BIOGRAPHICAL SKETCH -- Craig L. Wiegand

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Dr. Wiegand first joined the U.S. Department of Agriculture in 1955 as a Soil Scientist working with Dr. E. R. Lemon at Texas A&M University. He worked with the late Dr. Sterling Taylor at Utah State University from 1956 to 1959. Dr. Wiegand rejoined the U.S. Department of Agriculture in 1959 as Research Soil Scientist at Weslaco, where he has served continuously since that time. In July 1966, he became Scientist in Charge of the Division's program at Weslaco, and in January 1969, Dr. Wiegand was named Director of the Rio Grande Soil and Water Research Center. This assignment involves both the direction of the Research Center and the conduct of creative research -- one area being the adaptation and use of remote sensing techniques in agricultural research.

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AGRICULTURAL APPLICATIONS AND REQUIREMENTS FOR THERMAL INFRARED SCANNERS

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INTRODUCTION

The short wavelength energy of the sun strikes the earth where plants, soil, water, and other objects at the earth surface absorb, transmit or reflect it. The part of the sun's energy absorbed by the earth either heats the surface or evaporates water. In a desert practically all the absorbed energy heats the earth so there is a wide temperature difference between night and day. In humid climates most of the sun's energy evaporates water; consequently high daytime temperatures are not experienced. You can see that how the sun's energy is used at the earth surface is very important to mankind -- and to Agriculture.

The earth also gives off the heat it has absorbed by the process known as thermal emission. This energy given off is not absorbed by the atmosphere, but it is absorbed by clouds. Therefore, the temperature of the earth can be observed from spacecraft when clouds don't interfere. The temperatures observed tell us a great deal about earth conditions important to Agriculture.

In the short time I have today, I will list some of the applications of thermal scanner data in Agriculture; illustrate some factors affecting the temperature of plants, soil, and water; and, present a few examples of thermal imagery.

APPLICATIONS

Agricultural applications of thermal scanners include:

- Detecting plant water stress due to --
  - Need for irrigation
  - Soil salinity
  - Shallow and droughty soil
  - Nematodes . . .
- Indicating occurrence of rainfall
- Measuring soil temperature for indicating when soil is warm enough to plant crops
- Studying occurrence and pattern of freezes
- Monitoring thermal pollution
- Detecting springs and subsurface flow into lakes, rivers, and oceans
- Estimating evapotranspiration of farmland, forest, and rangelands
- Estimating water evaporation from lakes, ponds, and reservoirs

Most of the listed applications are obvious. A few may not be. For example, a question the farmer faces each spring is: "When is the ground warm enough to plant?" A seeding advisory based on earth surface temperature measured from space at night seems feasible. One needs to be able to locate the area he is interested in (ground resolution must be adequate) and the measuring instrument must be working properly (be calibrated).

FACTORS AFFECTING EQUILIBRIUM TEMPERATURE

Thermal Properties

The observed relation between incoming solar energy (insolation) and the temperature of cotton plant leaves, bare soil, and water in a reservoir are presented in the lower part of Figure 1 (Wiegand, Heilman and Gerbermann, 1968); air temperature measured at 5 ft above bare soil, with shielded thermocouples, is presented in the upper part of the figure. Incoming solar radiation is reported in langleys per minute which is numerically equal to calories per square centimeter per minute. The relations are linear in the bottom graph except for the leaves of the cotton plant. This is expected for cotton plants (Wiegand and Namken, 1966) because heat transfer between the cotton leaves and the air keep the leaf temperature near that of the air. Air temperature rises during the day. Cooling due to evaporation of water from the reservoir, the large amount of energy required to change its temperature (i.e., its high heat capacity), and thermal mixing keep the water temperature nearly constant. The dry soil, lower graph, for which the morning and afternoon curves follow separate paths, had large mass and poor thermal conductivity with a consequent strong thermal dependence on insolation. Wet soil behaves thermally like plant leaves, because the energy is used to evaporate water. As shown in Figure 1, the temperature of bare dry soil can be 30°C warmer than plant leaves.

A portable radiometer (Stoll, 1954) was used to make the measurements of Figure 1. It had been calibrated over a wide range in target temperature and internal reference temperature against a Leslie cube blackbody source. The temperatures for soil, plant, and other surfaces, then, are equivalent blackbody temperatures, i.e., the temperature these objects would have if they had unit emissivity. This reporting form is used because the measurements necessary for correcting for deviations from unit emissivity of targets and for radiation from the surroundings were not made (Fuchs and Tanner, 1966; Conaway and van Bavel, 1966).

Insolation

Figure 2 shows the influence of solar radiation on leaf temperature of cotton plants (Wiegand and Namken, 1966). The data in Figure 2 were obtained on different days when air temperature (T_A) at plant height and relative turgidity (RT) were uniform among all experimental treatments. (Relative turgidity is the ratio of the water content of the leaf as sampled in the field to its water content after floating on water under illumination at room temperature overnight.) Air temperature at the time of measurement (2:30-3:00 p.m., central standard time (CST)) differed by 3.5°C, and relative turgidity of the cotton leaves differed by 10% on the two dates. The variable radiation was created by intermittent clouds.

In the study cited, it was found that individual cotton leaves equilibrated with a change in radiation intensity in about 45 seconds. Thus the leaf-temperature measurements were deferred until radiation remained steady for a minimum of 45 seconds.

The data show that the thermal response of leaves to changing radiation is linear, and they imply that if radiation conditions are variable it will be necessary to measure the incident radiation and leaf temperature simultaneously.

Plant Water Stress

The effect of water deficiency (plant water stress) on cotton leaf temperature when air temperature (T_A) and solar radiation (R_S) were approximately constant is depicted in Figure 3. The variable plant moisture conditions M-1, M-2, and M-3 were achieved by timing of irrigation during a rainless period. In midafternoon, cotton plant leaves exhibited symptoms of wilt at 70 to 72% relative turgidity. Leaves at 60% relative turgidity were extremely flaccid. These data indicate that cotton leaf temperature can vary about 3.5°C with plant water stress.

The standard deviations of air temperature and solar radiation associated with these observations were 0.7°C and 0.04 ly min^{-1}, respectively. The regression coefficient indicates that leaf temperature increased 0.15°C for each percent decrease in relative turgidity over the relative turgidity range 83 to 59%.

From the data for 37 individual days covering two crop seasons, it was determined that leaf temperature could be estimated with a standard error of 1°C from measurements of relative turgidity, solar radiation, and air temperature at plant height. For these measurements, solar radiation averaged 1.15 ly min^{-1}, and leaf temperature minus air temperature averaged 4°C (Wiegand and Namken, 1966).

A panchromatic photograph of small, differentially irrigated cotton plots and the plant canopy temperature patterns obtained with an infrared camera are presented (Figure 4) (Myers, Wiegand, Heilman, Thomas, 1966a). The thermograms are a composite of 4 thermograms taken at the time of day (CST) indicated below each thermogram.

The cotton plot in the foreground and the one in the background of each thermogram were at about the same moisture condition, and have the same tone. The middle plot was drier than the others. The calculated temperature difference between dry and wet plots was 0.1, 0.3, 2.0, and 0.2°C at the hours 0540, 0935, 1520, and 2210, respectively.

The first thermogram of Figure 4 was obtained at 0540, well in advance of daybreak. The light areas from bottom to top on this thermogram -- ignoring the one at the very bottom of the thermogram -- are a man kneeling between the plot in the foreground and the center plot, an incandescent lamp in the far plot, and three side-by-side instrument shelters just beyond the plots. The other three thermograms depict the same target at later times during the day.

In all the thermograms presented, the lighter toned areas represent warmer plant temperatures. Interpretation of the thermograms is made by matching the tone of a target within the field of view with one of the 8 gray scale steps printed automatically at the top of each thermogram. From the electronic settings used to obtain the thermograms and a parameter corresponding to the gray scale step, the target radiance may be calculated and then converted to target temperature. It was necessary to vary the electronic settings as the crop surface warmed; therefore, temperature differences cannot be compared by visual inspection except relatively within individual thermograms.

Soil Salinity

Soil salinity is a problem on irrigated, and on nonirrigated arid and semiarid land the world over. The presence of water soluble salts in the root zone causes an osmotic suction which reduces the availability of water to plants. This osmotic component plus the soil matric suction (Richards, 1949), which increases as plants extract water, constitute the total soil water suction. Plants growing in saline soil exhibit marked symptoms of moisture stress, and growth is retarded.

Figure 5 shows the relation between total soil water suction and leaf temperature of cotton growing in saline soil (Thomas and Wiegand, 1970). An increase in total soil water suction from 1 to 15 bars would raise the adjusted leaf temperature 1.82, 2.10, and 6.16°C, respectively, on May 27, June 4, and June 17. The osmotic suction accounted for nearly all the variation in leaf temperature attributed to total moisture suction.

A number of workers have applied remote sensing techniques to studying soil salinity (Myers, et al, 1963; Myers, Wiegand, Heilman, and Thomas, 1966a; Myers, Carter, and Rippert, 1966b; Myers and Allen, 1968; Myers, et al, 1970). Their findings demonstrate remote sensing's usefulness for this purpose.

Ground Cover

If plants incompletely cover the soil, a scanning instrument will sense the mixture of plant and soil background emissions in the instrument's field of view. Figure 6, taken from Myers and Heilman (1969), relates equivalent blackbody temperature to percent plant cover. As percent plant cover increased, equivalent blackbody temperature decreased.

Soil Survey

Another application of thermal data is in soil survey (Myers and Heilman, 1969). In this case, the soil profile characteristics influencing heat flow are related to surface temperatures. Timing of sensing, both diurnally and seasonally, must be carefully selected for this purpose. Park, Colwell, and Myers (1968) have suggested that soil moisture contrasts in bare soil can be detected using thermal infrared wavelengths.

For row crops, percent ground cover can be obtained by ground observers by measuring the distance between rows not occupied by leaves and dividing by the row spacing. Temperature of plant and soil mixtures have also been related to leaf area index and average plant spacing (Wiegand, Heilman, and Gerbermann, 1968). Ground cover can also be estimated from aerial photographs.

Gates (1970) presented energy balance equations which take the plant cover into account. However, the author is unaware that these equations have been applied in the field.

Evapotranspiration

Another application of thermal scanner data is in evapotranspiration research. Surface temperature is required directly or indirectly to calculate the water vapor pressure at the plant (soil) surface for all equations in which the latent heat flux density (evaporation) is calculated (Wiegand and Bartholic, 1970).

Freezes

Freezes are another hazard in Agriculture. Figure 7 is a composite of a panchromatic photograph and three thermograms of a test citrus tree taken on a night when a radiational freeze was forecast and petroleum coke heater blocks were burned under the trees (Bartholic and Wiegand, 1969). The electronic settings of these thermograms were such that the lighter in tone the images are, the colder the temperature. At 0250, 0348, and 0603 the predominate external leaf temperatures were 3.3, 2.4, and 4°C, respectively.

Gray scales are immediately above each thermogram. The temperature range from gray scale step 1 (dark tone; warm) through step 8 (light tone; cold) is 4.2°C. For the 0603 thermogram, the temperature range is also 4.2°C but the signal was electronically offset so that each step is 1°C warmer than the corresponding step of the other thermograms.

The infrared camera senses longwave thermal radiation emitted by the exterior leaves only if the tree is heavily leafed. However, if there are holes in the tree canopy, interior leaves and limbs are sensed. In the 0348 hour thermogram (and to a lesser extent in the other thermograms) holes in the canopy resulted in interior warmer objects being sensed giving lateral and almost vertical, nearly continuous dark patches. Likewise, gradations in tone occur because some leaves were shielded from the sky by leaves above them while others were fully exposed to the sky. Temperatures of shielded leaves, as measured by attached thermocouples, were about 2°C warmer than exterior leaves.

INSTRUMENTATION

Lowe (1968) lists some of the features of scanners that make them attractive: (1) measurements are possible both within and outside the photographic range; (2) the electrical output signal can be readily transmitted, recorded, analyzed, and processed; (3) detectors generally have wide dynamic range; (4) the scanner is easy to calibrate to yield quantitative radiometric data; and (5) simultaneous data collection in many wavelength channels is possible.

In the thermal infrared, quantitative or semiquantitative thermal maps can be obtained if the signals which are ac coupled for ease of signal handling and recording have been dc restored -- a technique that introduces a repetitive signal of known constant level from a source whose position in the video is known and which requires electronically sampling the output level of the known signal and adding or subtracting a dc voltage to make it constant. Then if the detector response is stable and reproducible and the amplifier gains are fixed, the instrument response can be calibrated from two or more internal or reference calibration sources (Lowe, 1968).

Myers and Allen (1968) have aptly stated: "The researcher must be warned, however, that use of relatively untried instruments with unknown characteristics with little or no attention to calibration may lead to wholly unsatisfactory research results. Radiometry is an exacting field and the use of poor experimental techniques will result in inadequate and misleading data, thus, the time of the experimenter and his readers will be wasted."

SUMMARY

There are many applications of thermal infrared scanners to problems faced by mankind in learning about the earth's resources and in managing and using them wisely. I hope that by talking about possible applications and factors affecting thermal measurements today you can better judge the usefulness of thermal scanners in your countries.

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GLOSSARY OF TERMS *

Insolation (contracted from incoming solar radiation) -- In general, solar radiation received at the earth's surface. Langleys/cm^2/min.

Heat capacity (thermal capacity) -- The ratio of heat absorbed (or released) by a system to the corresponding temperature rise (or fall).

Thermal conductivity (heat conductivity, coefficient of thermal conduction, coefficient of heat conduction) -- An intrinsic physical property of a substance, describing its ability to conduct heat as a consequence of molecular motion.

Blackbody -- A hypothetical "body" that not only absorbs all wavelengths, but also emits at all wavelengths and does so with maximum possible intensity (has an emissivity of unity) for any given temperature.

Equivalent blackbody temperature -- The temperature measured radiometrically corresponding to that which a "blackbody" would have. Most natural objects including soil, plant leaves, and water have emissivities >0.9 but <1.0.

Relative turgidity (relative water content) -- The ratio of the water content of a leaf sampled in the field to its water content after floating on water under illumination at room temperature overnight.

Leaf area index -- The cumulative one-sided leaf area per unit ground area projected from the canopy top to a plane at a given distance above ground level.

Evapotranspiration -- The combined processes by which water is transferred from the earth's surface to the atmosphere; evaporation of liquid or solid water plus transpiration from plants.

Internal reference temperature -- A standard surface or cavity of known temperature or radiometric intensity against which measurements of crops, soils, water, and other objects can be quantitized.

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* Definitions found in it are those given in Glossary of Meteorology edited by Ralph E. Huschke as published by American Meteorological Society, Boston, Mass. 1959.

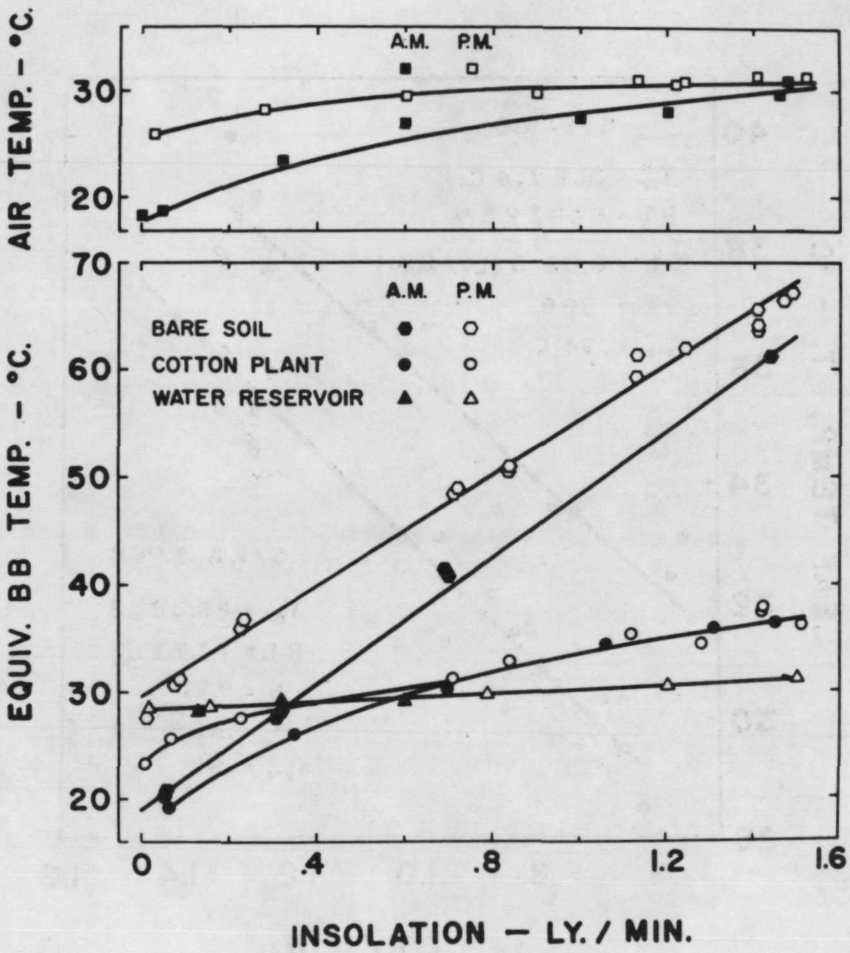

FIGURE 1. Equivalent blackbody temperature of dry soil, cotton plants, and a water reservoir and of air temperature versus incoming solar radiation on the day of a thermal scanner overflight, 6/1/66 (Wiegand, Heilman, and Gerbermann, 1968). Internal reference signal generation for the Univ. of Michigan scanner used (Lowe, Polcyn, and Shay, 1965) was not available until after these measurements were made. Therefore, the thermal imagery was calibrated against ground truth measurements such as the above taken simultaneously with the plane's overflight.

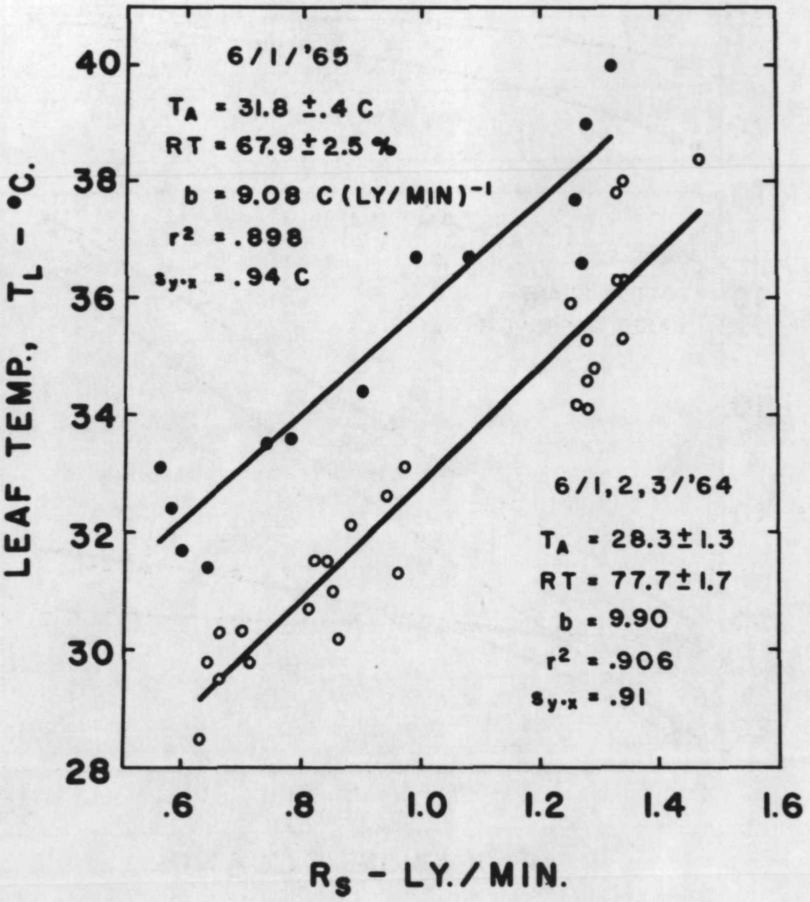

FIGURE 2. The influence of solar radiation (R_s) on cotton leaf temperature when air temperature (T_A) and relative turgidity (RT) were approximately constant. An increase in radiation from 0.6 to 1.6 ly min^{-1} resulted in a 9° to 10°C increase in leaf temperature as indicated by the regression coefficient, b. The standard errors of estimate, $S_{y.x}$, indicate that leaf temperatures could be estimated ± 0.9°C two-thirds of the time (Wiegand and Namken, 1966).

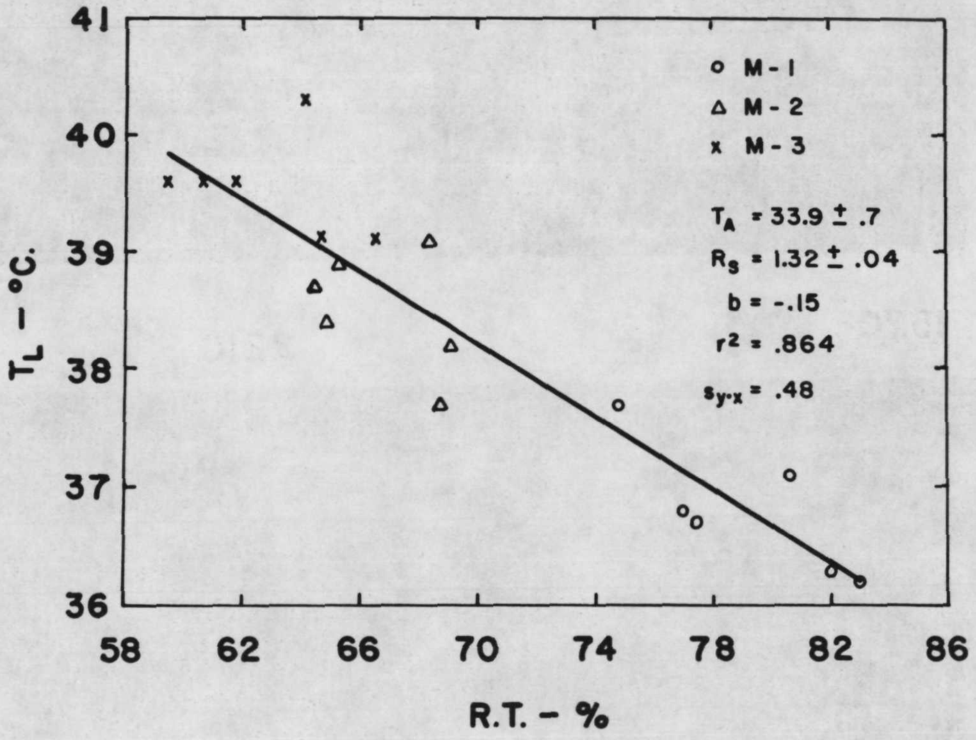

FIGURE 3. The effect of relative turgidity (RT) on leaf temperature when air temperature (T_A) and solar radiation (R_s) were approximately constant. The leaves on which relative turgidity measurements were made were sampled in midafternoon. Plant water condition ranged from freshly irrigated (83% RT) to extremely wilted (59% RT). Water stress is shown to cause a 3.5°C increase in plant leaf temperature. Therefore, plant temperatures should be useful for scheduling irrigations (Wiegand and Namken, 1966).

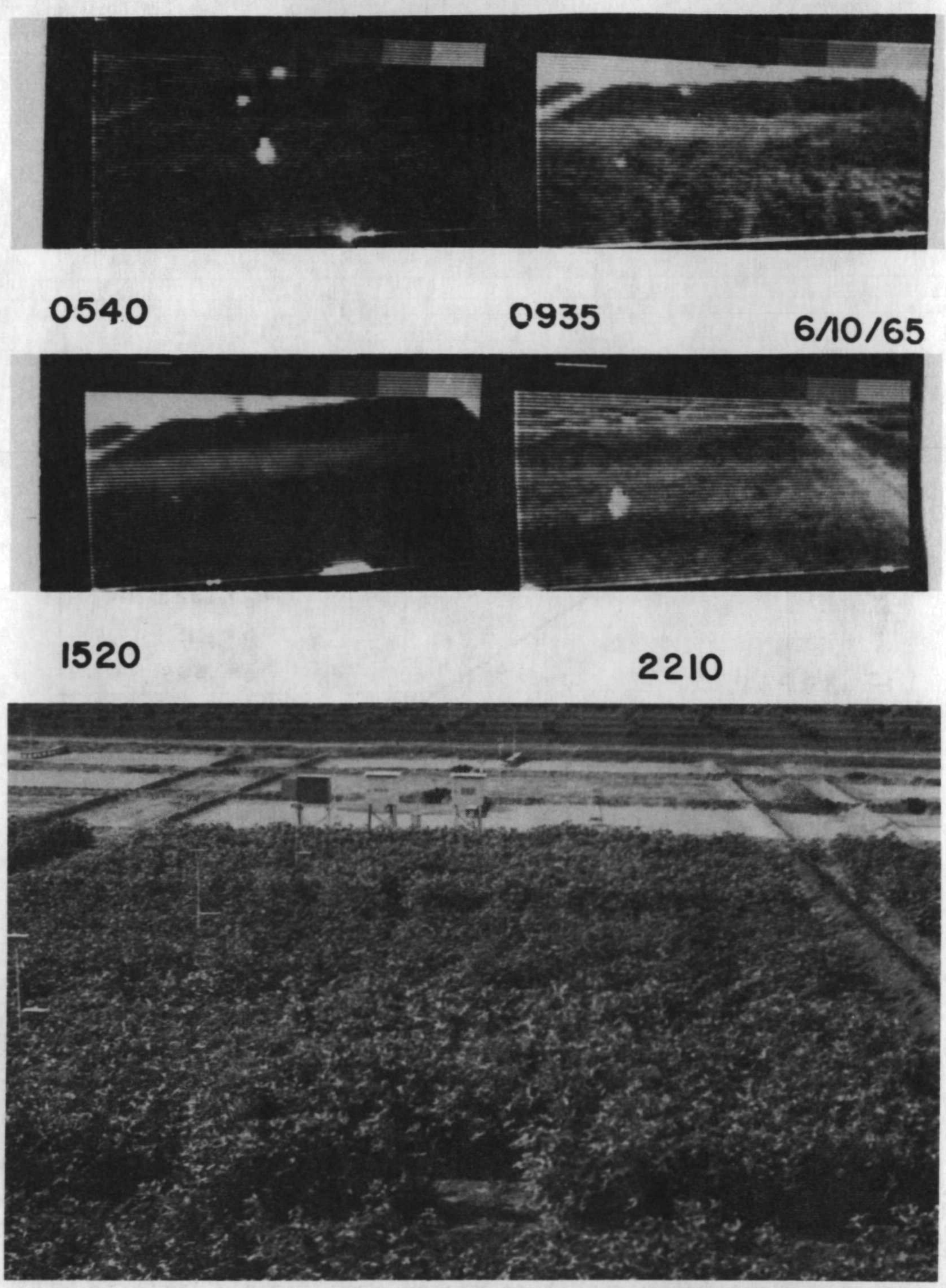

FIGURE 4. Panchromatic photograph and composite of 4 thermograms of small, differentially irrigated cotton plots. The center plot was drier than the others. The calculated temperature difference between the dry and wet plots was 0.1, 0.3, 2.0, and 0.2°C at the hours 0540, 0935, 1520, and 2210, respectively (Myers, et al., 1966a).

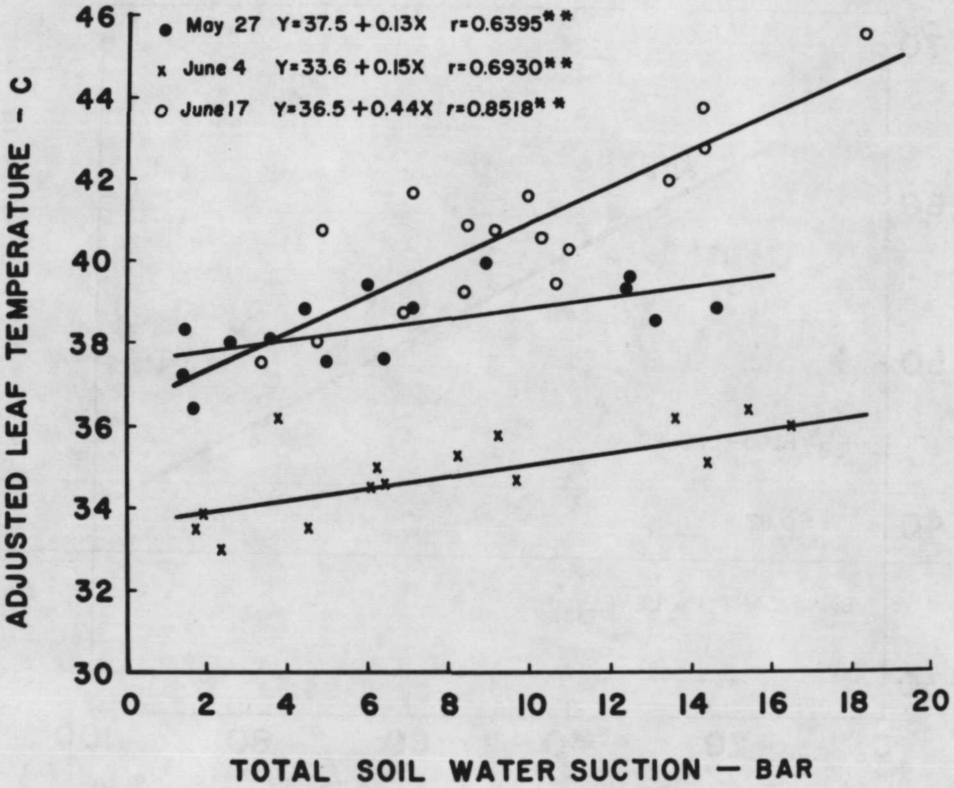

FIGURE 5. Leaf temperatures adjusted to mean solar radiation during the sampling period as related to total soil water suction (the sum of osmotic and matric suctions) on selected days in the growing season for cotton grown on saline soil. Nearly all the water suction was due to osmotic suction (Thomas and Wiegand, 1970).

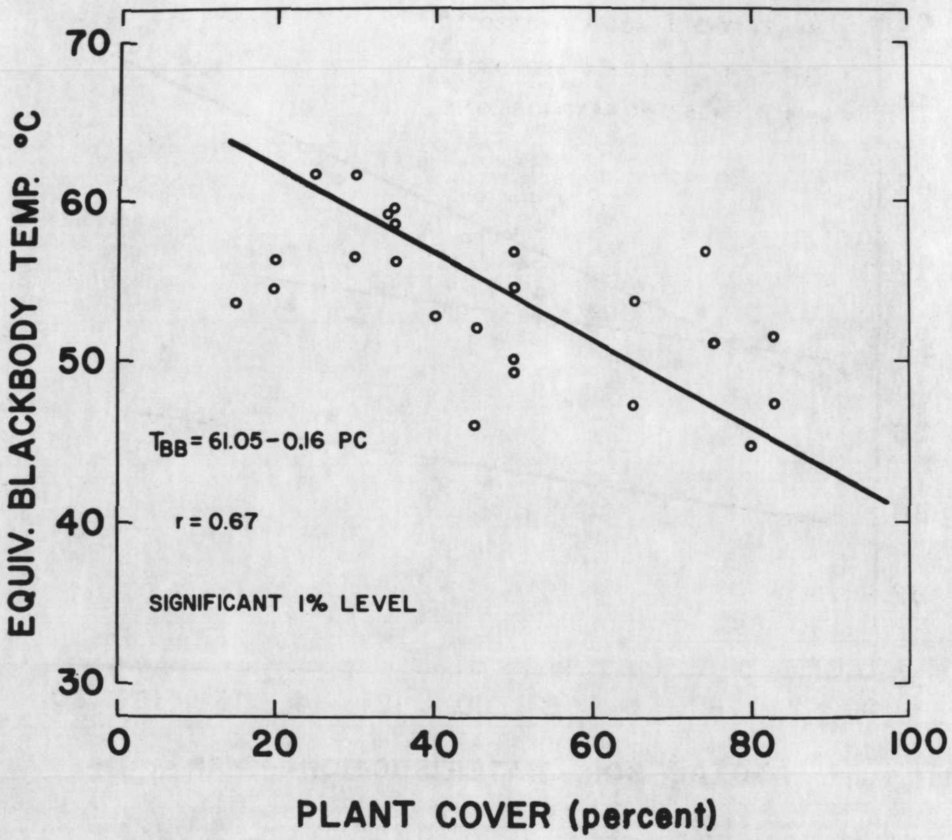

FIGURE 6. Relation between equivalent blackbody temperature of selected sites and percent plant cover for an overflight with the Univ. of Michigan scanner at 1400 hr on June 1, 1966 (Myers and Heilman, 1969). Incomplete plant cover results in the scanner recording a mixture of signals from the plant surfaces and the soil background.

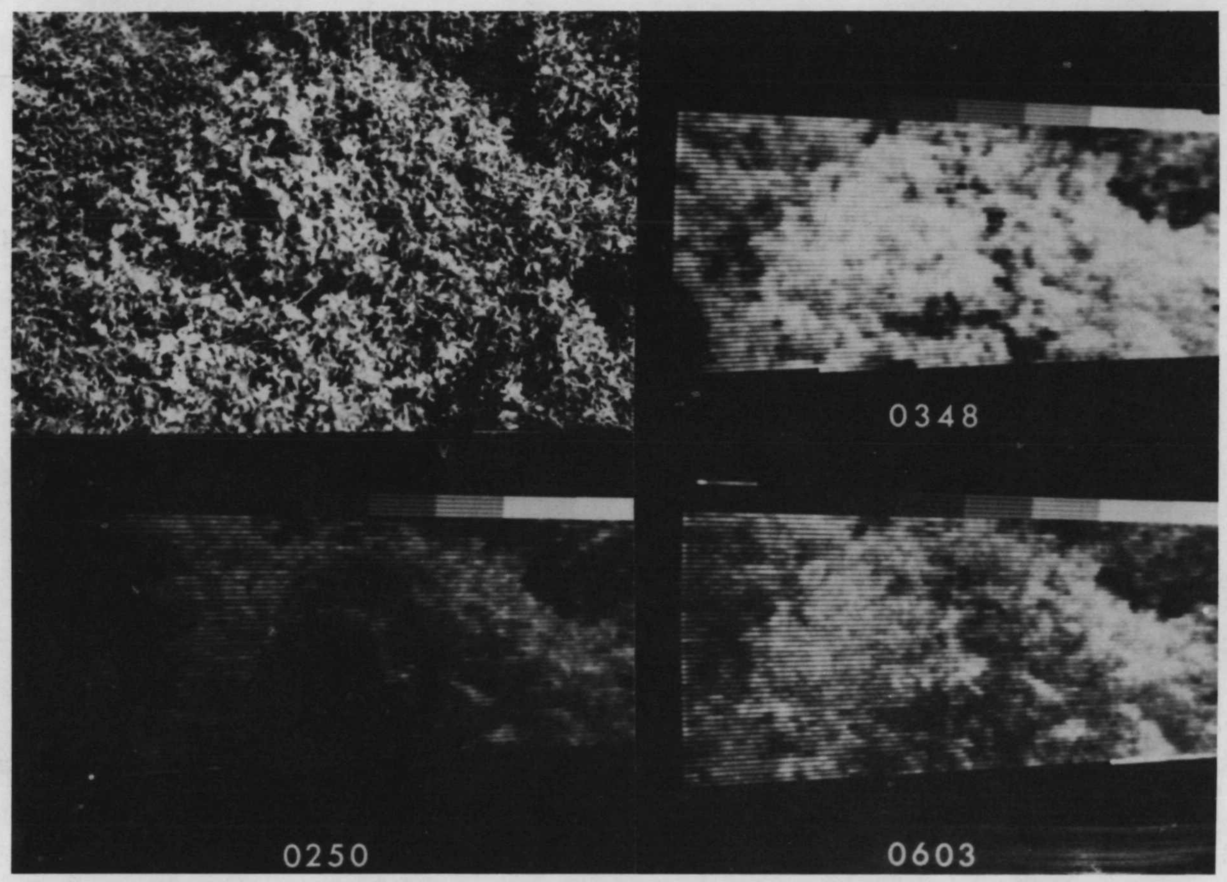

FIGURE 7. Panchromatic photograph (upper left) and thermograms taken in a citrus orchard at the hours indicated below each thermogram on a night of strong radiational cooling. For these thermograms, the temperature range depicted from gray scale step 1 (dark tone; warm) through step 8 (light tone; cold) is 4.2°C. Exterior leaves exposed to the sky were about 2°C colder than leaves shielded from the sky (Bartholic and Wiegand, 1969). The study of temperature distributions during a freeze is aided considerably by thermal scanners.