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Crop Water-Stress Assessment Using an Airborne Thermal Scanner*

Crop canopy temperatures obtained from an airborne thermal scanner correlated well with plant water stress measurements. These results show promise for irrigation scheduling and crop yield predictions.

Abstract: *An airborne thermal scanner was used to measure the temperature of a wheat crop canopy in Phoenix, Arizona. The results indicate that canopy temperatures acquired about an hour and a half past solar noon were well correlated with presunrise plant water tension, a parameter directly related to plant growth and development. Pseudo-colored thermal images reading directly in stress degree days, a unit indicative of crop irrigation needs and yield potential, were produced. The aircraft data showed significant within-field canopy temperature variability, indicating the superiority of the synoptic view provided by aircraft over localized ground measurements. The standard deviation between airborne and ground-acquired canopy temperatures was 2°C or less.*

Introduction

Many regions of the United States and, indeed, the world depend upon irrigation for producing crops. Water supplies long thought to be abundant are proving to be inadequate. In some Arizona agricultural areas, for instance, the water table is dropping at a rate of nearly eight feet per year. As energy costs increase, the price for pumping water increases proportionally. In California, which has faced drought the last two years, the problem of water supply has become particularly acute. Water must be proportioned fairly to all domestic, industrial, and farm users; but, since agriculture is the prime user of water, strict allocation of irrigation water will have a greater conservation impact on total usage than would similar control of either of the other two user groups.

A valuable aid to solving these problems would be a means of more rationally assessing when crops need water, so that they need not be irrigated arbitrarily. Secondly, a

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means of assessing the yield of crops before harvest would be valuable for planning purposes. If such techniques could be applied from aircraft or spacecraft, then large areas could be assessed in a timely manner.

NASA/Ames Research Center and the USDA's Agricultural Research Service are currently conducting a program of research aimed at developing Remote Sensing Techniques for the scheduling of irrigations and the prediction of crop yields. Intensive groundwork by the USDA group has provided a good foundation for the program[1,2]. The objectives of the work were to demonstrate that measurements made with ground-based instrumentation could be accurately repeated from an aircraft, and to determine if the USDA teams's basic concepts were suited to application within such an airborne context.

Ground studies[3] have shown the relation of plant canopy temperatures to plant water tension, a parameter directly related to plant water needs. Remote measurements of canopy temperatures thus have potential for indicating the water status of plants.

Two techniques exist for remotely monitoring irrigation needs and potential crop yields. The first employs the difference between crop canopy and ambient air temperatures at the time of maximum solar heating (1 to 1.5 hours after local solar noon). When a crop has sufficient moisture, it will transpire freely and its temperature will be lower than that of the ambient air; when moisture is insufficient its temperature will be higher than that of the ambient air, due to a reduced transpiration rate. The daily sum of this temperature difference, termed "stress degree day," is the tool used to determine crop irrigation needs and yield potentials.

The second and more purely remote technique does not rely on ambient air temperatures being acquired at the exact crop locations. Instead it utilizes the difference between the previously mentioned crop maximum temperature and minimum temperature (just before sunup), which is then normalized by ambient air temperatures acquired regionally within a few kilometers of the field site. These values are summed daily, thereby producing a value for the "stress degree day." Both forms of "stress degree day" were found to be equally valid in a recent study in Arizona[1,2]. Other investigators have used canopy temperature as an indicator of plant water stress[4-11].

The major results of Idso *et al.*[1] can be summarized with the aid of Figure 1. The

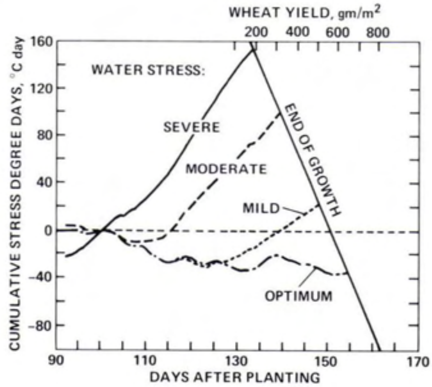

FIG. 1. Stress degree day vs. days after wheat planting vs. yield. Adapted from Idso *et al.*[1]

cumulative values of "stress degree day," SDD, are plotted versus days after planting. Data are presented for four wheat fields irrigated in various amounts. The wheat suffering most from lack of water exhibits high values of SDD, whereas fields with adequate irrigation exhibit negative values. The sloping line in this figure corresponds to the end of kernel filling, or just prior to ripening. Actual yield for any field is found by projecting the point of intersection of its SDD curve and the solid sloping line to the upper abscissa. Thus, it is seen that the wheat having the lowest cumulative SDD value also produced the greatest yield.

In view of these promising results, USDA and NASA are cooperating to determine the feasibility of using remote sensing techniques to monitor crop stress. The subject crops, primarily wheat, were grown by USDA in Phoenix, Arizona. Ground measurements were made by USDA and airborne infrared imagery was acquired and processed by NASA; data were analyzed jointly. Airborne measurements of plant canopy temperatures were correlated with similar ground measurements and with plant water tension. Pseudo-colored thermal images reading directly in SDD increments were produced. This study opens the door to actual application of the subject techniques in future demonstration studies designed to schedule irrigations and predict crop yields.

1976 Aircraft Program

Airborne and ground measurements were made at an agricultural test site in Phoenix, Arizona on April 1 and 29, 1976.

OBJECTIVES

The objective of the aircraft program was to ascertain if infrared techniques developed on the ground for monitoring the water status of crops could be applied from aircraft. Since the ground program had established, or was establishing, the relations between stress degree day and crop irrigation scheduling and yield, the aircraft program was aimed at (1) the airborne measurement of plant canopy temperatures, especially for wheat, (2) the correlation of airborne with ground-based measurements, (3) the correlation of airborne plant canopy temperatures with plant water stress, and (4) the identification of problem areas associated with airborne measurements of canopy temperature that do not exist for ground measurements.

APPROACH

The measurement program was conducted on field's, Plate 1, of the U.S. Water Conservation Laboratory and the University of Arizona' Cotton Research Center at Phoenix, Arizona. This area is of a homogenous soil type, Avondale loam. The prime measurement area was a centrally located 72 × 90-m section planted in durum wheat. After planting, this section was subdivided into six 72 × 15-m plots, which were irrigated with different amounts of water over the growing season. The irrigation schedule, given in Table 1, was selected to represent amounts above, below, and in agreement with local recommended practices. Plot 1 was highly stressed, whereas plot 6 was considerably overwatered. Plot 2 received what was considered an optimal amount of water, while the remaining plots, 3, 4, and 5, respectively, received progressively more irrigation. Plots 1 and 3 were subdivided late in the season after experiencing severe water stress, at which time their southern portions received additional water. Surrounding areas were planted in alfalfa and wheat; a portion of the site was bare soil.

TABLE 1. WHEAT IRRIGATION SCHEDULE

Wheat Plot	Days After Planting						
1 N	5						
1 S	5				125		
2	5	83		110	125		146
3 N	5	83					
3 S	5	83			125		146
4	5	83		110			
5	5	83		110	125		
6	5	83	99	110	125	132	146

AIRCRAFT AND GROUND MEASUREMENT:

Ground-based measurements of plant canopy temperatures were made using Barnes† PRT-5 Radiation Thermometers. Seven measurements were made at each of two locations in each of the six small wheat fields using radiometers operating in the 8 to 14 micrometer bandpass region. A 20° field-of-view (FOV) radiometer was used to make a straight-down measurement. Measurements were then made with the radiometer aimed at a 45° angle and readings were taken in each of the cardinal compass directions. Next, measurements were made to the north and to the south, near grazing incidence, using a 2° FOV radiometer.

Measurements in the surrounding fields were made with a 20° FOV, 10.5 to 12.5 micron bandpass radiometer. These were made only in the north and south directions with the exception of the alfalfa field just west of the six small wheat plots, where a downward measurement was included.

Plant water tensions were measured with the Scholander Pressure Bomb technique.

Airborne measurements were made with a Texas Instruments model RS-25 infrared line scanner, operating in the 8 to 14 micrometer bandpass region. The RS-25 contains two black body calibration sources with platinum-resistance temperature readout. These sources can be heated so as to provide calibration temperatures both above and below those of the scene being viewed. Owing to the predawn surface temperature at flight altitude, this span was not achieved during the morning flights; therefore, all predawn airborne data were adjusted to ground-measured temperatures of a 1.3-m-diameter tank of water and to the temperature of wheat plot 2 south, the optimally irrigated wheat. For consistency, the afternoon aircraft data also were adjusted to the ground-measured temperature of Plot 2 south. The black body temperature span was not altered, and this adjustment in temperature level was less than 2°C, thus probably accounting for atmospheric effects and possible ground instrument drift. The scanner data were recorded on a Sangamo Saber III 14-channel tape recorder. In addition to the scanner, color infrared photography was acquired with a 70-mm Hasselblad camera.

DATA REDUCTION

The airborne scanner data were recorded

† Trade names and company names are included for the benefit of the reader and imply no endorsement or preferential treatment of the product listed by NASA or USDA.

in analog form, converted to digital form, and processed by using digital image techniques. This processing yielded computer listings of temperature and temperature differences between predawn and afternoon data, pseudo-colored maps of these temperatures and temperature differences, and pseudo-colored maps of daily incremental stress degree day.

The most difficult portion of the data reduction was the registration of the predawn and afternoon data. To provide for registration of the data, 28 4-foot-square sections of plywood, painted with low-emitting aluminum spray paint, were randomly placed about the test site. These panels served as control points to which the scanner data were "rubber-sheeted."

In order to process the RS-25 scanner data, it was necessary to convert the analog data to a computer-compatible digital format. This was done by inputting the analog signal into an A/D converter by using "sample and hold" techniques, which integrate the analog signal for a predetermined period of time. This integrated signal is then measured and a value assigned to represent its relative amplitude. The "sampling" period represents one picture element (or pixel), and the pixel amplitude is converted to a digital value ranging from 0 to 255 (8 bits). The thermal infrared data was processed on an HP-3000 computer system configured with a COMTAL video display, two 1600 BPI tape drives, and a pair of 50 megabyte disk memories. The software program, called IDIMS, acted upon the digital image. Since the RS-25 scanner collects data in a scan-line-to-scan-line sequence, each line represents a row in the digital image. Similarly, the selected sample interval for digitizing determines the number of pixels in each scan line. Since each scan line contains the same number of picture elements, the pixels make up the columns in the image array. Eight separate processing steps were used to generate the final output images reported here.

(1) Scene Selection. All recorded digital image data were reviewed on the COMTAL display. Thermal calibration, high-frequency image jitter, bad or missing scan lines, image noise, and general image appearance were used as selection factors.

(2) Scene Reduction. The portion of the scene outside the area of interest was edited out. This conserved processing time.

(3) Sweep Distortion Correction. Geometrical distortions caused by the constant angular velocity of the scanner mirror were corrected.

(4) Transfer of black body digital values to the reduced scene. This step was required since the position of the calibration signals on the original total scene caused them to be edited out in Step 2, above.

(5) Geometric Registration (image-to-image). In order to process data between corresponding points on the ground in two different scenes (morning and afternoon), a transformation had to be developed to map pixels in one image to the corresponding pixels in the other image. The aluminum-painted panels were used to do this.

(6) Geometric Registration (photo-to-image). A transformation was next employed to map a base (airborne) photograph to the registered pair of images. Thus, the pixels, approximating the ground truth points on the photograph, were identified.

(7) Thermal Calibration. The basic digitized image was created with 256 (8-bit) grey levels. These levels were proportional to the energy received by the RS-25 scanner from each point on the ground. The thermal black body references were also imaged within 256 grey levels, but their temperatures were known. Thus, all image grey levels could be transformed into apparent temperatures by using the black bodies as function generators. The output image, then, has real-valued pixels which represent the apparent temperatures on the ground as seen by the RS-25 scanner.

(8) Presentation of Processed Image. Final results were presented in the following forms:

- Pseudo-colored video display, where each color represents a discrete temperature interval.
- Total scene display or selected areas expanded to fill video screen size.
- Line printer output of apparent temperature values or temperature differences.
- Single pixel values selected by the operator.

Results

April 1, 1976

On April 1, 1976 the wheat crop had been growing for 120 days and had first headed about 20 days earlier. Plot 1 was suffering from severe lack of water, and appeared very sparse. Plot 3 also appeared sparse, but the remaining plots were of uniform full canopy. The large wheat and alfalfa fields to the south were very healthy. The alfalfa adjoining the small wheat plots, however, was very sparse and irregular because of significant water stress.

Aircraft measurements were made at 5:53 a.m. and 2:06 p.m., local time. Pseudo-colored temperature images resulting from these data are shown in Plates 1 through 4. Accompanying each plate is a legend designating the temperature spread represented by each color in the plate. Plate 1 shows results of the morning flight. At the time of the over-flights, the air temperature 150 cm above the ground was 7.2°C at plot 2. From this plate it can be observed that wheat plots 1 and 3 were at ambient air temperature. Temperatures of the other small wheat fields were about 3° to 4° lower than ambient, which indicates a healthy water status.

The morning scanner measurements of the large wheat field to the south were about a degree less than those of plots 2 and 4 through 6, in nearly exact agreement with ground measurements. The temperature of the large alfalfa field adjacent to the small wheat plots was nearly the same as that of the bare dry soil, but the lush alfalfa to the south of the bare soil had the lowest temperature of all fields, about 7°C below the measured air temperature.

The afternoon-acquired scanner data are shown in Plate 2. During the time of measurement, the air temperature 150 cm above plot 2 was 28.3°C. Plate 2 shows that (1) the extremely water-stressed plot 1 was as much as 8°C warmer than ambient, (2) the less water-stressed plot 3 was running as much as 6°C warmer than ambient, (3) the better irrigated plots 2 and 4 through 6 were below ambient by as much as 6°C, (4) the lush alfalfa field and the wheat field to the south were identical in temperature, and (5) the bare soil was the hottest of all fields, reaching 14°C above the measured air temperature.

The difference image, derived by subtracting the morning data from the afternoon data, is shown in Plate 3. The most noticeable features in this image are the very large diurnal temperature variation of the bare soil, and the very small variations of the well-irrigated fields of wheat and alfalfa. The severely water-stressed wheat showed diurnal temperature variations of about 10°C greater than the well-irrigated wheat. Table 2 lists values of daily incremental stress degree days corresponding to the various colors of the plant canopies in Plate 3. These were computed by the methods of Idso *et al.*[1, 12] where

$$\text{SDD} = \frac{(\text{p.m.} - \text{a.m.})\ \text{crop temperature}}{(\text{p.m.} - \text{a.m.})\ \text{air temperature}} \times 18 - 18.$$

Based on these values, wheat plots 1 and 3 have positive values of SDD, and are therefore considered to be under water stress, as would be concluded from the irrigation schedule of Table 1.

As stated in the introduction, an alternate technique for measuring SDD is to measure the difference between canopy and air temperature at the time of maximum solar heating. Pseudo-colored imagery maps of these values were produced. A very practical form of presenting this imagery is illustrated in

PLATE 1. Pseudo-colored thermal imagery of the Phoenix test site acquired at 5:53 a.m., April 1, 1976. The six differentially-irrigated wheat plots appear in the center and are identified as 1 through 6 going from bottom to top, which is west to east. Bare soil adjoins these plots to the east and alfalfa to the west. South of the bare soil is another field of alfalfa; and west of it is another field of wheat.

	°C		°C
Red	6–7	Green	2–3
Orange	5–6	Lt. Blue	1–2
Violet	4–5	Md. Blue	0–1
Yellow	3–4	Dk. Blue	(−1)–0

PLATE 2. Pseudo-colored thermal imagery of the Phoenix test site acquired at 2:06 p.m., April 1, 1976.

	°C		°C
Red	40–42		
Orange	38–40	Aqua	28–30
Violet	36–38	Dk. Green	26–28
Grey	34–36	Md. Blue	24–26
Yellow	32–34	Dk. Blue	22–24
Lt. Green	30–32	White	20–22

PLATE 3. Pseudo-colored imagery of the difference between p.m. and a.m. surface temperature measurements, April 1, 1976, Phoenix.

	°C		°C
White	41–43	Dk. Green	26–28
Red	38–40	Lt. Blue	23–25
Orange	35–37	Dk. Blue	20–22
Yellow	32–34	Violet	17–19
Lt. Green	29–31	Black	14–16

PLATE 4. Pseudo-colored imagery of positive values of daily incremental stress degree days (afternoon crop minus air temperatures), April 1, 1976, Phoenix.

	°C		°C
Red	8		
Orange	7	Lt. Blue	3
Yellow	6	Dk. Blue	2
Lt. Green	5	Violet	1
Dk. Green	4	Black	0

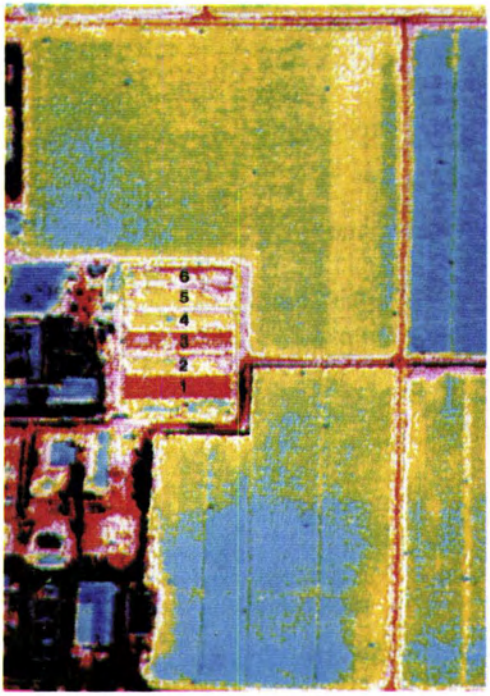

PLATE 1.

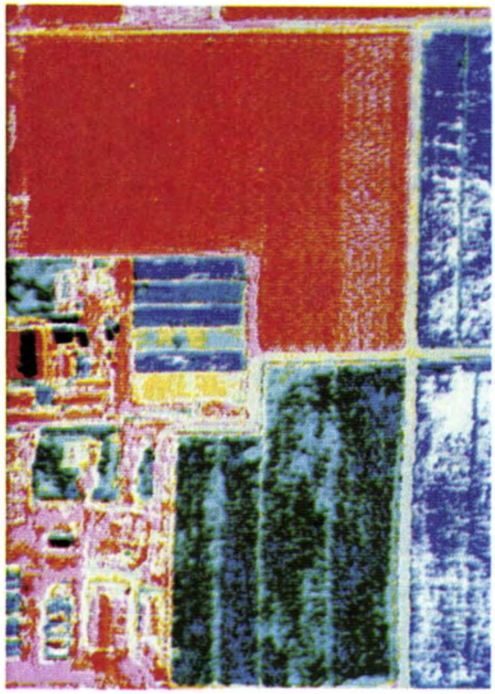

PLATE 2.

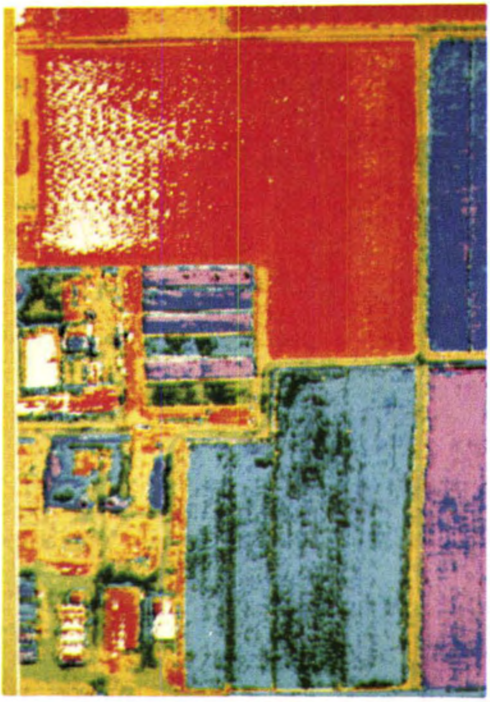

PLATE 3.

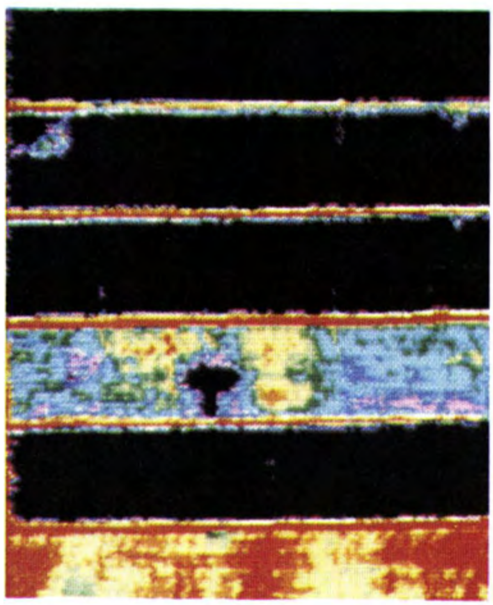

PLATE 4.

(See captions on page 81)

Plate 4. Here, only positive values indicative of water stress are displayed for the six small wheat plots. It is readily apparent that plots 1 and 3 are under water stress.

For the correlation studies of airborne-acquired vs. ground-acquired canopy temperatures, the airborne data utilized were computed as the average of the four pixels nearest the estimated points of ground measurement. The results are shown in Table 3. The first correlation run was for the six central wheat fields. Since the airborne-acquired data had actually been "calibrated" by equating airborne- and ground-acquired data over plot 2S and a small water tank, good absolute value agreement in the mean was expected, and indeed, this is what we found, with a correlation coefficient of 0.99. The unknown quantity to be investigated was the amount of scatter in the data, due to unevenness of canopy fullness among the several plots. In this instance, the standard deviation was only 0.7°C.

The next correlation included these same data in a larger group additionally containing results for all of the other wheat, alfalfa, and bare soil fields. Again, a high correlation coefficient of 0.98 was obtained, with a standard deviation of 1.3°C.

The final two correlations to be run dealt with the stress degree day concept as applied to the six wheat plots. The first correlation utilized airborne-acquired data and compared the two different formulations of the concept, i.e., afternoon canopy-air temperature difference vs. normalized afternoon-early morning canopy temperature difference. The second correlation utilized early morning air temperatures in place of crop canopy temperature. The 0.99 correlation coefficient and 0.6°C standard deviation indicated that for the small wheat plots, early morning canopy temperature measurements were perhaps not necessary.

TABLE 2. STRESS DEGREE DAY VALUES FOR PSEUDO-COLORED IMAGE OF PLATE 3.

Color	(P.M.—A.M.) Normalized Stress Degree Day
Lt. Green	6.9 – 8.7
Dk. Green	4.4 – 6.1
Lt. Blue	1.8 – 3.5
Dk. Blue	(−0.8) – 0.9
Violet	(−3.4) – (−1.7)
Black	(−6.0) – (−4.2)

APRIL 29, 1976

The same four correlation studies were performed for this day's data as for those of April 1. Corresponding results, shown in Table 3, in terms of correlation coefficients and standard deviations in the same order of presentation were 0.95, 1.6°C; 0.97, 2.0°C, 0.96, 1.3°C and 0.96, 1.3°C, respectively.

Afternoon canopy temperatures were observed to be much more diverse than were morning temperatures, for both 1 April and 29 April. Thus, the afternoon crop canopy-air temperature differential was used for assessing plant water stress, with air temperature being measured at screen height above the field. As the primary measurement of the plant water stress, however, presunrise plant water tension measurements were used, since very great fluctuations from plant to plant (and possibly over short time intervals) are regularly observed in the afternoon.

Figure 2 thus presents a comparison of these two data sets. Only nine data points are plotted for 29 April, since the wheat on the north and south halves of the driest plot had about reached maturity, and plant water tension measurements were no longer being made on that date. The south half of one of the other plots was additionally deleted on this day. It, too, was close to maturity, having

TABLE 3. CORRELATION STUDY RESULTS

Factors Correlated	Correlation Coef.		Std. Deviation, °C	
	4/1/76	4/29/76	4/1/76	4/29/76
Airborne vs. Ground Canopy Temps for 6 Wheat Fields	0.99	0.95	0.7	1.6
Airborne vs. Ground Canopy Temps for All Fields	0.98	0.97	1.3	2.0
Two Airborne Techniques for Determining SDD	0.99	0.96	0.6	1.3
Airborne p.m.—a.m. Canopy Temp Difference vs. p.m. Canopy Temp—a.m. Air Temp	0.99	0.96	0.6	1.3

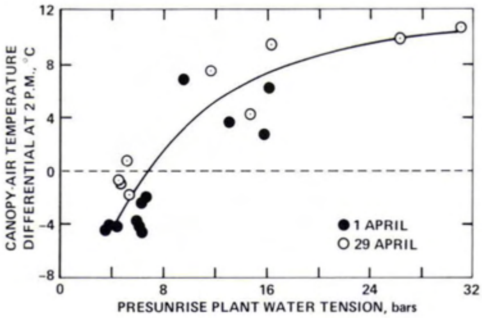

FIG. 2. The 2 p.m. aircraft-acquired canopy temperature minus concurrent air temperature at screen height above the six wheat plots as a function of presunrise plant water tension measured with the Scholander pressure bomb technique.

been stressed severely, and a recent irrigation had not been given in time for the plants to adapt themselves properly to the new conditions.

CONCLUSIONS

The results of this program demonstrate the potential for monitoring crop irrigation needs and yield potential by airborne infrared techniques. Crop canopy temperature measurements can indeed be used to detect plant water stress in wheat, and appear well adapted for use with the stress degree day concept developed by Idso, Jackson, and Reginato[1]. For wheat, this technique now can be extended from the ground to aircraft. Having established this fact, intensive field studies that utilize aircraft actually to schedule irrigations now seem warranted for those crops whose temperature-yield relationships are well established.

The major emphasis in this study was upon wheat. Because all measurements were made after wheat heading, the canopies were mostly full and little confusion existed between canopy and soil background temperatures. Further research is necessary to correlate airborne acquired canopy temperatures with actual plant temperatures during sparse canopy conditions.

Temperature differences of up to 5°C can occur within a single small wheat plot of dimension 72 × 15 m, even under the best of experimental conditions. Knowledge of this fact is extremely important, for it indicates that spot ground measurements of canopy temperature may not be indicative of field conditions. Thus, beyond the inherent advantage of covering large geographical areas, the airborne technique allows an integrated synoptic view to be obtained of the most representative field data.

Finally, application of these techniques would be most practical if remote measurements were required only once a day. The results indicate that both techniques could be used with a single remote canopy temperature measurement if simple air temperature transmitters were located in individual fields. It is believed that the afternoon crop minus air temperature technique would provide the most accurate data. Future efforts will be directed toward determining the time-frequency of coverage required to monitor accurately irrigation needs and potential yields.

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