

AIRBORNE MONITORING OF CROP CANOPY TEMPERATURES FOR
IRRIGATION SCHEDULING AND YIELD PREDICTION^{1/}

John P. Millard
NASA/Ames Research Center
Moffett Field, California 94035

Ray D. Jackson
USDA, Agricultural Research Service
Phoenix, Arizona 85040

Robert C. Goettelman
LFE Corporation
Richmond, California 94804

Robert J. Reginato
USDA, Agricultural Research Service
Phoenix, Arizona 85040

Sherwood B. Idso
USDA, Agricultural Research Service
Phoenix, Arizona 85040

Richard L. LaPado
ESL Incorporated
Sunnyvale, California 94086

Abstract

An aircraft program is being conducted by NASA's Ames Research Center and the USDA's Agricultural Research Service to develop techniques for remotely measuring crop irrigation needs and predicting crop yields. Airborne and ground measurements were made on April 1 and 29, 1976, over a USDA test site consisting mostly of wheat in various stages of water stress, but also including alfalfa and bare soil. These measurements were made to evaluate the feasibility of measuring crop temperatures from aircraft so that a parameter termed "stress degree day", SDD, could be computed. Ground studies have shown that SDD is a valuable indicator of a crop's water needs, and that it can be related to irrigation scheduling and yield. The aircraft measurement program required predawn and afternoon flights coincident with minimum and maximum crop temperatures. Airborne measurements were made with an infrared line scanner and with color IR photography. The scanner data were registered, subtracted, and color-coded to yield pseudo-colored temperature-difference images. Pseudo-colored images reading directly in daily SDD increments were also produced. These maps enable a user to assess plant water status and thus determine irrigation needs and crop yield potentials.

Introduction

Many regions worldwide depend on irrigation for producing crops. Growing populations with expanding agricultural programs will further increase the demand for irrigation water. In fact, the effects of these expanded programs are already being felt in the farm community. In some Arizona agricultural areas, for instance, the water table is dropping nearly 8 feet per year. The cost of pumping water increases as energy costs rise. When faced with drought, such as California has had in the last two years, the problem of water supply becomes 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. Obviously, insufficient irrigation will decrease farm production.

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 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, large areas could be assessed in a timely manner.

We have two potential techniques for attaining these goals. They are based upon using the crops' canopy temperature as a direct indication of water stress. The first technique uses 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. Indeed, 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 from the nearest National Weather Service location. The 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, 10). Other investigators have used canopy temperature as an indicator of plant water stress (2, 3, 4, 5, 6, 7, 8, 9).

The major results of Idso, et al (1) can be summarized with the aid of Fig. 1. The cumulative values of stress degree day, SDD, are plotted versus days after planting. Data are presented for four wheat fields irrigated differentially. The sloping line in this figure corresponds to the end of wheat head growth. 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 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. The major objective of this study was to determine if temperature measurements made with ground-based instrumentation could be accurately repeated from an aircraft, and to see if the SDD concept was suited to airborne application. The several problems involved in such a program, along with proposed solutions, are also described.

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 detection of wheat under various degrees of water stress by utilizing airborne measurements, 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 fields of the U.S. Water Conservation Laboratory and the University of Arizona's 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-x 90-m section planted in durum wheat. After planting, this section was subdivided into six 72-x 15-m plots, which were irrigated with different amounts of water over the growing season. The irrigation schedule is given in Table 1. 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 south portions received additional water. Surrounding areas were planted with alfalfa and wheat; a portion of the site was bare soil.

AIRCRAFT AND GROUND MEASUREMENT:

Ground-based measurements of plant canopy temperatures were made using Barnes^{2/} 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 using 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.

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 were also 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 in analog form, converted to digital form, and processed 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, twenty-eight 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".

To computer 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 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 COMTOL 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). 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 pixel 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 Figs. 2 through 5. Accompanying each figure is a legend designating the temperature spread represented by each color in the figure. Figure 2 shows results of the morning flight. At the time of the overflights, air temperature 150 cm above the ground was 7.2° C at plot 2. From this figure 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° C 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. 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 Fig. 3. During the time of measurement, air temperature 150 cm above plot 2 was 28.2° C. Figure 3 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 Fig. 4. 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 about 10° C greater than the well-irrigated wheat. Table II lists values of daily incremental stress degree days corresponding to the various colors of the plant canopies in Fig. 4. These were computed by the methods of Idso et al (1, 11), where

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

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 I.

As stated in the introduction, an alternate technique for measuring SDD, is to measure the difference between canopy and air temperatures 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 Fig. 5. 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-obtained 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 III. 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 central wheat plots. The first 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 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.

April 29, 1976

As of April 29, 1976, the wheat crop had been growing for 148 days. Figure 6, a color infrared photograph of the fields, shows that the status of the crops varied widely. Plot 1 was under severe water stress. Table I shows that it was irrigated 5 days after planting in December, and that the south portion was irrigated once more 125 days after planting. The bare soil field of April 1 had been recently tilled and planted to cotton which had not yet emerged.

The thermal imagery acquired on the afternoon flight is shown in Fig. 7. Air temperature 150 cm above the ground was measured to be 30.4° C. From this figure it can be deduced that, as compared with measured air temperature: (1) the bare soil temperature was about 20° C higher, (2) temperatures of the lush wheat and alfalfa fields to the south were about 4° C lower, and (3) temperatures of wheat plots 2 and 6 were lower, but those of all others were higher. Another significant feature of these data is that they show a large difference in temperature between the north and south segments of plot 1. This difference was a result of an irrigation to the south segment of April 13. This feature is not detectable on the color IR photography of Fig. 6.

A map of positive values of daily incremental stress degree days analogous to Fig. 5 is presented in Fig. 8 for April 29, 1976. All plots except plots 2 and 6 were under water stress. The magnitude of stress can be determined from the legend.

The same four correlation studies were performed for this day's data as for those of April 1. Corresponding results, Table III, 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.

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 acquired by aircraft appear well adapted to use with the stress degree day concept developed by Idso, Jackson and Reginato (1). For wheat, this technique can now be extended from the ground to aircraft.

The major emphasis in this study was upon wheat. Because all measurements were made after wheat heading, the canopies were full and no confusion existed between canopy and soil back-ground temperatures. Further research is necessary to correlate percent plant cover with airborne-acquired canopy temperatures in the early stages of growth.

The superiority of thermal IR data over color IR photography was clearly established. Water stress undetected in color IR photography was clearly detected in thermal imagery. A value of color IR photography, however, is to establish those fields supporting vegetation. Thus, both techniques used together enhance the strong points of each.

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 accurately monitor irrigation needs and potential yields.

Acknowledgment

The authors gratefully acknowledge the superb efforts of Ms. Mary Leroy in computer processing most of the data described herein.

References

1. Idso, S.B., R.D. Jackson, and R.J. Reginato, "Remote Sensing of Crop Yields", *Science* 196:19-25, 1977.
2. Blad, B.L., and N.J. Rosenberg, "Measurement of Crop Temperature by Leaf Thermocouple, Infrared Thermometry, and Remotely Sensed Thermal Imagery", *Agron. J.*, 68, 635-641, 1976.
3. Ehrler, E.L., "Cotton Leaf Temperatures as Related to Soil Water Depletion and Meteorological Factors", *Agron. J.*, 65, 404-409, 1973.
4. Ehrler, W.L., and C.H.M. van Bavel, "Sorghum Foliar Responses to Changes in Soil Water Content", *Agron. J.*, 59, 243-246, 1967.
5. Idso, S.B., and W.L. Ehrler, "Estimating Soil Moisture in the Root Zone of Crops: A Technique Adaptable to Remote Sensing", *Geophys. Res. Letters*, 3, 23-25, 1976.
6. Nixon, P.R., L.N. Namken, and C.L. Wiegand, "Spatial and Temporal Variation of Crop Canopy Temperature and Implications for Irrigation Scheduling, 2nd Ann. Remote Sensing Earth Resources Conf. Tullahoma, TN, II 634-657, 1973.
7. Okuyama, T., "Measurements of Active Surface Temperature of Rice Plant Grown in a Small Model of the Paddy Field Using an Infrared Thermometer", *Nogyo Kisho (J. Agric. Meteorol.)*, 30, 191-194, 1975 (In Japanese).
8. Wiegand, C.L., and L.N. Namken, "Influence of Plant Moisture Stress, Solar Radiation, and Air Temperature on Cotton Leaf Temperature", *Agron. J.*, 58, 582-586, 1966.
9. Bartholic, J.F., L.N. Namken, and C.L. Wiegand, "Aerial Thermal Scanner to Determine Temperatures of Soils and of Crop Canopies Differing in Water Stress", *Agron. J.*, 64, 603-608, 1972.
10. Jackson, R.D., R.J. Reginato, and S.B. Idso, "Wheat Canopy Temperature: A Practical Tool for Evaluating Water Requirements", *Water Resources, Research*, 1977.
11. Idso, S.B., R.D. Jackson, and R.J. Reginato, "Compensating for Environmental Variability in the Thermal Inertia Approach to Remote Sensing of Soil Moisture", *J. Appl. Met.*, 811-187, 1976.

TABLE I. WHEAT IRRIGATION SCHEDULE

<u>Wheat Plot</u>	<u>Days After Planting</u>						
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

TABLE II. STRESS DEGREE DAY VALUES FOR PSEUDO-COLORED IMAGE OF FIG. 4

<u>Color</u>	<u>(P.M. - A.M.) Normalized Stress Degree Day</u>
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)

TABLE III. CORRELATION STUDY RESULTS

Factors Correlated	Correlation Coef.		Std. Deviation, °C	
	Apr 1, 1976	Apr 29, 1976	Apr 1, 1976	Apr 29, 1976
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

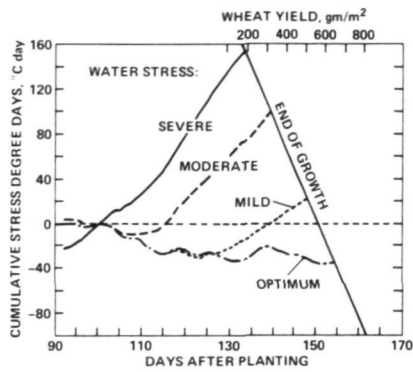


Figure 1. Stress Degree Day vs Days after wheat planting and vs yield. Adapted from (1).

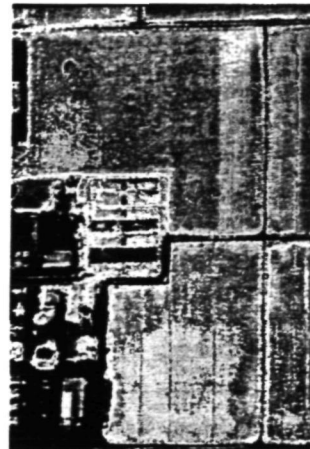


Figure 2. Pseudo-colored thermal imagery of the Phoenix test site acquired at 5:53 A.M., April 1, 1976. The six differentially-irrigated wheat plots appear in the center and are identified as 1 through 6 going from bottom to top, which is west to east. Bare soil adjoins these plots to the east and alfalfa to the west. South of the bare soil is another field of alfalfa; and west of it is another field of wheat.

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

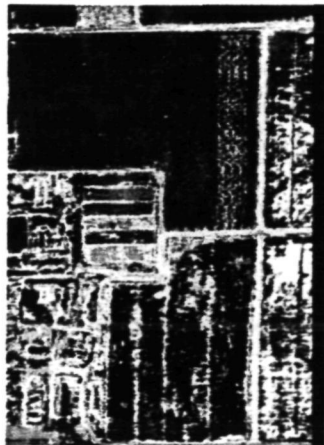


Figure 3. Pseudo-colored thermal imagery of the Phoenix test site acquired at 2:06 P.M., April 1, 1976.

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



Figure 4. Pseudo-colored imagery of the difference between P.M. and A.M. surface temperature measurements, April 1, 1976, Phoenix.

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

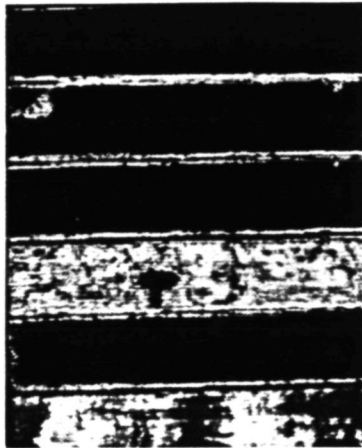


Figure 5. Pseudo-colored imagery of positive values of daily incremental stress degree days (afternoon crop minus air temperatures), April 1, 1976, Phoenix.

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

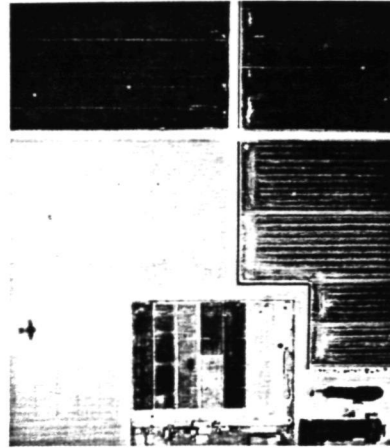


Figure 6. Color IR photograph of the Phoenix test site, April 29, 1976.

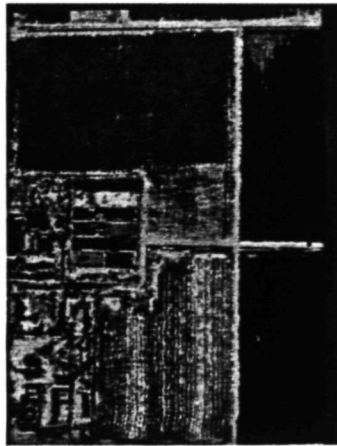


Figure 7. Pseudo-colored thermal imagery of the Phoenix test site acquired at 1:54 P.M., April 29, 1976.

	°C
Orange	50-53
Yellow	46-49
Lt. Green	42-45
Dk. Green	38-41
Lt. Blue	34-37
Dk. Blue	30-33
Black	26-29



Figure 8. Pseudo-colored imagery of positive values of daily incremental stress degree days (afternoon crop minus air temperatures), April 29, 1976, Phoenix.

	°C
Red	13-14
Orange	11-12
Yellow	9-10
Lt. Green	7-8
Lt. Blue	5-6
Dk. Blue	3-4
Violet	1-2
Black	0