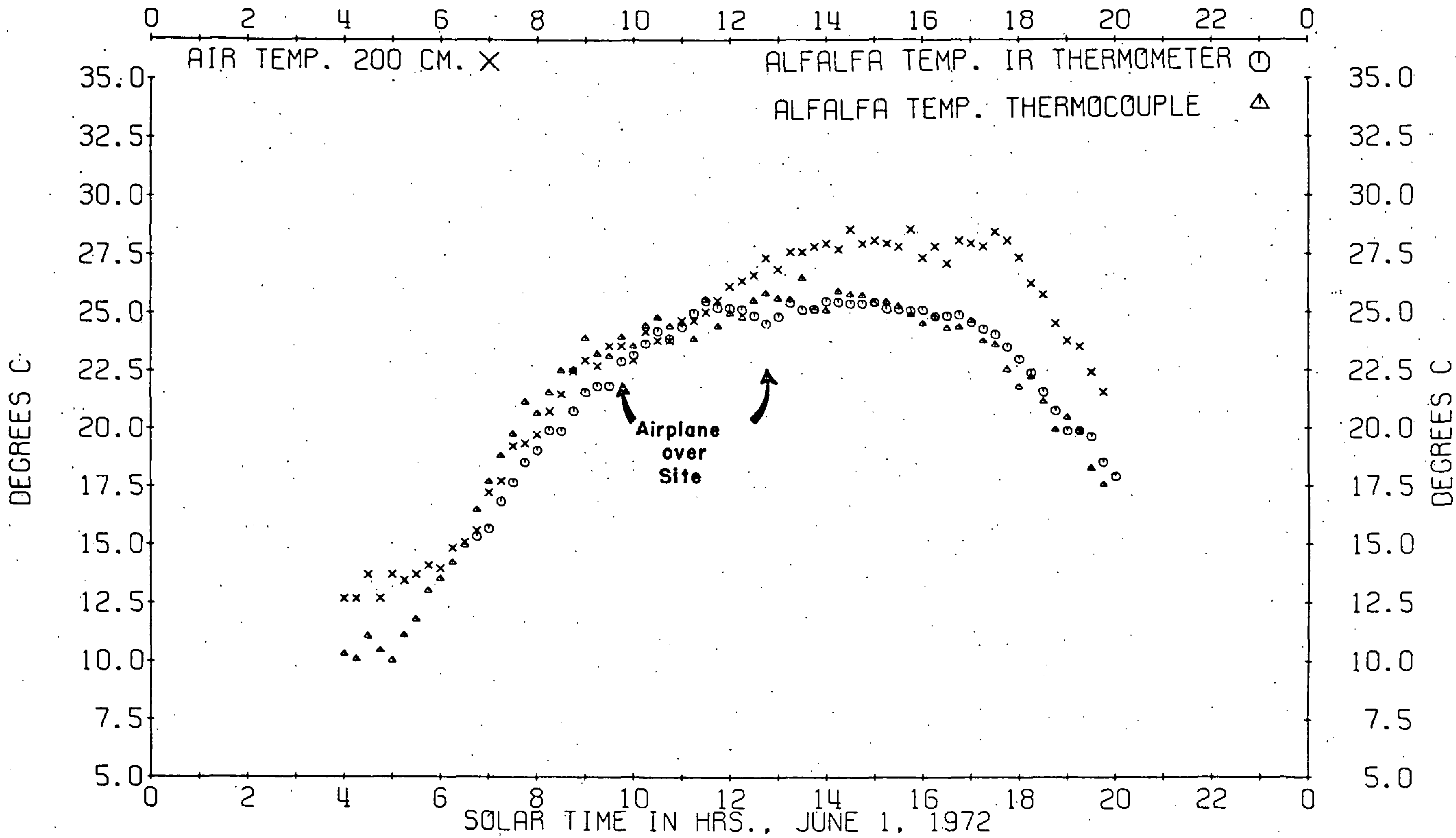

Fig. 2. As in Fig. 1 for June 1, 1972.

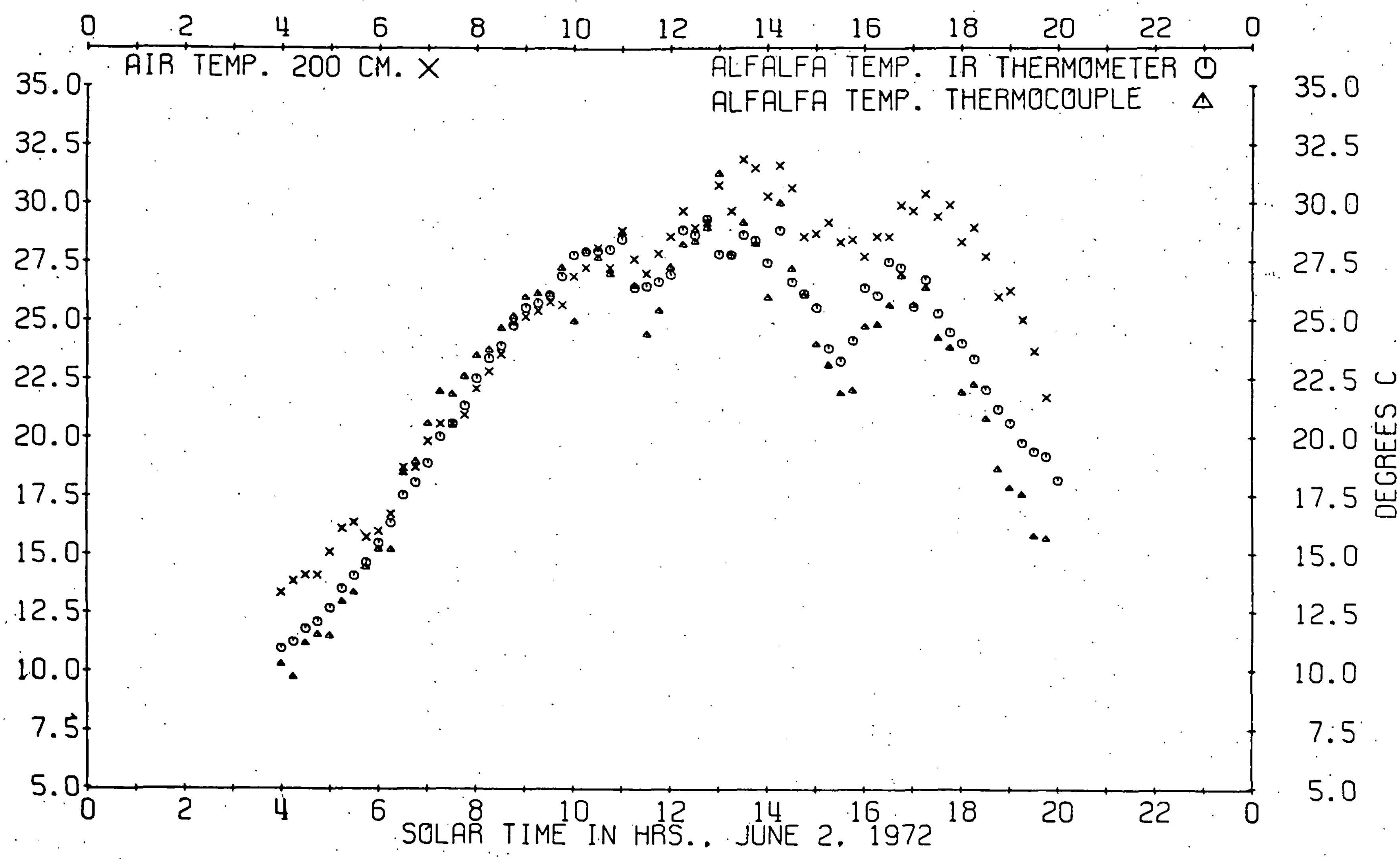

Fig. 3. As in Fig. 1 for June 2, 1972.

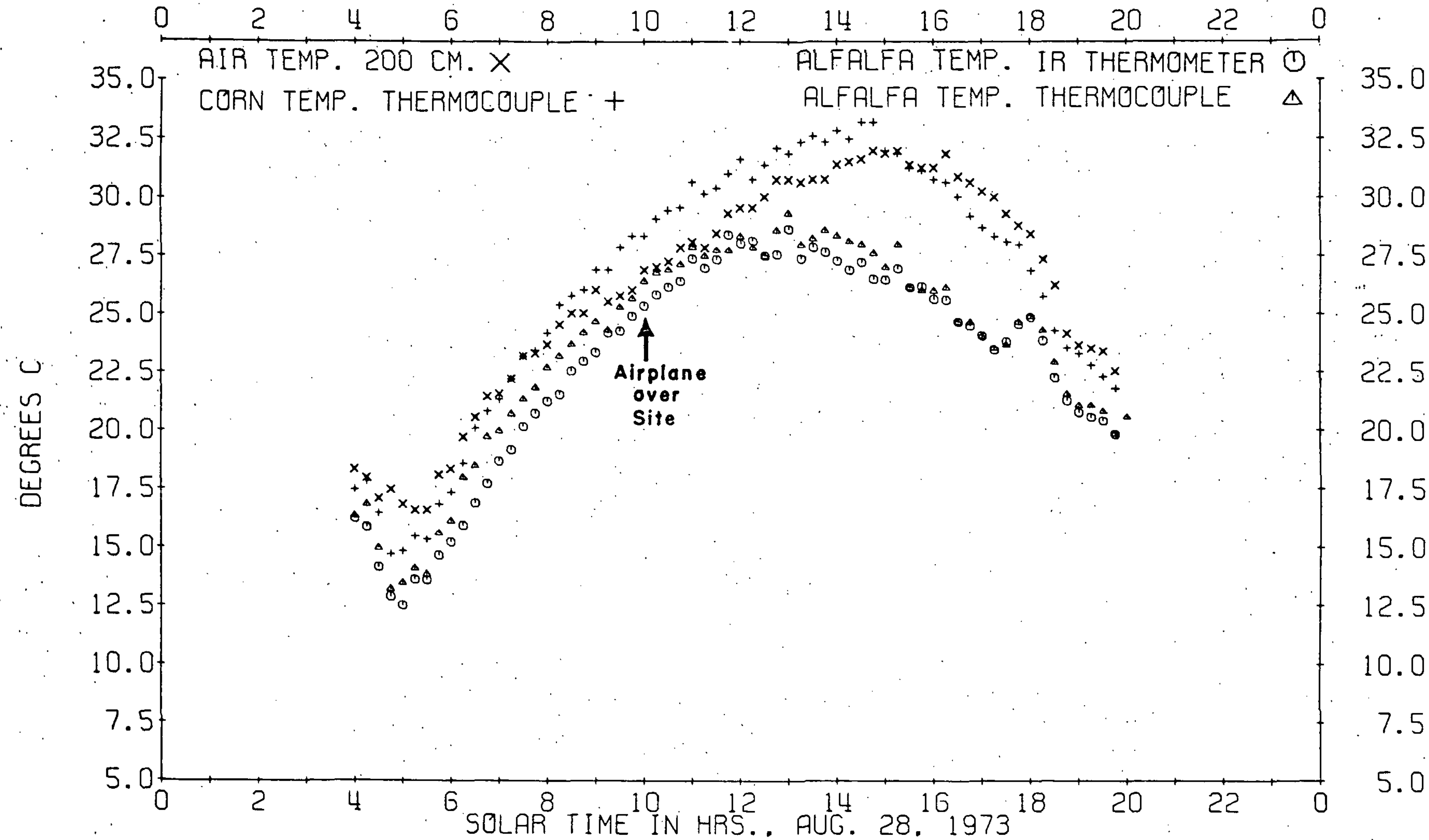

Fig. 4. Daily pattern of air temperature measured at 200 cm above ground, alfalfa temperature measured with an IR thermometer and with thermocouples and corn temperature measured with thermocouples. August 28, 1973 at the Cozad site.

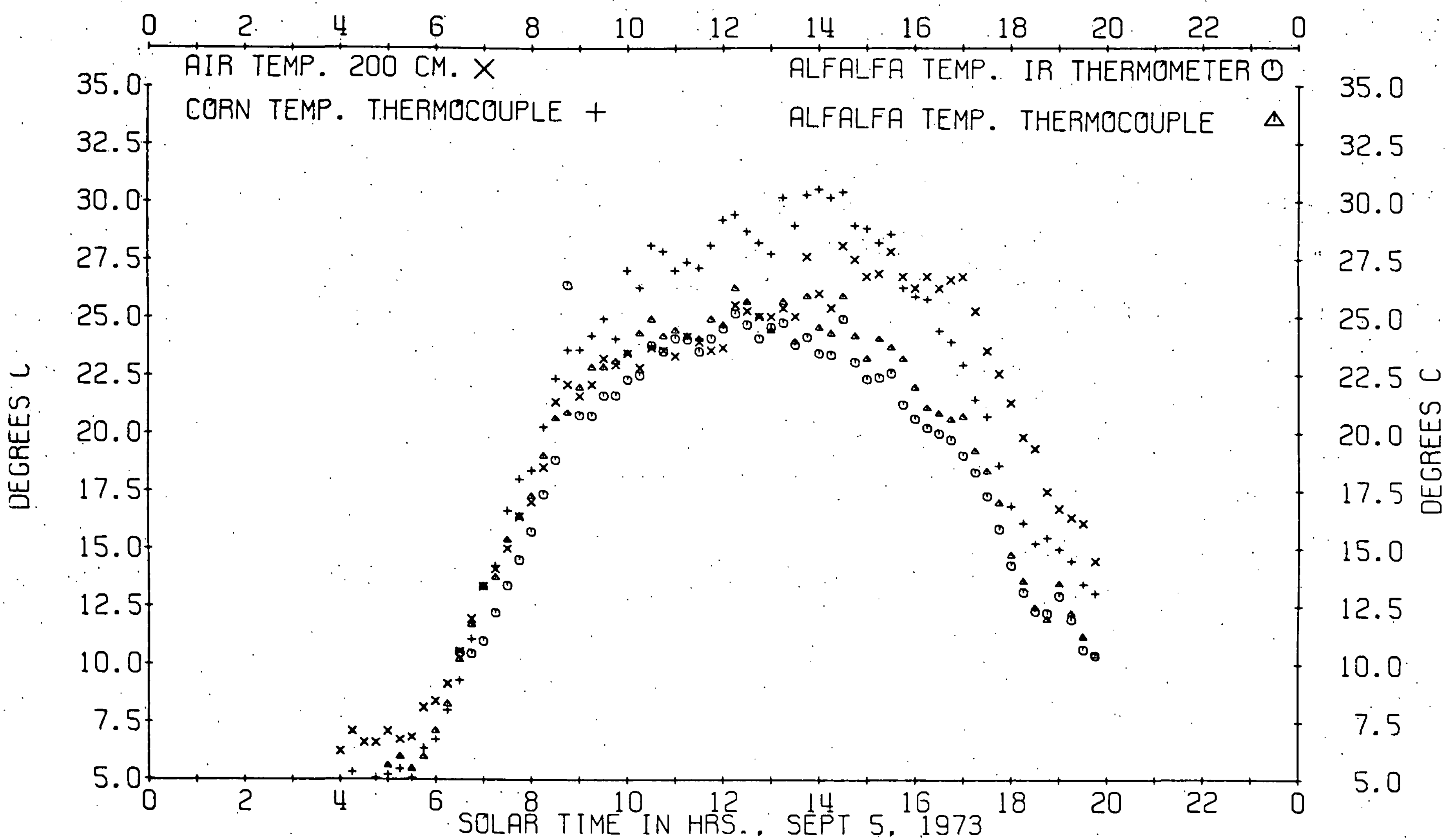

Fig. 5. As in Fig. 4 for September 5, 1973.

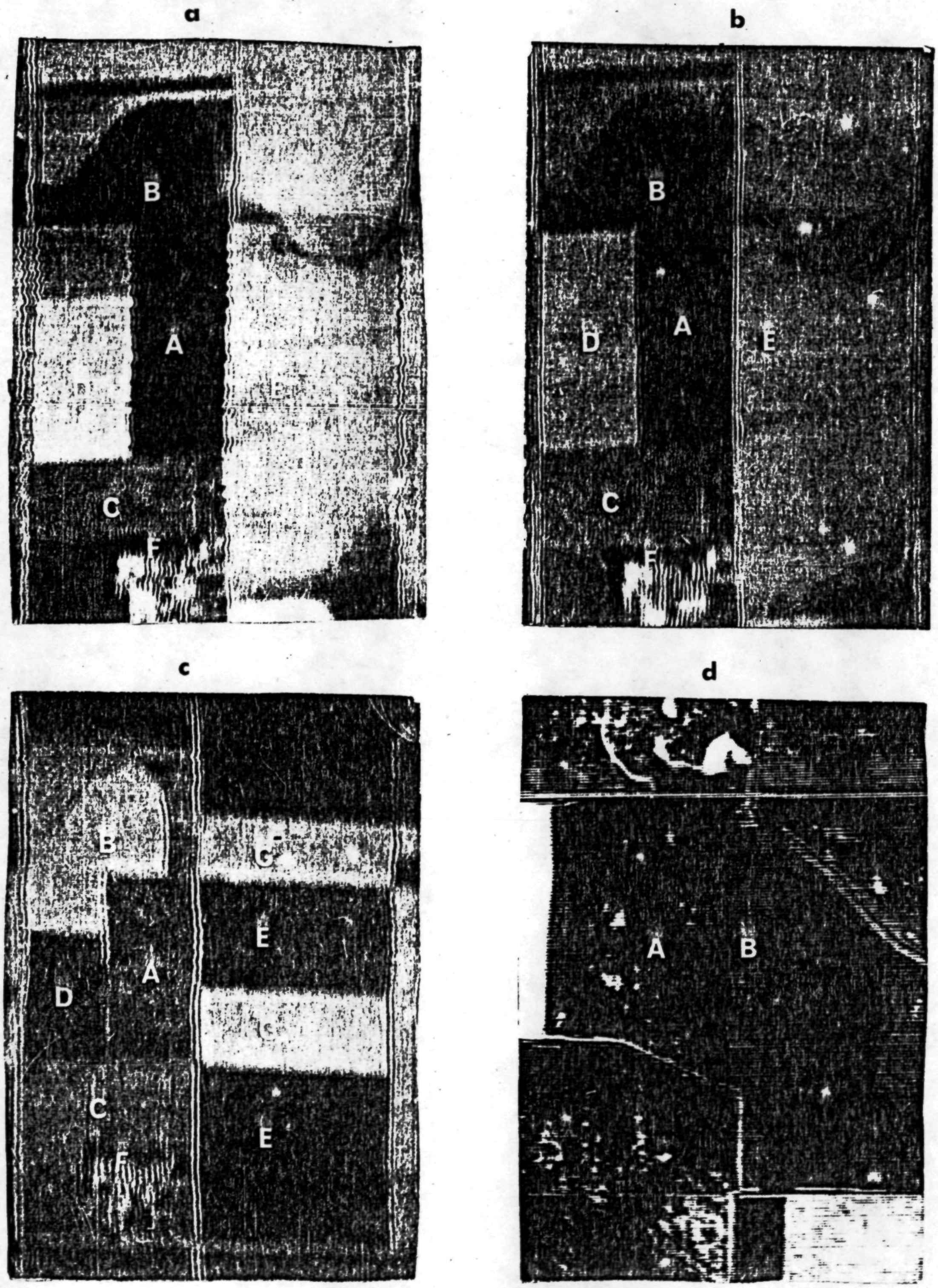

Fig. 6. Thermal imagery from airborne thermal scanners. Scans a, b, and c were obtained from 1200 m above ground at Schuyler-Columbus site at 1400 hrs on May 31, 1000 hrs on June 1 and 0900 hrs on August 16, 1972, respectively. Field (A) is alfalfa, (B) is wheat (stubble in c), (C) is pasture, (D) is bare soil (soybean in c), (E) is bare soil (corn in c), (F) is a farmstead, (G) is fallow. Scan d was obtained from 900 m above ground at 1000 hrs on August 28, 1973 at Cozad site. Field (A) is alfalfa, (B) is corn.

Table 1. Energy balance and climatic conditions on selected days at the Schuyler Columbus site in 1972 and the Cozad site in 1973. Daily totals are for the 0600-1800 period.

Date	Net Radiation	Soil Heat Flux	Sensible Heat Flux	Latent Heat Flux	Evapo-transpiration		Air Temperature	Air Vapor Pressure	Relative Humidity	Wind Speed
	----- Cal cm^{-2} day^{-1} -----				mm day^{-1}		C	mb	%	m sec^{-1}
				Schuyler-Columbus Site						
May 31	437	-8	-32	-397	6.8	Max	23.5	12.3	92	2.7
						Min	9.0	10.2	41	.5
						Avg	18.6	10.4	54	2.1
June 1	445	-9	262	698 ~~-706~~	12.0 12.1	Max	28.0	16.7	78	4.8
						Min	13.9	12.6	39	2.4
						Avg	24.2	14.8	50	3.8
June 2	375	-9	102	-469	8.0	Max	30.2	21.6	79	2.5
						Min	17.1	15.0	36	.4
						Avg	26.2	17.6	52	1.4
				Cozad Site						
Aug. 28	328	-10	211	-530	9.1	Max	30.6	23.4	81	4.9
						Min	17.8	16.4	50	2.2
						Avg	26.5	20.5	60	3.9
Sept. 5	326	-11	49	-365	6.2	Max	25.1	15.1	94	2.5
						Min	7.3	9.6	45	1.1
						Avg	20.4	13.8	60	1.8