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Effect of Solar Azimuth and Infrared Thermometer View Direction on Measured Soybean Canopy Temperature[1]

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ABSTRACT

Measurements of radiative canopy temperature taken with infrared thermometers (IRTs) are strongly influenced by amount of crop cover and amount of viewed soil background. This influence can be minimized by making off-nadir measurements so that mostly vegetative surface is viewed. But off-nadir measurements vary with the relative azimuthal positions of the sun and the IRT due to the measurement of true variations in the individually sunlit and shaded canopy elements. The geometrical relationship between solar azimuth and IRT view azimuth on measured canopy temperatures was investigated for soybeans grown at two Nebraska locations in 1982. Soils at the two locations were a Typic Argiudoll and a Typic Ustipsamment. Canopy temperature as measured by the IRT declined linearly as the difference between the solar azimuth and IRT view azimuth increased from 0° to about 110°. As this difference increased to angles greater than 110°, the viewed canopy temperature remained fairly constant at about 0.3°C below the average of the canopy temperatures measured at the four cardinal directions. The declining linear relationship seen for angles between 0° and 110° was found to be more strongly defined during the vegetative growth stages than during the reproductive growth stages. This was attributed to declining heliotropic response of soybean [*Glycine max* (L.) Merr.] leaves as the canopy ages.

***Additional index words:* *Glycine max* L., Plant temperature, Radiation interception, Remote sensing, Solar elevation angle.**

PLANT temperature is an important variable in estimating and quantifying plant water use, moisture stress, grain yield, etc. The use of recently developed lightweight, portable infrared thermometers (IRTs) featuring direct temperature readout makes remotely sensed canopy temperature measurements simple and easy. One problem in using infrared thermometry is that the measured canopy temperature depends on the position and viewing angle of the instrument. For example, Hatfield (1979) made measurements of wheat (*Triticum aestivum* L.) canopy temperature using an IRT positioned 1.0 m above the canopy in the nadir orientation (i.e., directly above point of measurement), and from the cardinal directions (N, S, E, W) with the IRT inclined 45°. He found that the differences between measurements made at nadir and at 45° inclination were greatest when crop cover was incomplete because more soil area was viewed at nadir than at 45°. Kimes et al. (1980) measured wheat canopy temperatures from the nadir-view and horizontally in layers within the canopy from 12 azimuthal directions. They showed that differences between the nadir-viewed canopy temperature and the average, 12-direction layer canopy temperatures were greatest with less than full canopy cover. Similar results were found by Kimes (1980) for soybeans (*Glycine max* L.) where agreement between nadir viewed temperatures (a composite of soil plus canopy temperatures) and vegetation canopy temperatures was greatest at high percent ground cover, and decreased as percent ground cover decreased.

This problem of biased canopy temperatures due to viewed soil can be minimized by making off-nadir measurements. However, another bias is thereby introduced, i.e., the dependence on solar azimuth and view direction. This arises because true variations exist in the temperature of individual leaves comprising the plant canopy, due mainly to the influence of canopy geometric structure on solar radiation interception. Norman (1979), using a comprehensive plant-environment model, predicted large variations in leaf temperatures throughout a canopy due to absorption of incident radiation. Sunlit leaves were much warmer (5 to 10°C, depending on environmental and plant conditions) than shaded leaves.

Kimes (1981) has documented the variation in measured wheat canopy temperatures arising from changing solar azimuth and different sensor viewing azimuths. Maximum canopy temperatures were recorded when viewing mostly sunlit leaf area, and minimum canopy temperatures were recorded when viewing mostly shaded leaf area.

Wiegand and Namken (1966) (cotton, *Gossypium hirsutum* L.), Wiegand and Swanson (1973) (cotton), and Stone et al. (1975) (sorgum, *Sorghum bicolor* L. Moench) found a high correlation between canopy temperature and incoming solar radiation. Monteith and Szeicz (1962) (long grass) and Fuchs et al. (1967) (soybean) have reported that the IRT-sensed canopy temperature is on the order of 3°C warmer when viewing the sunlit side of the crop than when viewing the shaded side. Fuchs et al. (1967) found little effect of solar altitude on IRT-sensed canopy temperature.

The objective of this study was to evaluate the influence of the difference between the solar azimuth and the instrument view direction on soybean canopy temperatures measured with a hand-held IRT.

MATERIALS AND METHODS

Data were collected during the 1982 growing season at the Univ. of Nebraska Agricultural Meteorology field laboratory near Mead, Nebr. (41°09′N96°30′W, alt. 354 m above mean sea level), and at the Univ. of Nebraska Sandhills Agricultural Laboratory (SAL) (41°37′N100°50′W, 975 m above mean sea level). Soils at the Mead Laboratory and SAL are, respectively, Sharpsburg silty clay loam (a fine, montmorillonitic, mesic Typic Argiudoll) and Valentine fine sand (a sandy, mixed, mesic Typic Ustipsamment). Soybeans (cv. Harosoy) were planted in rows oriented N-S, with a final plant population of approximately 390 000 plants ha^{-1}. Row spacing was 0.51 m at Mead and 0.76 m at SAL.

Measurements of infrared canopy temperature were made at Mead throughout the growing season with a hand-held IRT.[3] The instrument has a 5° field of view and a bandpass of 10.5 to 12.5 μm. Measurements were taken near the beginning of each solar hour on days with clear sky conditions

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[3] Telatemp Model AG-42, Telatemp Corp., Fullerton, CA.

from a standing position at each of the four cardinal directions around a plot (Fig. 1). The IRT was inclined approximately 15° from the horizontal. Data were recorded by a portable, microprocessor-controlled data logger.[4] The measurements made at SAL were taken with a similar IRT[3] having a bandpass of 8 to 14 μm and inclined approximately 30° from the horizontal. The IRTs were calibrated at the beginning of the season by the method described by Blad and Rosenberg (1976).

RESULTS

The relationship between Δ AZIMUTH and Δ TEMPERATURE for the Mead data taken in 1982 is shown in Fig. 2A, where:

Δ AZIMUTH is the angular difference between the solar azimuth and the azimuth from which instrument views the field,

and

Δ TEMPERATURE is the difference between the IRT-sensed temperature measured from a given view direction and the average of the four IRT-sensed temperatures taken around a plot.

Figure 1 depicts an example of the measurement procedure at 1000 h on 25 Aug. 1982. At this time canopy temperature is measured from the north, south, east, and west sides of the plot. The average of these four temperatures is computed and the difference between any one of the four measured temperatures and the average is Δ TEMPERATURE. Δ AZIMUTH in this example is equal to 130° when making the measurement from the north side of the plot, and 40° when measuring from the east side. When Δ AZIMUTH = 0°, the sun was directly behind the observer and the IRT viewed mostly sunlit leaves. When Δ AZIMUTH = 180°, the observer faced the sun, and the IRT viewed a smaller proportion of sunlit leaves.

Δ TEMPERATURE was observed to decline linearly for Δ AZIMUTH between 0° to 110° (Fig. 2A). The negative relationship was statistically significant. Warmest canopy temperatures were observed when Δ AZIMUTH = 0°. As Δ AZIMUTH increased to angles greater than about 110°, the viewed canopy temperature remained fairly constant at about 0.3°C below the average canopy temperature. No significant relation was found between Δ AZIMUTH and Δ TEMPERATURE for values of Δ AZIMUTH greater than 110°. The portion of the curve plotted beyond this point represents the mean Δ TEMPERATURE value for Δ AZIMUTH greater than 110°.

Figure 3 shows why this relationship between Δ TEMPERATURE and Δ AZIMUTH exists. As the sun rises the east-facing side of the plant canopy intercepts the incoming solar radiation most effectively and becomes warmer than the other sides of the canopy. As the sun moves more into the southern position of the sky, the south-facing side of the canopy becomes warmest. Later in the day, when the sun is in the western sky, the west-facing side of the canopy intercepts more incoming radiation than the other sides of the canopy, and is the warmest. The relationship shown in Fig. 2A is a result of the measurement of true variations in the canopy temperature that exist because sunlit leaves are warmer than shaded leaves.

A similar relationship was observed for soybeans

[4] Polycorder, Model 516, Omnidata Int., Logan, UT.

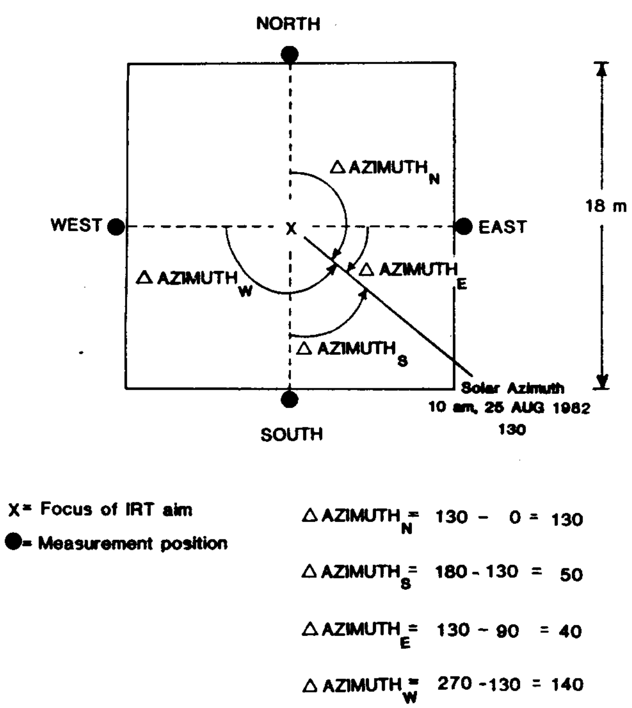

Fig. 1. Calculation of Δ AZIMUTH for four measurement positions at 1000 h on 25 Aug. 1982.

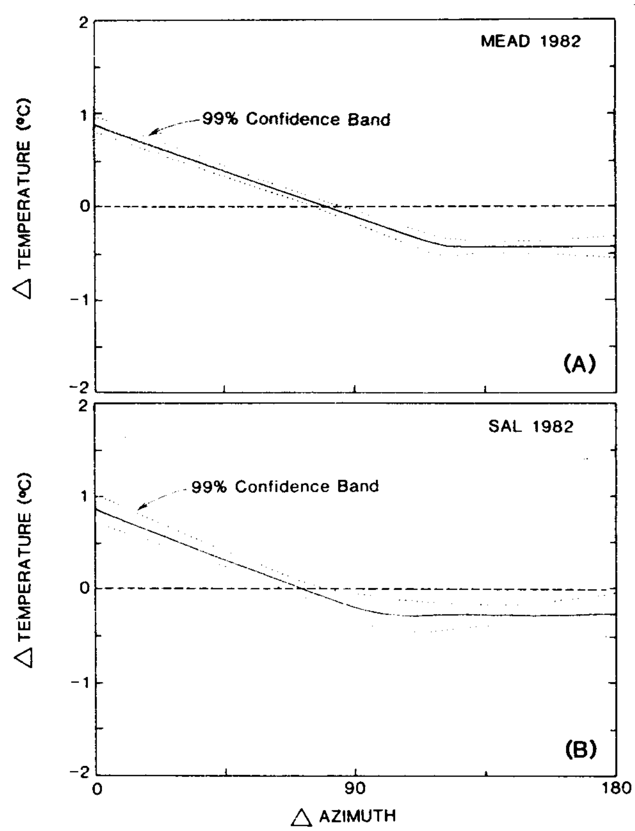

Fig. 2. Deviation of viewed canopy temperature from average canopy temperature due to difference between solar azimuth and infrared thermometer (IRT) view direction for data from (A) Mead; (B) Sandhills Agricultural Laboratory (SAL).

Table 1. Linear regression coefficients and r^2 values for all Mead and all Sandhills Agricultural Laboratory (SAL) data fitted to model Δ TEMP = a + b•(Δ AZIMUTH) for 0 ≤ Δ AZIMUTH ≤ 110.

Location	a	b	r^2
Mead	0.865	−0.012	0.274
SAL†	0.888	−0.011	0.329

† SAL = Sandhills Agricultural Laboratory.

during the 1982 growing season at SAL (Fig. 2B). The relationship was the same for plants grown under full irrigation and nonirrigated conditions.

Although the declining linear relation of Δ TEMPERATURE to Δ AZIMUTH was highly significant for 0° ≤ Δ AZIMUTH ≤ 110°, the variability of the data was quite high (Table 1). For individual days, the r^2 values were considerably higher, ranging from 0.40 to 0.80. Solar elevation angle was found to be highly correlated with Δ TEMPERATURE, but the inclusion of solar elevation angle in the regression model did not significantly improve the r^2 values nor the predictive ability of the model. Perhaps the low r^2 values are due to turbulent mixing of canopy air. Wind speeds during the measurement period were generally between 2 and 5 m s^{-1}. Kimes (1981) found the systematic variation of measured wheat canopy temperature with solar azimuth was only detected under conditions of no wind (wind speed less than 0.1 m s^{-1}).

Some of the variability may be explained by the fact that the data used to construct Fig. 2A and 2B included 11 days at Mead and 18 days at SAL throughout a major portion of the growing season. From the regression coefficients in Table 2, it is seen that at both Mead and SAL the linear response of Δ TEMPERATURE to Δ AZIMUTH becomes weaker as the soybeans age. This occurs in conjunction with the physiological changes that occur as the soybean plant changes from vegetative growth to reproductive growth. As this happens, the heliotropic nature of leaflets in soybean canopies has been shown to change (Kawashima, 1969). Apparently, as the soybean plant shifts its physiological functions to support reproductive growth as opposed to increasing vegetative growth, the leaves become less responsive to solar position. During the vegetative growth stage, the leaflets are apparently oriented to allow for maximum interception of incoming solar radiation, but later in the season as plant photosynthate goes primarily to development of reproductive structures, leaflets tend to maintain orientations which result in less than maximum interception of radiation (Wofford and Allen, 1982). Apparently the cause of the greater slope of the Δ AZIMUTH vs. Δ TEMPERATURE relationship earlier in the season is due to the more effective interception of incoming solar radiation by soybean leaflets.

Table 2. Linear regression coefficients and r^2 values for data fitted to model Δ TEMP = a + b•(Δ AZIMUTH) for 0 ≤ Δ AZIMUTH ≤ 110.

Location	Date	V Stage†	R Stage†	a	b	r^2
Mead	7-31	11	2	1.21	−0.017	0.653
Mead	8-25	17	6	1.08	−0.015	0.354
Mead	9-02	--	6	0.72	−0.009	0.092
SAL‡	7-31	10	2	1.19	−0.014	0.568
SAL	8-17	14	5	0.69	−0.077	0.594
SAL	9-03	--	6	0.58	−0.070	0.380

† Soybean growth stages as defined by Fehr and Caviness (1977).
‡ SAL = Sandhills Agricultural Laboratory.

The influence of view direction on IRT-sensed temperature is seen clearly in Fig. 4. The data are separated according to IRT view direction (e.g. EAST refers to measurements made on the east side of a plot with the observer facing west). The relationship for data taken on the east and west sides of the plots was nearly identical. No dependence of IRT temperature on Δ AZIMUTH was observed for measurements taken from the north. There was a strong linear relation between Δ AZIMUTH and Δ TEMPERATURE for the measurements made from the south caused by a change in the proportion of sunlit leaf area which is viewed throughout the day.

The difference between the EAST (or WEST) line and the SOUTH line is probably due to a combination of solar elevation angle, the IRT viewing elevation and the heliotropic response of soybean leaves. At Δ AZIMUTH = 0° (near sunrise for the EAST line, near sunset for the WEST line, noon for the SOUTH line), the IRT view of the sunlit leaves is dependent on the time of day the measurements are made. At the low

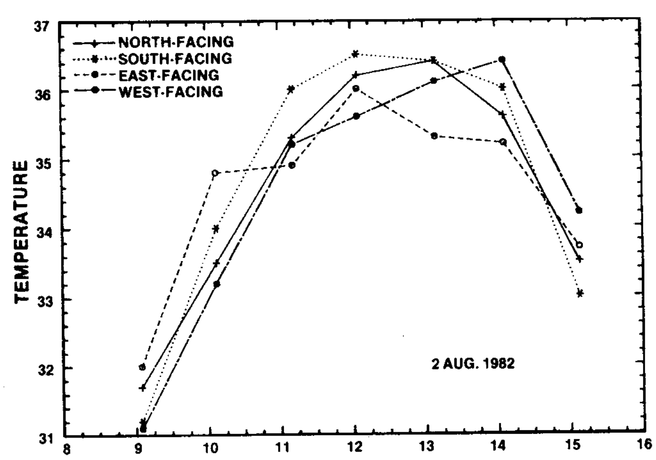

Fig. 3. Diurnal change in canopy temperature as viewed from four directions.

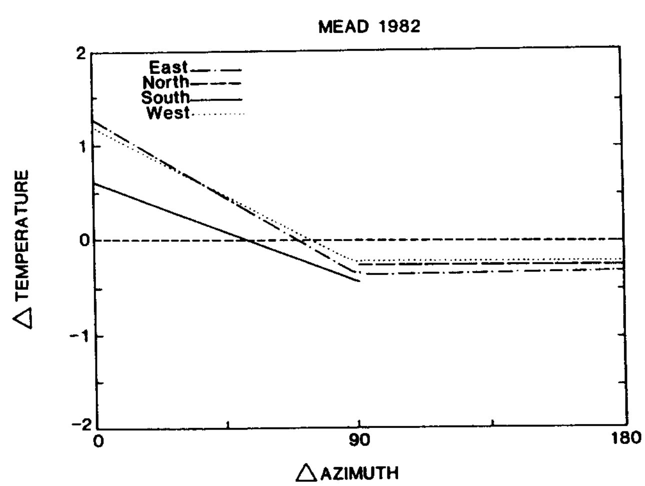

Fig. 4. Deviation of viewed canopy temperature from average canopy temperature due to difference between solar azimuth and infrared thermometer (IRT) view direction; data separated by IRT view direction.

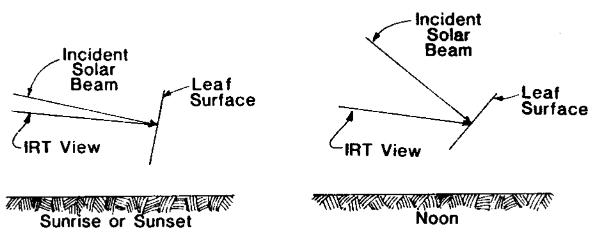

Fig. 5. Change in leaf presentation to infrared thermometer (IRT) with changing solar elevation angle.

sun angles near sunrise and sunset, the leaves are oriented more perpendicular to the IRT view. Under these conditions, more sunlit leaf area is viewed by the IRT than from the south position near solar noon when the solar altitude is high and the leaf surfaces are less perpendicular to the IRT view (Fig. 5). The slope of the EAST and WEST lines is greater than the SOUTH line for $0° \leq \Delta$ AZIMUTH $\leq 90°$. Although differences in solar elevation angle appear to explain the difference in slope between lines plotted in Fig. 4, the inclusion of solar elevation angle in the model to predict Δ TEMPERATURE did not significantly reduce the error sums of squares when Δ AZIMUTH was already included in the model.

The nearly identical response between Δ AZIMUTH and Δ TEMPERATURE measurements from the east and west sides of the plots suggests this relationship is not affected by the temperature of the surface. Canopy temperatures measured at the WEST location would generally be much warmer than those measured at the EAST location for Δ AZIMUTH = 0. The line labeled EAST represents points taken from sunrise to sunset over the range of $0° \leq \Delta$ AZIMUTH $\leq 180°$ (Fig. 4). For the line labeled WEST, Δ AZIMUTH = 0° corresponds to sunset and Δ AZIMUTH = 180° corresponds to sunrise.

Data were taken throughout the growing season under a variety of ambient temperature conditions (daily maximum temperature ranging from 22.5 to 34.4°C). No consistent effect of ambient temperature was seen on the Δ AZIMUTH vs. Δ TEMPERATURE relationship.

CONCLUSION

A range of canopy temperatures may be observed with an IRT at a given point in time depending on the relationship between solar azimuth and IRT view direction. This is a result of actual variations in leaf temperatures and orientations. It is difficult to determine which of these canopy temperatures is the "true" temperature representative of the canopy. An average of temperatures viewed from several directions is probably the best approximation of the true canopy temperature. The results of this study have shown that the canopy temperature of soybeans observed with an IRT from a given azimuthal position may vary considerably from the average as determined from four measurements made from the four cardinal direction points. With knowledge of the difference between the solar azimuth and the IRT view direction, the average canopy temperature can be predicted from the measurement of canopy temperature at only one position. This may be of great advantage when access to plots limits the positions from which measurements can be made, or when available time does not allow four measurements per plot to be taken.

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