USE OF INFRARED THERMOMETRY TO MEASURE CANOPY-AIR TEMPERATURE DIFFERENCE AT PARTIAL COVER TO ASSESS CROP WATER STRESS INDEX

by

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APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

Donald C. Slack ______ July 10 1986

Donald C. Slack ______ Date

Professor of Agricultural Engineering

To my mother and father

Zulmira and Americo Almeida

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ABSTRACT

A study on the potential for extracting canopy temperature from composite scenes of plant and soil background using infrared thermometry was carried out. Using field and laboratory data, Heilman's equation was tested for its sensitivity and ability to predict actual canopy temperature. Using Idso's approach, crop water stress index values were calculated for partial and full canopies. The study showed that under partial canopy situations calculated leaf temperature is very sensitive to soil background and composite scene temperatures and moderately sensitive to canopy emissivity and cover. Negative values as well as values greater than unity for crop water stress index were calculated for partial canopy conditions. Negative values were also reported for the full canopy cover conditions thus, establishing a need for better estimates of data used in calculation of crop water stress index values. Infrared thermometry does not show much promise as an irrigation scheduling technique for canopies under partial cover using the approach investigated in this study.

CHAPTER 1

INTRODUCTION AND OBJECTIVES

Timing of irrigation, or irrigation scheduling, is considered one of the most important and difficult tasks of irrigation science. Many methods have been developed for timing irrigation, the most common ones being soil based, climatic based and plant based (Jackson, 1983; Geiser et al., 1982). Soil based techniques have generally consisted of a means of directly or indirectly estimating soil moisture (i.e., neutron probes, tensiometers, gravimetric) and then replenishing the soil with water when a certain management allowed depletion level has been reached. Generally, the level of depletion is set at 50 to 60 percent (Geiser et al., 1982); however, it is dependent on crop, soil type, management and, water availability. Climatic based methods have been developed as alternatives to soil based methods. They are based on the evaporative demands incurred on the plants by the environment and, because they may include a plant factor, they are sometimes considered better than soil based approaches.

Since the objectives of irrigation is to minimize plant stress, it would be to no one's surprise that the best scheduling technique should be considered plant based. Examples of plant based methods would be the pressure bomb, leaf diffusion porometer, leaf water content and, temperature. Of all these methods, temperature is the one which probably holds a more promising future. The temperature method has caught the attention of many researchers interested in irrigation scheduling in the last decade. Most of the above mentioned techniques are based on measurements made on individual plant parts, whereas the temperature method can be representative of a large number of complete plants over a representative field area. Researchers like Tanner (1963) and Gates (1964) have long recognized the importance of temperature as an indicator of plant water status and tried to use it not only as a means of predicting crop yield but also, as a means of irrigation timing. Other researchers that have used crop temperature as a means of irrigation timing include Isdo et al. (1981), Idso (1982), Geiser et al. (1982), Jackson (1981), Hiler and Clark (1971) and, Hiler et al. (1974).

The development of small portable infrared thermometers (IRT) has made canopy temperature an easily measured parameter in the field. Such IRT's are accurate to within ±0.5 °C. This development has opened the way for the much needed research in this subject. IRT's can survey a large field area, thus, yielding an integrated value of the crop temperature in the field. Even though most of the research done has been on fields at (or close to) full cover, recent literature shows that there is interest in partial cover situations. In spite of the complexities involved, some researchers like Heilman et al. (1981), Wanjura et al. (1984), Hatfield et al. (1985) Kimes (1981, 1983), Matthias et al. (1986) have recognized the importance of monitoring plant temperatures at less than full cover. Empirical (Wanjura et al., 1984; Hatfield et al., 1985) as well as theoretical (Heilman et al., 1981; Kimes, 1981, 1983; and Matthias et al., 1986) approaches have all been taken with very little success thus far. The potential for extracting canopy temperature from composite scenes has been recognized but, it has not yet been done successfully in a way to allow field application. That is the basic motivation for a study on this difficult subject.

The objectives of this study are:

1. to study the possibility of extracting canopy temperature from a composite scene measurement and compare actual measured with calculated canopy temperature.
2. to do a sensitivity analysis of the calculated crop temperature to the other measured parameters used in extracting canopy temperature.
3. to do a crop water stress index analysis, under partial canopy cover using observed canopy temperatures.

CHAPTER 2

LITERATURE REVIEW

Infrared Theomometry

With the development of portable infrared thermometers (IRT) a number of ways in which plant temperature can be used to predict crop water status have been developed by irrigation scientists and engineers.

Hiler and Clark (1971) and Hiler et al. (1974) proposed the use of plant temperature in the application of a stress day index, based on plant parameters, for irrigation scheduling. The stress day index of Hiler and Clark basically consisted of the product of a plant stress factor, which is an indicator of water availability to the plant, and a crop susceptibility factor, which is dependent on the growth period and crop species. The crop susceptibility factor is an indicator of the crop vulnerability to a certain stress day factor. The crop susceptibility factor increases or decreases as the crop becomes more or less vulnerable to stress during the growth stages.

In most attempts to use plant temperature to quantify plant stress, the foliage (or canopy)-air temperature difference has been the most successful. It has been used by Idso et al. (1977), Jackson et al. (1977) and, Walker and Hatfield (1979) on the development of the stress degree day (SDD) and more recently on the development of the crop water stress index (CWSI) by Idso et al. (1981) and Jackson et al. (1981) and the critical temperature approach by Geiser et al. (1982).

The SDD concept first developed by Idso et al. (1977) preceded the CWSI also developed by Idso et al. (1981a). Idso used the SDD concept not only to predict crop yield but also to assess crop water stress. When first developed, the SDD concept had no accountability for environmental and climatic parameters, in spite of the fact that Ehrler (1973) had already found a linear relationship between leaf air temperature difference $(T_f - T_a)$ and vapor pressure deficit (VPD) in cotton. T_f and T_a are, respectively, foliage and air temperatures. Ehrler had concluded that scheduling irrigation in cotton using the $(T_f - T_a)$ concept had merit and recommended that more studies be done. Later, Idso (1981) came to realize that there was a need to normalize the SDD concept to accomodate for environmental variabilities. In an attempt to do so, Idso had the same findings as Ehrler had eight years earlier. He also found that there was a linear reltationship between $(T_f - T_a)$ and VPD. Idso then concluded that it was important to study the significance of climatic factors to $(T_f - T_a)$ if crop water stress arising from soil moisture deficit was to be better quantified. Since the straight line relationship was found under well watered conditions, the line was termed the unstressed baseline. That also led Idso to an empirical development of a fully stressed baseline, which, by his definition, represented the maximum stress that a crop could attain. Having the maximum and the minimum stresses that a plant can experience it was only natural to think that the two could be related to express the crop water status at a given climatic and soil water conditions. It was then that Idso came up with the crop water stress index concept. By measuring canopy-air temperature differences at times of the day when the crop is most susceptible to stress, solar noon, Idso was able to relate that temperature to the upper and lower baselines, thus, defining the crop water stress index. The crop water stress index was then defined, for any measured $(T_f - T_a)$, as the ratio of the differences between the upper baseline (T_u) and $(T_f - T_a)$ and the upper and the lower baseline (T_L). In an equation form, the $T_f - T_a = T_m$, this is expressed as

$$\mathrm{CWSI} = \frac{T_u - T_m}{T_u - T_L} \qquad (1)$$

The not very convincing way which Idso used to empirically develop the upper stressed baseline led Jackson et al. (1981) to a theoretical development of the CWSI. Using energy balance considerations they came up with a series of equations which theoretically defined the CWSI. The fact that Jackson et al. (1981) theoretically justified Idso's findings can only be seen as a plus not only for Idso but also for the irrigation science community. Jackson's et al. (1981) CWSI equation took the following form:

$$\mathrm{CWSI} = 1 - E/Ep = \frac{\gamma(1-r_c/r_a)-\gamma^*}{\Delta+\gamma\left(1+r_c/r_a\right)} \qquad (2)$$

where E/Ep is the ratio of actual to potential evapotranspiration, γ is the psychrometric constant (Pa/°C), r_c and r_m are respectively canopy and aerodynamic resistances, Δ is the slope of the vapor pressure-temperature relation (Pa/°C) and, γ^* is the psychrometric constant corrected for canopy resistances when transpiring at potential. From Jackson et al. (1981) considerations the canopy-air temperature difference can also be obtained from

$$T_c - T_A = \frac{r_a Rn}{\rho cp} \times \frac{\gamma(1+r_c/r_a)}{\Delta+\gamma\left(1+r_c/r_a\right)} - \frac{VPD}{\Delta+\gamma\left(1+r_c/r_a\right)} \qquad (3)$$

where Rn is the net radiation (W/m^2), ρ is the density of air (kg/m^3) and VPD is the vapor pressure deficit (Pa), given by the difference between saturated and ambient air vapor pressures. Therefore, Jackson et al. (1981) were able to establish a much needed theoretical basis for understanding Idso's findings. These developments were possible with the availability of portable IRTs that can perform rapid and accurate temperature measurements in the field.

Confronted by the need for irrigation scheduling in crops at less than full cover, at stages where crops are sometimes more susceptible to stress, and in spite of all the unknown difficulties existent in extracting canopy temperatures from composite scenes, some researchers have taken the task of performing such studies. In doing so basically two approaches have been taken, as previously mentioned; a theoretical approach and an empirical one.

Theoretical Approach. Heilman et al. (1981), using energy balance considerations developed an equation for predicting canopy temperature at less than full cover; the equation based on a balance of radiation flux from the canopy and the surroundings took the following form:

$$T_c = \left[\frac{R-(1-f_c)\varepsilon_s\sigma T_s^4-f_c(1-\varepsilon_c)B^*-(1-f_c)(1-\varepsilon_s)B^*}{f_c\varepsilon_c\sigma}\right]^{1/4} \qquad (4)$$

where R, the longwave flux density (W/m^2) is given by Heilman et al. (1981) as,

$$R = \varepsilon\sigma T_{comp}^4 \qquad (5)$$

f_c is the field cover (fraction), ε_s and ε_c are respectively soil and canopy emissivities, T_s and T_c are soil and canopy temperatures (°K), σ is the Stefan-Boltzmann constant ($5.67 \times 10E - 8 W/m^2/K^4$), B* is the sky irradiance (W/m^2), given by,

$$B^* = \varepsilon \sigma T_{sky}^4. \tag{6}$$

T_{comp} is the composite (soil + canopy) temperature (K) and T_{sky} is the sky temperature (K).

Heilman's findings were somewhat encouraging but, he failed to actually prove that canopy temperature could be successfully extracted from a composite scene using equation (4). He found differences of observed from predicted canopy temperature ranging anywhere from -1.84 to 2.50°C when he used B* in the equation. In his paper (Heilman et al., 1981) reported an agreement between observed and predicted canopy temperatures of $R^2 = 0.88$. However, when he neglected the effect of the sky irradiance on equation (4), he found differences that ranged from 0.8 to 10.7°C with a coefficient of determination equal to 0.66. In face of his findings, he was optimistic about extracting canopy temperatures from composite scenes using equation (4).

Kimes (1981, 1983) took the same basic approach. However, his model was based on inversion techniques applied to a geometric projection of a row crop. He tried to separate not only crop (both, sunlit and shaded) and soil temperatures from a composite scene, but also row structure parameters such as height, width and spacing.

His findings showed that the prediction accuracy of vegetation and soil parameters were on the order of one and two degrees centigrades respectively, if no a priori knowledge of the row crop structure was assumed.

More recently, Matthias et al. (1986) used this model and tried to separate plant and soil temperatures from composite scenes as viewed by an IRT. This study focused mainly on sunlit and shaded soil and plant temperatures. Matthias et al. reported that the accuracy of the model's predictions varied from ±5 percent in estimating the plant temperature to a ±43 percent in estimating shaded soil temperatures. In addition, they did a study of the sensitivity of the projected temperatures to the other parameters used in the extractions. They found that the calculated temperatures were most sensitive to composite temperature measurement, moderately sensitive to emissivity and component areas and, least sensitive to longwave radiation, B*.

It appears that Kimes' model might have an advantage over Heilman's model, since it can distinguish among more than two components (sunlit and shaded plants and soil temperatures) whereas Heilman's model can only distinguish between two components (soil and plant). Though that might be an advantage, it may also be a disadvantage since it makes the model more complicated and, thus, less likely to be used by a farmer in his chores of irrigation scheduling. That requires that a more extensive study be done on

Heilman's model in order to determine not only its prediction accuracy, but also, its applicability in irrigation scheduling.

Empirical Approach. Wanjura et al. (1984) used both Idso's and Jackson's approach to calculate CWSI values in both, partial and full canopies. In their studies they used cotton grown under rainout shelters, to control the quantity of water applied in each soil moisture regime used. They found that the slope of the unstressed baseline for partial canopy is less than that for full canopies. The reduced sensitivity of the canopy-air temperature difference to VPD in partial canopies was attributed to factors such as crop (r_{cp}) and aerodynamic (r_a) resistances. Wanjura et al. found reasonable agreement with r_{cp} values between 50 to 60 s/m and ra values of 10 to 15 s/m for cotton, while Jackson et al. (1981) found reasonable agreements for $r_{cp} = 5$ s/m and $r_m = 10$ s/m for irrigated wheat. They suggested that such differences may be site and crop specific, and may be influenced by factors such as crop architecture, cultural factors, and wind speed.

Hatfield et al. (1985) investigated changes in the unstressed baseline of the CWSI under full and incomplete ground cover, under well-watered conditions, with the objective of developing a theoretical model to evaluate roughness on canopy energy exchanges. Like Wanjura et al. (1984), they found the same differences in the unstressed baseline for partial and full cover, and attributed the differences to low aerodynamic resistances in partial canopies which, they claimed, induces high evapotranspiration rates. On the other hand, they say, the plant in response to those demands through a dynamic feedback mechanism reduces its evapotranspiration rate (by closure of the stomates) thus leading to a high canopy resistance. It should be noted that in both of the approaches discussed above only foliage temperatures were measured when plants had achieved sufficient size so that low angle viewing would provide a scene of foliage only with no soil background. Thus, in this instances there was no need to extract foliage temperature from a composite scene. However, this approach would not apply for some time after emergence when even at low viewing angles a composite scene would result.

Digital Imagery

The use of digital imagery and robotics is also fastly expanding in the agricultural industry (Whittaker et al., 1984). Digital imagery is being studied not only as a means of helping robots (robots eyes) in harvesting operations (Whitaker et al., 1984) but also, as a means of identifying agricultural products such as fruits and seeds (Kranzler et al., 1984), identify plant species (Guyer et al. (1984), and sorting fruits (Sakar and Wolfe, 1984) among many other tasks.

For example, Whittaker et al. (1984) used a so called Hough transform to sort tomatoes under conditions similar to those encountered at the field. The transform, at first, used mathematical parameters (slope and intercept) to identify colinear points in a digital image. However, Duda and Hart (1972) normalized the transform in a way that it could also identify circular lines by the use of parameters like radius and center. The beauty of the model, in this case, lies in the fact that arcs of the same object do not have to be concurrent. That is extremely important since most fruits are imperfect in shape. After testing the model, Whittaker et al. (1984) felt satisfied and concluded that it could indeed be used to identify tomatoes - and other fruits and vegetables such as melons, citrus and apples - from images acquired under field conditions. It should be noticed here that they did not perform their experiment under actual field conditions but rather used vidiotaped images of tomato plants grown in greenhouses. Their objective was to develop an algorithm that was capable of locating tomatoes in natural field conditions but that was, a) not color dependent, b) able to operate in presence of noise caused by brightness and shadows and, c) able to distinguish partially occluded tomatoes. The paper shows that they were able to attain their objectives.

On the other hand, Guyer et al. (1984), also using digital imagery, tried to identify plants of different species as well as plants of the same species but at different growth stages. Even though they were somewhat successful in identifying plants of different species, they were not able to distinguish among plants of the same species at different growing stages. Their problems, they thought, were related to poor resolution of the images and to processing time. Resolution and time varied inversely, which implied that they had to sacrifice one for the other.

In view of the relative success already attained with digital imagery (Whittaker et al., 1984; Guyer et al., 1984), in this research, it was proposed to use digital imagery in a way that it probably has never been used before. That is, to measure canopy cover under field conditions. The literature shows that the approach has potential and that it can be accurate.

Line Source Sprinklers

Line source sprinklers have been documented to be excellent means of developing crop water production functions, Hanks et al. (1976), and Hanks et al. (1980). In a system like this, there is a uniform application of water along and parallel to the system, while it decreases uniformly from the system to the edges of the field. Therefore, water application can vary from a designated maximum adjacent to the source to a minimum determined by the system at some distance from the source. If the application rate varies linearly with distance from the source, then depth at any distance can be determined by the slope of the pattern and, the distance from the source. The advantages of a system like this is that treatment effects are visual and plots can be relatively small. The size of the plot can be variable in length but in width it is dependent on the wetted radius of the nozzle used. A clear disadvantage of such a system is the fact that irrigation treatments are applied in a systematic way and all dependent on some pre-established control factor. By its nature, the system yields two replicates of the same treatment, one on each side of the source. A border of one meter is recommended on the edges of the plot by Hanks et al. (1976). When operated under proper conditions (calm winds) these systems can be excellent research tools,(Hanks et al., 1976).

CHAPTER 3

METHODS AND MATERIALS

Materials

The materials used in this experiment consisted of 2 IRT's, 1 digital camera with a computer, 1 temperature and humidity probe, 1 net radiometer, 1 neutron probe, 6 tensiometers, and other miscellaneous equipment.

The two IRT's were Everest Interscience, model 110. One, IRT1, had a 3 degree (solid angle) field of view and, the other, IRT2, had a 15 degree (solid angle) field of view, both with a band-pass of 8-14 microns. They both had a temperature operational range of -30 to 100°C with an accuracy of ±0.5°C. The emissivity can be set by the operator and ranges from 0.1 to 0.99. Both can be operated from a range of 2 centimeters to infinity.

The Micromint Incorporated digital camera (refer to Appendix 4) uses an IS32 Optic Ram (by Circular Cellar Inc), composed of 65,536 pixels divided into two rectangular arrays of 128 × 256 pixels each, to process the digital image. Each pixel is, by itself, an individual image sensor. The optic Ram then uses the Micro D-Cam software to transmit either a black and white or gray shades of the image to the computer graphics screen. The computer used in this case was an apple IIe with an extended memory of 128K, equipped with one disk drive and an Epson LX-80 printer.

The temperature and relative humidity probe (RH) used was a Campbell Scientific, model 207. It uses a Phys-Chemical Research PCRC-11 RH sensor and a Fenwell Elelectronics UUT5151 thermistor which is configured for use with a CR7 datalogger. Even though both sensors are combined in a single probe, separate programming instructions can be used to input and output each sensor separately. The thermistor has an accuracy of ±0.2°C on a range of temperatures from -33 to +48°C, while the RH sensor has an accuracy which is within 5 percent over a range of 12 to 100 percent. In both cases the error is a combination of the resistors used and linearization of the measurements.

A Micromet Instruments Fritshen type net radiometer with a calibration factor of 25 $W/m^2/uV$ was used. Sensitive to solar and terrestrial radiation on the range of 0.3 to 60 uM, it is assumed to be accurate within 5 percent. The transducer, covered with black paint, consists of a 22-junction manganim-constant temperature thermopile with a resistance of 200 ohms and a time constant of approximately one minute on the range of 10 to 50°C. It has a nominal sensitivity of 5 $uV/W/m^2$. Polyethelene domes 0.15 cm thick protect the sensor.

Most of the data was processed through a 21X Campbell Scientific Inc. programmable micrologger with a 16 digit keyboard and an 8 digit LCD display. The number of input channels are 8 if double ended channels and 16 if single ended channels are used, plus a 9 pin I/O port. Only four (two single and two double ended) of those channels were used at any time.

The neutron probe, by CPN Corporation, was also programmable. It has a range of water measurement of 0 to 9.75 cm/30cm (0 to 3.84 in/ft) and uses as the source of neutrons 50 mci Americium-241 Be, with a precision of 0.24 percent at 24 percent volume at a one minute count time. Count times vary from 1 to 256 seconds.

The tensiometers, manufactured by Irrometer Company, had a range of moisture measurement from 0 to 100 centibars.

Miscellaneous instruments used were two tripods, styrofoam pads painted with flat black paint, optic filters (1 polarizer, 1 yellow and, 1 red), one copper-constantan thermocouple and a wheeled cart.

Methods

The experiment was conceived to be performed under field conditions. The location was to be the University of Arizona Campus Agricultural Center Farm (UACACF), located about 5 kilometers to the north of the University of Arizona Campus. However, it was later transferred to lab conditions after it was realized that not enough control could be exerted on the experiment at the farm. It was transferred to the Agricultural Engineering Teaching Laboratory (AETL) on the University of Arizona Campus.

At the field, the experiment was set up on a 21 × 79 meter plot of Gila sandy loam (coarse loam, calcareous thermic Typic Torrifluvents). The field was planted to cotton (variety Delta Pine 55) and was located at the north end of the irrigation lab building. With rows running east and west, the field was divided in two halves which were planted to different densities; both halves planted to cotton. The north half was planted every row while the south half was planted every other row. The purpose of having different planting densities was to insure partial ground cover throughout the growing season and an adequate cover at starting time. It is obvious that the north half would reach full cover much earlier than the south half would, since it was planted every row. A line source sprinkler irrigation system was installed in the plot, running perpendicular to the rows. That way, the irrigation gradient would be along the rows and experimental rows could be better determined. The system had a capacity of 1.87 L/sec (29.59 gpm) with eleven 7/64 impact sprinklers, of 14VH Rainbird nozzle series, spaced 9 meters apart. The wetted diameter of each nozzle is given by the manufacturer to be 23.3 meters at 414 KPa.

In addition to the planting densities, the nature of the irrigation system allowed two replicates of the same experiment on each side of the line source (east and west). The use of the line source was to generate a water treatment gradient going from well watered, adjacent to the line to stressed, at the edges of the field.

Neutron probe access tubes were installed in the middle of each half of the plot, at the site chosen for data collection. A set of three access tubes (located 0.3, 3.3, and 9.4 meters from the line) were installed.

The data were taken generally between 11:30am and 2:00pm, preferably on calm and clear days. Totally cloudy days were also accepted but partially cloudy days or windy days were avoided. The data, collected in the order which is indicated below, consisted of the following:

> IRT1 was used to monitor composite, canopy, canopy-air difference, and soil temperatures. Those temperatures were taken with minimum amount of time lag among them so that errors caused by climatic variation (wind velocity changes, cloudiness, radiation) were minimized. Then, using the digital camera a measure of the soil cover was taken and a picture recorded on a diskett. A measurement of sky temperature using IRT1, for calculating B* (see Appendix 1), was also recorded at this time. Soil emissivity measurements were only recorded at site 2, using a thermocouple and IRT1, after all other measurements at the site had been recorded. For all measurements, the emissivity of the IRT was set at 0.99 (black body) and then

appropriate corrections made according either to an assumed emissivity (in the case of the canopy, 0.98; Jackson (1983); Idso et al. (1969)) or a calculated one (the case of soil). Since data collection proved to be time consuming and, because of other problems described later in this section, only SE and NE plots (according to Figure 1) were used in this experiment. The NE plot was only used for about 2 weeks and then abandoned since it had already reached full cover.

The problems encountered were mostly related to the starting time and the use of the digital camera. The first problem occurred when the Optic RAM chip was destroyed while trying to adapt it to a circular vision rather than rectangular as it is designed. A new chip was promptly ordered but, between ordering and installation one month elapsed. After that problem was corrected and the camera accepted without external modifications, it was then taken to the field for experimental purposes. At this time, access roads had to be dug through the field so that it would be possible to place the digital camera at a suitable distance from its target. That was one of the principal reasons why the western half of the plot was abandoned. A second major problem occurred. The camera was not able to distinguish among vegetation, shades or soileven though it had performed well under artifical lighting indoors. That problem was later attributed to light intensity. After a number of trial and error approaches it was determined that a combination of a

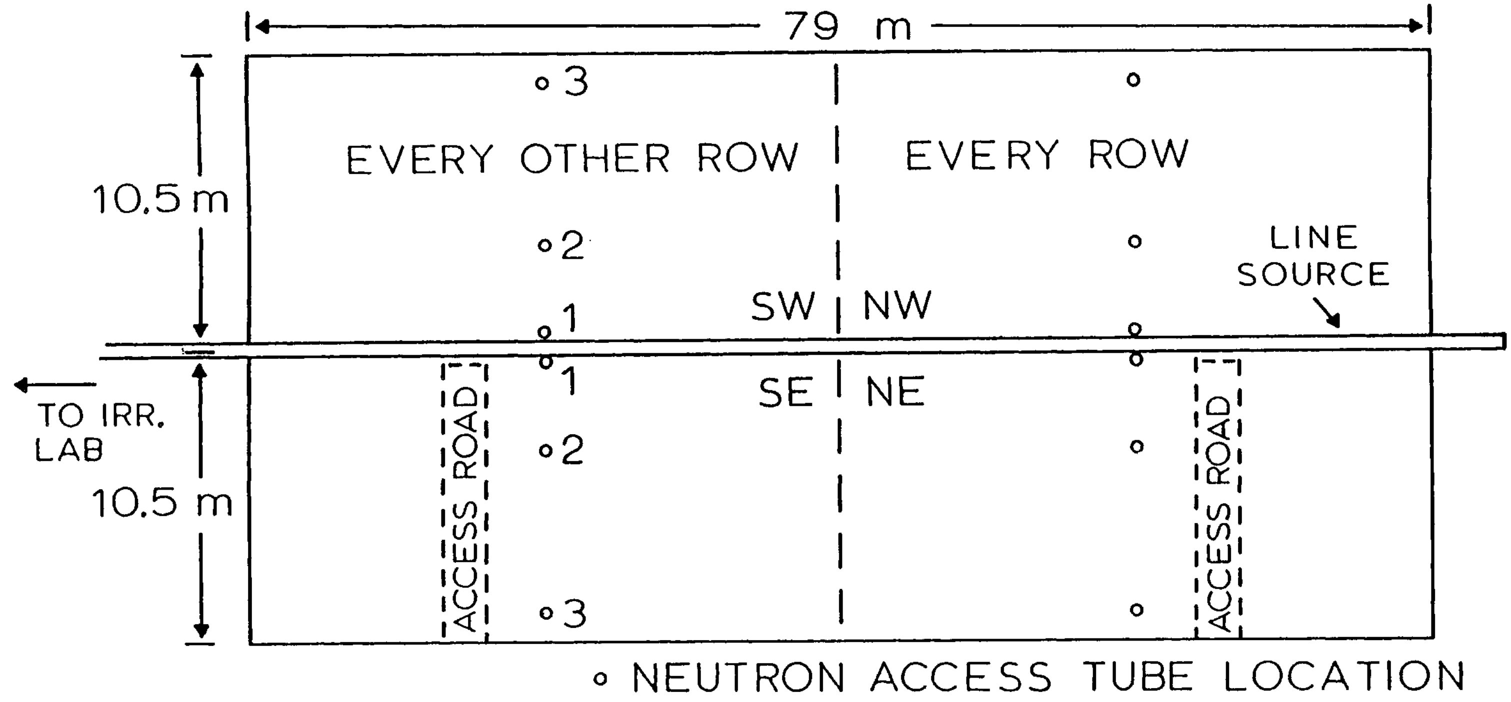

Figure 1. Field plot layout.

polarizing, a yellow, and a red filter (in that order) plus a black background against the soil (styrofoam pads) was a perfect solution.

With the camera problem solved data collection could be started. However a new problem developed. Four weeks after emergence. the plants were already too big. It was planned that data collection would start two weeks after emergence. Moreover, IRT1 and the digital camera both had very small angles of view, with IRT1 being even more limiting than the digital camera. For the camera and IRT1 to view an acceptable spot and area they had to be positioned according to the calibrations described in Appendices 2 and 4. That meant that IRT1 had to be positioned further away from target than the digital camera had to be, according to equations (A2.1) and (A4.2). At the beginning of the experiment that was not as big a problem as it later became. The plants increased in size so fast that at the later stage of data collection the digital camera and IRT1 had to be positioned respectively, 4.2 and 15.8 meters away from their target, while before they were positioned respectively, 2.1 and 8.2 meters from the same target. Since IRT1 had no sighting device, the degree of accuracy in positioning IRT1 relative to the real target was indeterminate. Therefore, the composite temperature was, in this case, being compromised, and as it will be shown later the predicted canopy temperature is very sensitive to the accuracy with which one measures the composite temperature.

In order to solve these problems it was decided that more control was needed and that the only way to accomplish that was to transfer the experiment to a laboratory environment. Thus the field experiment was terminated and a lab experiment undertaken in pots at the AETL.

At the AETL the experiment consisted of the same approach with differences introduced only in the way that the measurements were taken. Also, a second IRT, IRT2, was used. IRT2 had a much wider field of view, thus allowing a closer placement of the IRT to the plant. Since more control could be exerted on data collection at the lab, precision was being emphasized. The plants were smaller and therefore sensitive data such as canopy and composite temperature could be better monitored. It was not only possible to look at the plants vertically from above but also, to be much closer to them. Accuracy in prediction increased.

The data set collected as described above was termed AETL.1. The results started to look much better, however, they were not yet what one would expect. An investigation as to what was really causing the improvement led to the discovery of the fact that the soil temperature had a wide spatial variability. It was decided to give more attention to the soil temperature collection. A circle corresponding to the IRT's circle of view at the height from which the composite temperature was measured was then drawn on the soil and, a new approach was given to the soil data collection. For a number of days four data points were taken within this circle of view and then averaged to give a single soil temperature value. This data set was termed AETL.4A. Since preliminary analysis showed an improvement over the farm data (FARM.SE.1) and over the AETL.1 data, another set of data was then collected, one in which eight individual soil temperature measurements were taken within the circle of view and then averaged to yield a single value. That particular set was termed AETL.8A1. The results were even better. Another set of soil temperature data was also collected at this time. This set, AETL.COMP, consisted of positioning IRT2 at the site from which composite temperature was measured (same angle and distance) and, pulling the plant away from the view of the thermometer to take the reading. At this point, 10 December 1985, the experiment at AETL, which had started September the 15th was terminated.

CHAPTER 4

RESULTS AND DISCUSSION

Sensitivity Analysis

One of the objectives of this research is to analyze the sensitivity of the projected canopy temperature, using equation (4), to the other measured parameters used in its prediction.

To accomplish such a task, it was decided to vary one parameter at a time, while holding the others constant. It was chosen to vary each parameter by ±10 percent. Actual field data were used for parameters not being tested and, only points for which difference between the measured (T_m) and the predicted (T_p) canopy temperatures was either less than or equal to one degree centigrade were included in the analysis. In other words, only the most accurate data points were chosen. That gave a range of soil cover from 11 to 100 percent. Such a range will be pertinent in studying the relationship between $(T_m - T_p)$, since Heilman et al. (1981) found relatively high correlations $(r = 0.79)$ between $(T_m - T_p)$ and soil cover. The soil cover range which he used in the regression varied from about 50 to 90 percent.

Figures 2 through 5 show the parameters for which the predicted canopy temperature was sensitive. It appears that the predicted canopy temperature is highly sensitive to variations in soil and composite temperatures, and moderately sensitive to canopy cover and canopy emissivity.

Figure 2 shows the effect which a 10 percent error in estimating the canopy cover would have on the predicted canopy temperature. The trend shown implies that at very low covers the predicted temperature is not sensitive to small errors in estimating the canopy cover, but that it becomes more sensitive as the soil cover increases. It appears to become sensitive after the 40 percent cover range. Effects varied from about 0.15 and 0.26°C to about 3.24 and 2.74°C both at 30 and 69 percent cover, when canopy cover was increased and decreased by 10 percent. This trend can be explained by the fact that at very low cover small changes are masked by the larger soil area, i.e., a small change over a very small area is also very small and thus, in this case, "unaccounted" for. However, as the soil cover increases the same small change is now occurring over a much larger area which, therefore, cannot be masked and has an effect on the predicted canopy temperature. Also, as the soil cover increases, the parameter in equation (4) involving soil temperature becomes less significant. As shall be seen later on, the accuracy of the predicted temperature is highly dependent on the accuracy with which soil temperature is measured.

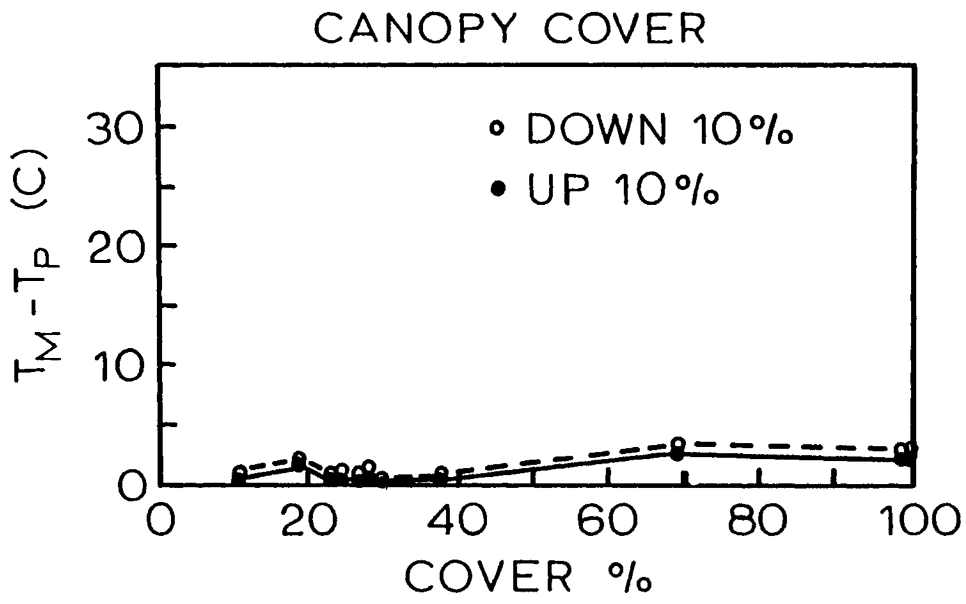

Figure 2. Sensitivity of the predicted canopy temperature to a 10 percent change in canopy cover as shown by canopy cover versus absolute value of observed minus predicted temperatures.

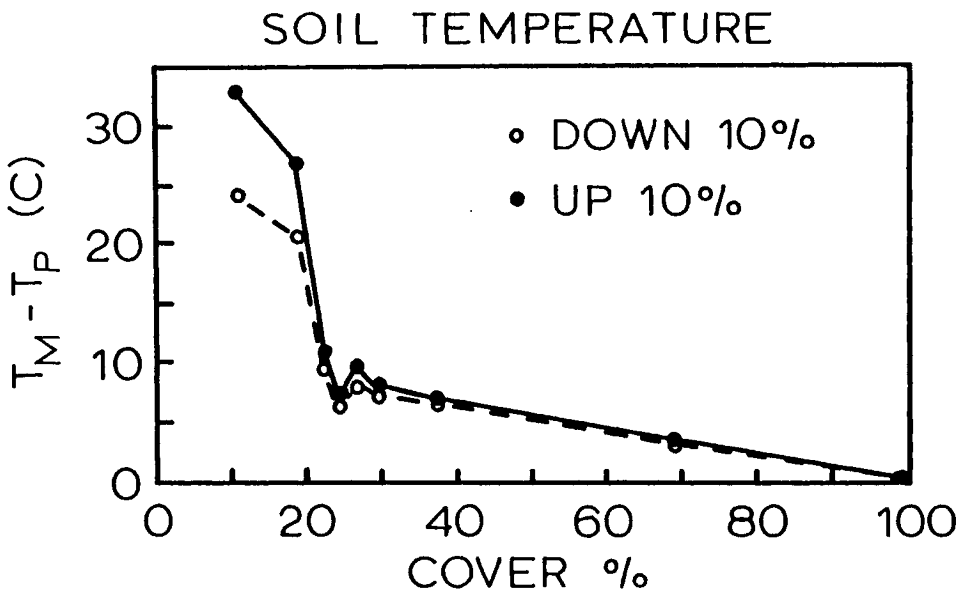

Figure 3. Sensitivity of the predicted canopy temperature to a 10 percent change in soil temperature as shown by canopy cover versus absolute value of observed minus predicted temperatures.

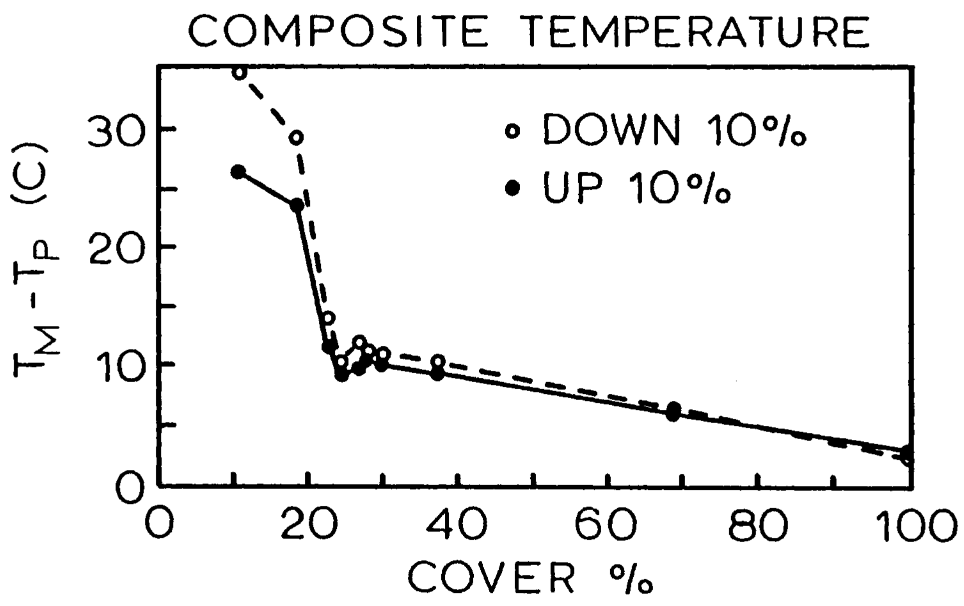

Figure 4. Sensitivity of the predicted canopy temperature to a 10 percent change in composite temperature as shown by canopy cover versus absolute value of minus predicted temperatures.

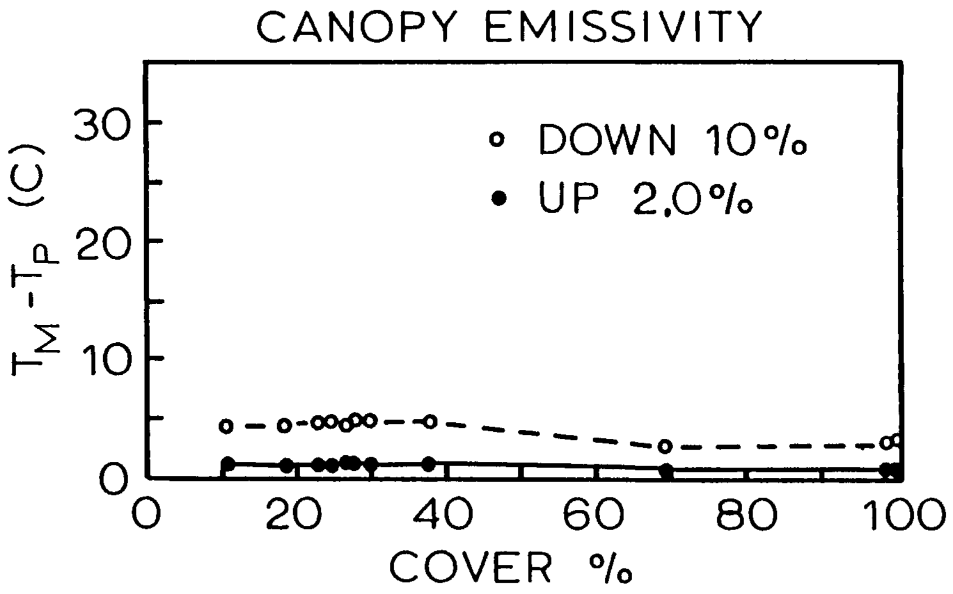

Figure 5. Sensitivity of the predicted canopy temperature to a 10 percent change in canopy emissivity as shown by canopy cover versus absolute value of observed minus predicted temperatures.

Figure 3 clearly establishes that the predicted canopy temperature is very sensitive to changes in soil temperature. Differences between observed and predicted canopy temperatures ranged from 32.78 to 0°C, respectively at 11 and 100 percent soil cover, when the soil temperature was increased by 10 percent. The range, at the same covers went from 23.99 to 0°C when the soil temperature was decreased by 10 percent. From these results it is not only clear that the predicted canopy temperature is extremely sensitive to soil temperature at very low covers, but also, it is more sensitive to overestimates than it is to underestimates. It is also obvious from Figure 3 that a sharp breakdown in the sensitivity occurs betweem 20 and 30 percent soil cover. The fact that the predicted canopy temperature is extremely sensitive to soil temperatures at very low cover can be explained by the same masking effect of the soil area over the canopy area. That can be proved by looking at the term in equation (4) involving soil temperatures. It implies that the soil temperature becomes less and less significant in the prediction of the canopy temperature, for as canopy cover increases the term goes to zero. That being true, then the break down in sensitivity at the cover range of 20 to 30 percent would be justified by some kind of equilibrium reached between soil and canopy areas, proportional to their individual effects on the prediction of the canopy cover.

The sensitivity of the predicted canopy temperature to the composite temperature is shown in Figure 4. It is somewhat similar to the effect of soil temperature. The major differences are that in this case, increasing the composite temperature by 10 percent had a smaller effect than decreasing it had on the prediction of the canopy temperature. Moreover, it is yet sensitive to changes at 100 percent cover. Sensible effects ranged from 34.64 to 2.75°C and from 26.41 to 2.76°C, respectively at 11 and 100 percent canopy cover, when the composite temperature was decreased and increased by 10 percent. It is again obvious that the predicted canopy temperature is extremely sensitive to composite temperature. The trends observed with soil temperature are also observed in this case, including the fact that the sensitivity breaks down considerably between 20 and 30 percent soil cover. The same explanations are believed to apply here.

The canopy emissivity effect, shown in Figure 5, shows an almost constant effect on the predicted canopy temperature, over the range of canopy cover studied. Although small, it appears to be a little more sensitive until about 50 to 60 percent cover. Even though the predicted canopy temperature is somewhat sensitive to changes in canopy emissivity, it appears that errors resulting from emissivity estimates would not be significant under most field conditions. That can be verified if one looks at the effect of increasing emissivity by 2.0 percent which corresponded to going from an assumed crop emissivity of 0.98 to 1.00.

The predicted canopy temperature was insensitive to either sky irradiance or soil emissivity for the ±10 percent change.

Measured Versus Predicted Canopy Temperatures

One way to study the accuracy of equation (4) is to compare the actual observed canopy temperature to that predicted by the equation. This comparison was done for all sets of data collected, using linear regression and a t-test was done on the AETL.8A1 data. With the t-test only observed canopy temperature and that predicted using the mean value of eight individual readings for soil temperature were compared. Also, the coefficient of variation for the eight soil temperature readings was calculated.

In general the linear regression shows that there is a lack of correlation between measured and predicted canopy temperatures. However, it also indicates that as the technique being used was improved, the correlation also improved, and, in some cases, significantly. Under field conditions and with only one soil temperature measurement, the correlation was 0.326, while at the lab it was 0.66, with soil temperature being the mean of eight individual measurements. Table 1 shows how the correlation improved with the technique used. The techniques have been described under methods and materials. The fact that the correlation improved with

Table 1. Correlations between observed and predicted temperature by technique used.

Technique Used	Correlation
FARM.SE.1	0.326
AETL.1	0.350
AETL.4A	0.599
AETL.COMP	0.527
AETL.8A1	0.660

technique improvement is clearly established. Figures 6-10 show the scatter in observed versus predicted canopy temperature with technique improvement for all sets of data. The solid line in these figures is a 1:1 line for which the observed canopy temperature equals the predicted canopy temperature. It is very clear from these plots that as the technique was improved, both by better measurement of the soil temperature and by moving from the field to the lab where better control was possible, the scatter around the line decreased, thus implying better accuracy.

It should be noticed that at least theoretically, the set of data AETL.COMP should have given a better prediction of the real canopy temperature than the set AETL.8A1. That proved not to be

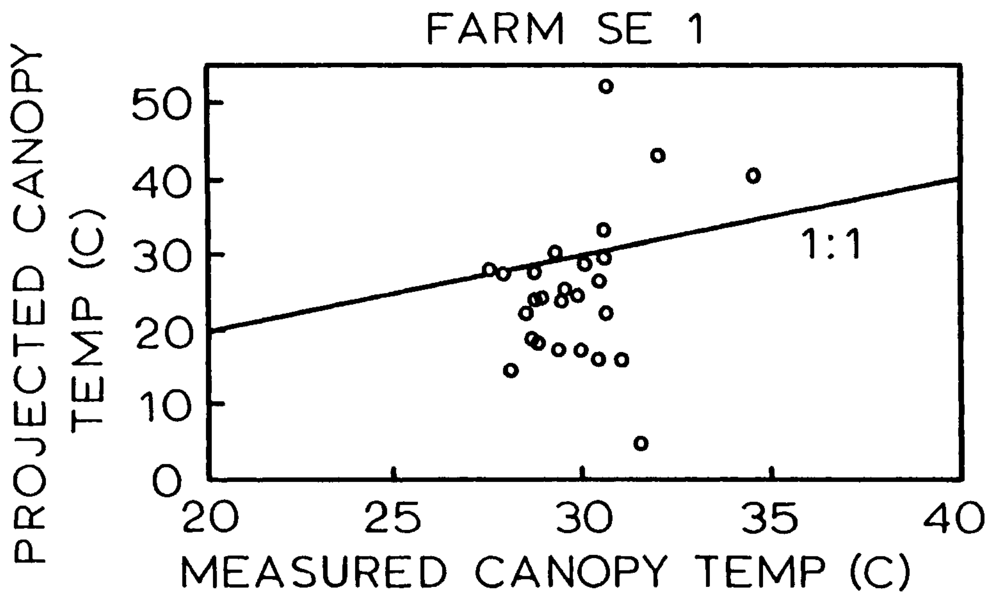

Figure 6. Relationship between observed and predicted canopy temperatures for field data (FARM.SE.1).

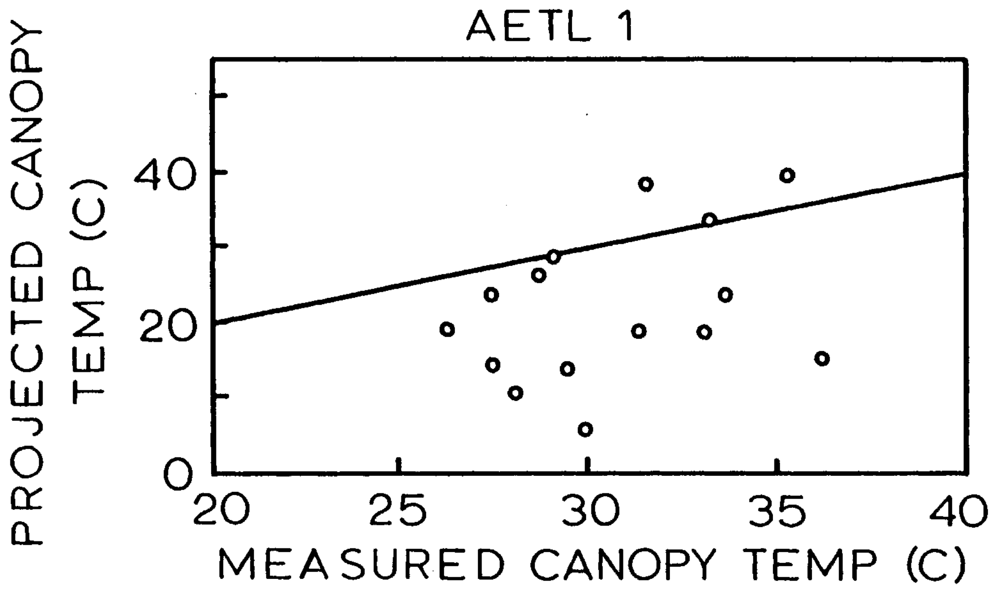

Figure 7. Relationship between observed and predicted canopy temperatures for laboratory data (AETL.L).

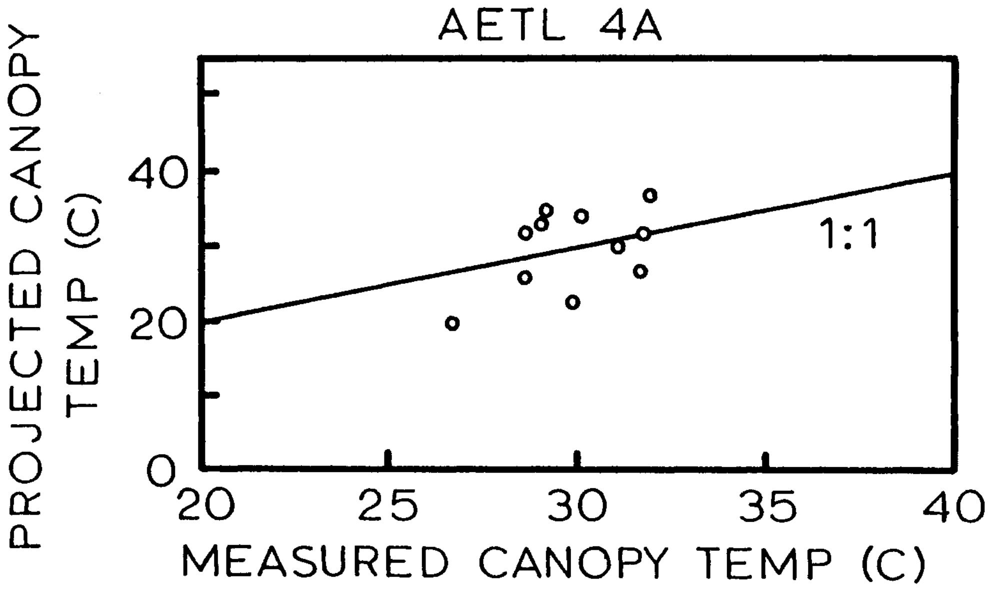

Figure 8. Relationship between observed and predicted canopy temperatures data (ATEL.4).

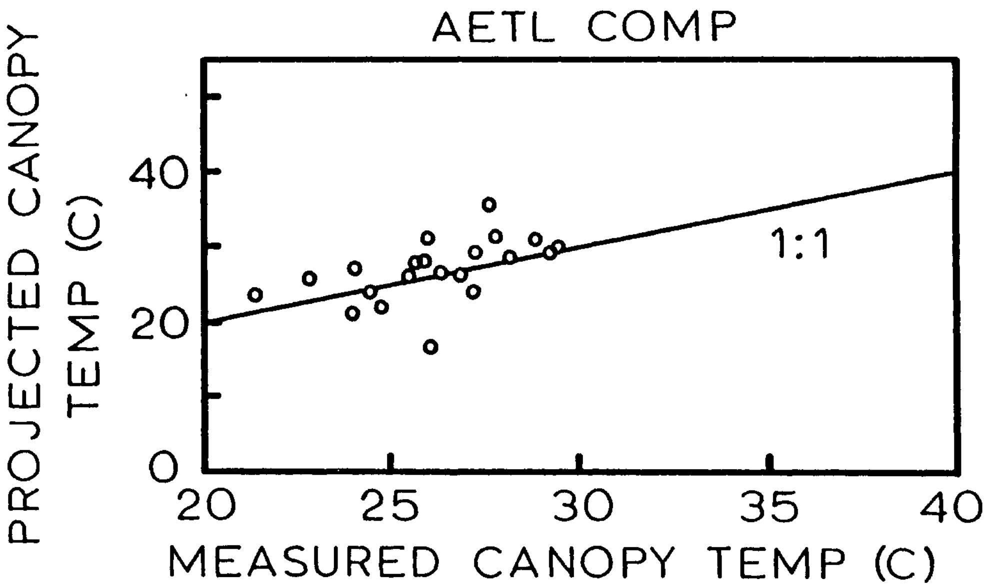

Figure 9. Relationship between observed and predicted canopy temperatures for laboratory data (AETL.COMP).

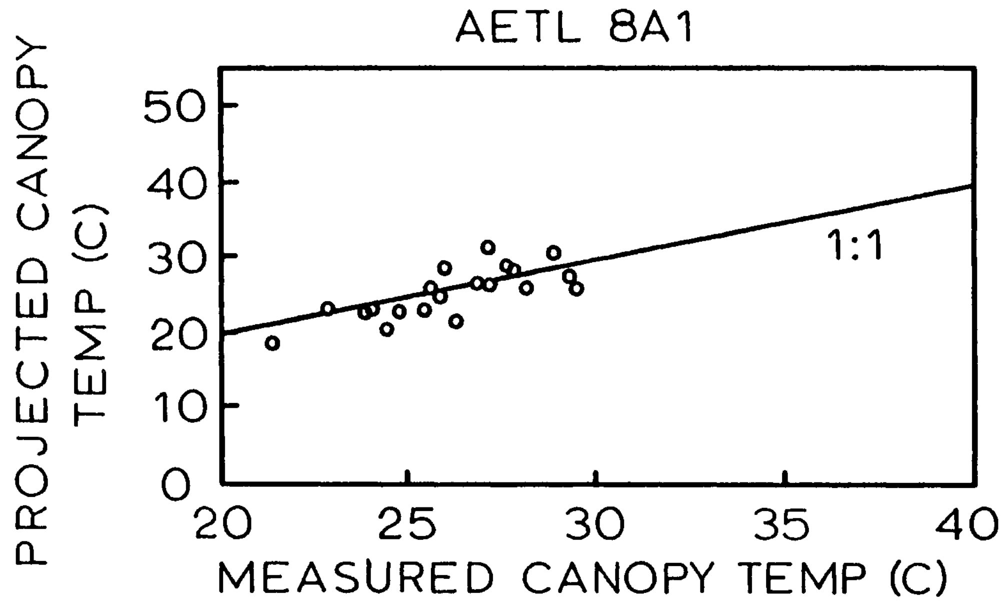

Figure 10. Relationship between observed and predicted canopy temperatures for laboratory data (AETL.8A1).

true. An explanation for that is the fact that the shadow of the plant changed the actual soil temperature, and, while one is measuring the composite temperature of plant and soil, the IRT does not see the soil underlying the plant. This implies that the eight individual measurements of soil temperature around the plant should be a better estimate of the soil temperature, since that more closely represents what is "actually" seen by the IRT. That should explain the lower correlation of the AETL.COMP data compared to the AETL.8A1 data. The correlation between the measured and predicted temperatures is 0.527 for the AETL.COMP data and 0.66 for the AETL.8A1 data (Table 1).

Table 2 is a summary of the t-test at three levels of significance. It shows the number of times that the test was either accepted or rejected at each level. The hypothesis tested was that the measured canopy temperature is different from that predicted by equation (4) using mean soil temperature. At the 95 percent level of confidence the null hypothesis was rejected only about 55 percent of the time for which it was tested. That means that for the sets of data studied 55 percent of the time the predicted canopy temperature can be statistically considered equal to that observed in the field. That does not look very promising if one is to rely on this approach for irrigation scheduling. It should be

Table 2. Rejections and acceptances of null hypothesis at three confidence levels.

	Confidence Levels		
	90	95	99
accepted	7	9	17
rejected	13	11	3

noticed that at the 90 percent level of confidence the results do not appear to be much better than those at the 95 percent level of confidence. At the 90 percent level of confidence, the null hypothesis was rejected 65 percent of the time, compared to 55 percent of the time at the 95 percent level of confidence. That, in this particular case, does not imply a significant improvement since, if this was used for irrigation scheduling, one would probably be wrong in predicting the stress condition of the crop 35 percent of the times. I believe this strengthens what has previously been found, that the predicted canopy temperature is extremely sensitive to the accuracy with which one measures the soil temperature.

Although the approach does not look very promising, there may still be hope. Previous analysis showed that prediction accuracy improved considerably with technique improvement, in spite of the fact that the improvement made the technique less practical. The analysis of the soil temperature data can also be of some importance here. The coefficient of the variation was calculated for each set of data collected for the AETL.8A1 data set. It indicated variation ranging from 2.31 to 16.4 percent. If this is added to the fact that the predicted canopy temperature is highly sensitive to variations in soil temperature, then, the variation pointed out above can explain the low rate of rejection of the null hypothesis. This implies that in order to better predict canopy temperature there has to be a more accurate way of measuring soil temperature.

In addition to the above analysis, differences between observed and predicted canopy temperatures were regressed on the canopy cover. Heilman et al. (1981) did a similar analysis and found a correlation coefficient of 0.79. However, his studies were done only on high canopy covers; ranging between about 50 to 90 percent. In this case the range varied from set to set with an overall variation from 7 to 100 percent cover. This in reality should yield a better understanding of prediction accuracy with canopy cover. Table 3 shows the range, set and correlation found for each set.

Table 3. Canopy cover range versus correlation coefficient for each set of data (technique).

Data Set	Canopy Cover Range - %	Correlation Coefficient
FARM.SE.1	38 - 100	0.588
AETL.1	7 - 27	0.544
AETL.4A	17 - 44	0.579
AETL.COMP	22 - 30	0.397
AETL.8A1	22 - 30	0.098

In agreement with Heilman et al. (1981), in this study higher correlation coefficients were associated with higher canopy cover (0.588 for the FARM.SE.1 data set which has a range of cover from 38 to 100 percent). The set corresponding to AETL.8A1 although considered the best set of data from the standpoint of accuracy shows the smallest correlation coefficient (0.098 with a range of cover from 22 to 30 percent). This low correlation can be explained in spite of the fact that the data shows the greatest accuracy. Thus the low correlation can be attributed to the fact that the 20 data points are all clustered in a very small range of canopy cover.

Figures 11 through 15 show the scatter of points for the two cases mentioned above. it should be noticed that whereas Figure 11

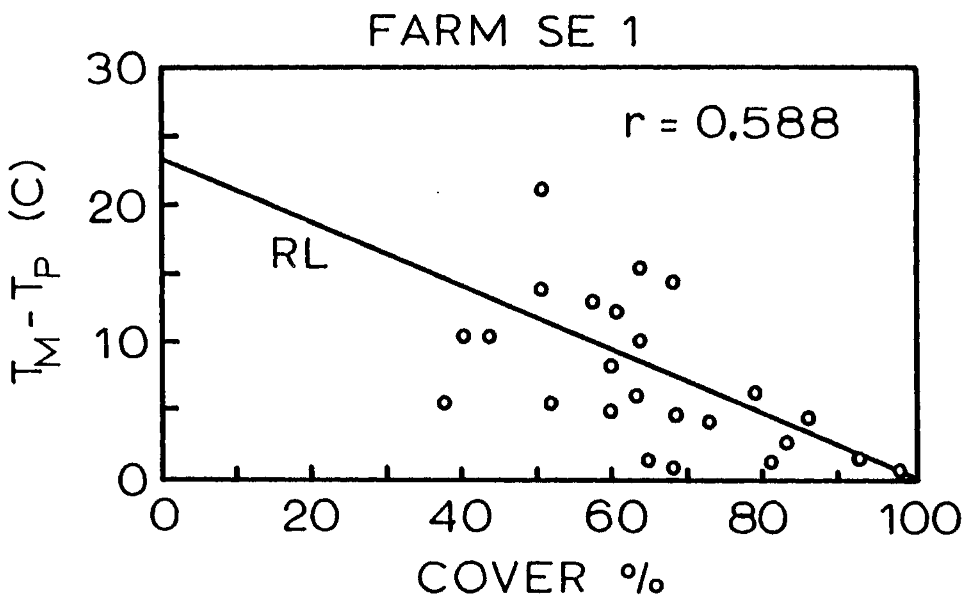

Figure 11. Relationship between canopy cover and absolute value of observed minus predicted canopy temperatures for field data (FARM.SE.1).

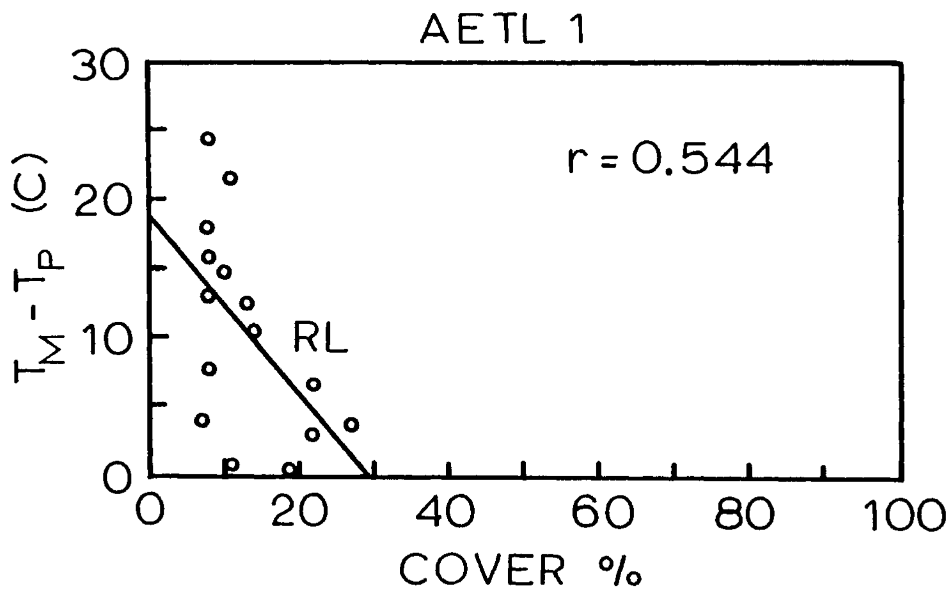

Figure 12. Relationship between canopy cover and absolute value of observed minus predicted canopy temperatures for laboratory data (ATEL.1).

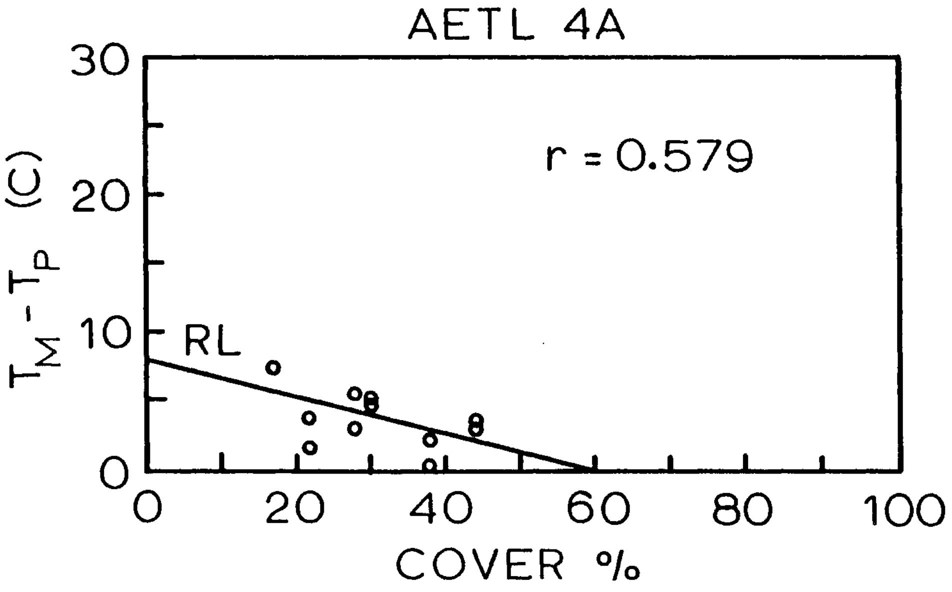

Figure 13. Relationship between canopy cover and absolute value of observed minus predicted canopy temperatures for laboratory data (AETL.4).

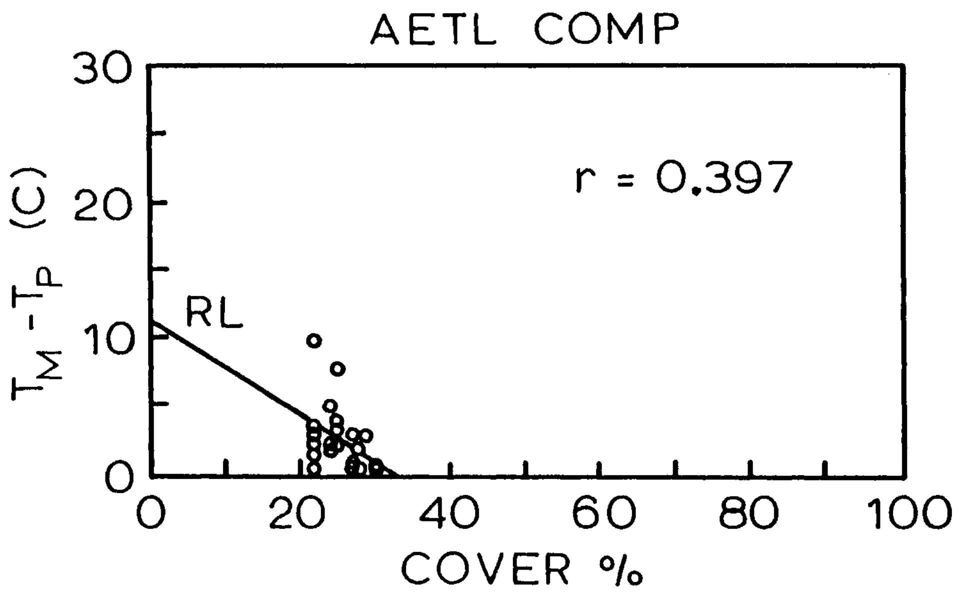

Figure 14. Relationship between canopy cover and absolute value of observed minus predicted canopy temperatures for laboratory data (AETL.COMP).

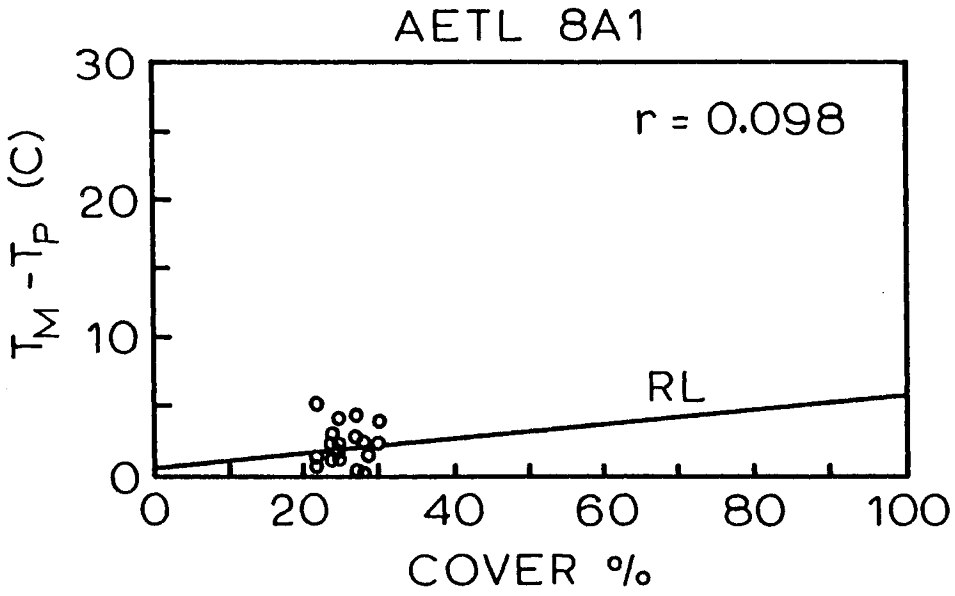

Figure 15. Relationship between canopy cover and absolute value of observed minus predicted canopy temperatures for laboratory data (AETL.8A1).

allows the assessment of the variation of predicted temperature with canopy cover, Figure 15 although limited in range of cover demonstrates the accuracy attainable.

Crop Water Stress Index

Partial Cover. The empirical approach of Idso et al. (1981) has been used to develop Figure 16 which shows the unstressed and stressed baselines for CWSI calculation purposes. Data from the FARM.SE.1 and from the AETL.8A1 sets were chosen to plot the figure. Canopy-air temperature difference was regressed upon VPD, thus defining an unstressed baseline with a slope of -2.00 and an intercept of 2.34. The correlation coefficient was 0.854.

CWSI is a plant based technique which uses plant temperature to characterize the water status of a particular crop. Depending on which approach one uses, i.e., the empirical (Idso et al., 1981) or the theoretical (Jackson et al., 1981), the required input varies. The empirical approach requires an estimate of canopy-air temperature difference and vapor pressure deficit, while the theoretical approach requires that plus an estimate of the net radiation, canopy and aerodynamic resistances.

Theoretically, the two sets of data used in the development of the unstressed baseline are a little different since at the farm there was a canopy while at the lab there were only individual plants. The difference comes from the fact that under the same conditions an individual plant is exposed to a much higher radiation

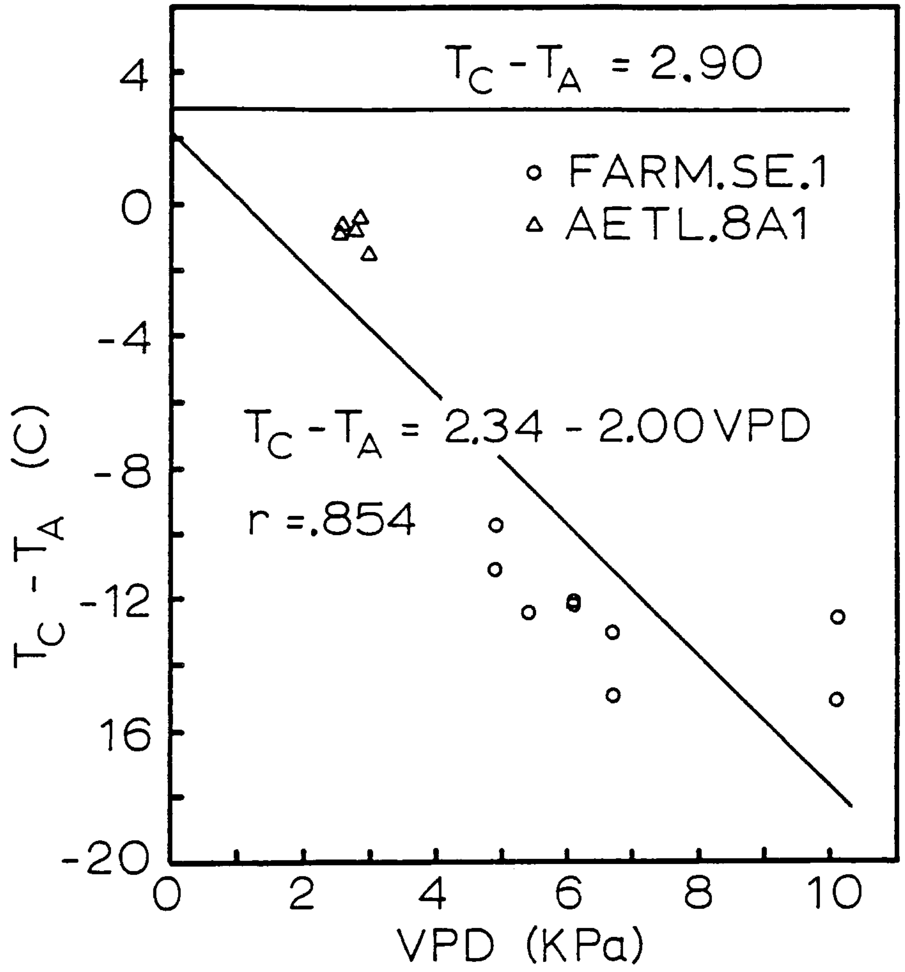

Figure 16. VPD versus Canopy-air temperature difference for partial field and laboratory data.

load than a canopy is. The reflected long and short wave radiation is greater for a single plant than it is for a group of plants. Therefore, if the case is that of a single plant, the single plant should be warmer than a canopy. Also differences should arise in canopy-air resistances. Theoretically, the canopy-air resistance, or leaf-air resistance, should be less in a single plant than what it is in a canopy. The single leaf is much more exposed to the wind and atmosphere than a canopy is. However, with that in mind, and since a suitable range of VPD was needed for the unstressed baseline, it was decided appropriate to plot the two sets of data together. Notice that the parameters calculated from the regression analysis for the unstressed baseline are in agreement with those reported by Idso et al. (1981) for cotton grown in Phoenix, Arizona. They reported a slope of -2.09 and an intercept of 1.49 for cotton at full cover. The small differences have been explained by researchers such as Hatfield et al. (1985) and Wanjura et al. (1984) who have found the canopy under partial cover to be warmer than that under full cover. That is what is represented by a shallower slope and a higher intercept.

Tables F7 and F8 show the calculated CWSI values for the FARM.SE.1 data and the AETL.8A1 data. In Table F7 CWSI values range from -0.35 to 0.69, with the majority of the points falling in the range of -0.35 to 0.0. Table F8 shows values ranging from 0.28 to 1.34. Even though some values are negative, the nature of the development of the CWSI concept only allows for values falling on the range 0.0 to 1.0 (Jackson et al., 1981). Negative values of CWSI have been reported by Wanjura et al. (1984).

To explain the negative values of CWSI reference to Figure 16 should be very helpful. The variability associated with the data used to plot the unstressed baseline should explain part of the reason why there were negative values of CWSI, since one would expect actual measured points to fall both below and over the line. Points falling over would give positive values while those falling below would give negative values. Other factors contributing to negative estimates of CWSI values would be erroneous measurements of canopy and air temperatures, as well as relative humidity. This is in agreement with the findings of Wanjura et al. (1984).

Values of CWSI greater than 1.0 are possible mainly due to erroneous estimate of the upper baseline as well as canopy and air temperature. The approach used in this case to determine the fully stressed baseline is that of Idso et al. (1981) which does not take into account radiation load on the plant. Their fully stressed baseline is mainly a function of air temperature. Jackson et al. (1981) as well as Geiser et al. (1982), using different approaches have shown that canopy-air temperature difference is sensitive to radiation changes. Had we used Jackson method to calculate both the unstressed and stressed baselines, it is possible that the discrepancies would be less. However, Idso et al. approach was preferred due to a lack of sufficient data to calculate resistances needed for the Jackson et al. approach.

Full Cover. Table F9 is a report of CWSI values calculated for the full cover situation. Likewise, they were calculated using the Idso et al. approach, using the reported parameters, by Idso et al. (1982), for an unstressed baseline for cotton with full cover. The reported parameters are a slope of -2.09 and an intercept of 1.49°C. No values greater than 1.0 resulted but values smaller than 0.0 were found. In this case, I believe that the negative values are not so much a function of variability in the unstressed baseline as it is due to errors in estimating canopy-air temperature difference and probably, in accordance with Wanjura et al. (1984), due to genetic and site differences. Idso et al. (1982) developed their reported unstressed baseline from 181 data points while Wanjura et al. (1984) and the one here were developed from 16 and 14 data points respectively. There is no doubt that in two latter cases the variability is greater and thus more important than it would be with the Idso et al. (1982) line.

CHAPTER 5

SUMMARY AND CONCLUSIONS

The sensitivity of the predicted canopy temperature to the parameters used in its determination, such as, canopy cover, soil temperature, composite temperature, and canopy emissivity has been shown. That has been found to be in agreement with Matthias et al. (1986) who found that calculated component temperatures were highly sensitive to composite scene temperatures, moderately sensitive to emissivity and component area estimates and relatively insensitive to variability inatmospheric long-wave radiation.

Researchers like Hatfield et al. (1985) have suggested that what might be responsible for variations between observed and predicted canopy temperatures are roughness length and displacement heights. They explain that in partial canopy situations those factors might be "larger than predicted by values often used in energy balance studies". In partial canopy situations variation between observed and predicted canopy temperatures appears to be due to spatial variation in component temperature measurements and a stronger radiation load rather than aerodynamic relationships between plants and atmosphere. That is not to mean that prediction accuracy is insensitive to plant aerodynamic resistances but rather it means that under partial canopy situations the sensitivity of the predicted canopy temperature to plant aerodynamic resistances is small when compared to other factors being studied here, such as soil and composite temperatures. Nonetheless, such a claim would need a much more detailed field study in which aerodynamic relationships would be included and effects on the prediction of canopy temperature studied in relation to other factors such as composite and soil temperature. Soil temperature variabilities of up to 16 percent were found under laboratory pots, and one would expect that under field conditions variability would be even greater.

CWSI values were calculated for full and partial canopy situations, in both cases using the Idso et al. (1982) approach. The results were discouraging since negative values and values considerably greater than one were found. As has been stated, such discrepancies might be due to errors in measuring canopy and air temperature and also variability in the data used to estimate the unstressed baseline and an erroneous estimate of the fully stressed baseline by the Idso et al. approach. Another error probably introduced in the calculations is the fact that mixed data from FARM.SE.1 and AETL.8A were used to determine the unstressed baseline.

From this study it was concluded that:

1. Predicted canopy temperatures using equation (4) were highly sensitive to composite and soil temperatures, moderately sensitive to canopy cover and canopy emissivity, and not

sensitive to soil emissivity and B* at the 10 percent change studied.

2. It is possible that canopy temperature can be extracted from composite scene temperatures, as shown by technique improvement in this study. However, the approach might be so complicated that it will not be practical for irrigation scheduling by farmers.
3. It may not be possible to reliably characterize the water status of a canopy under partial cover using the CWSI method. Negative values and values greater than 1.0 were found using the Idso et al. approach.
4. Before infrared thermometry can lend itself to irrigation scheduling in partial canopy situations, more extensive research should be completed. Spatial as well as temporal variability of the parameters used in predicting canopy temperatures have to be studied and understood. Techniques need to be perfected and yet made simple so that IRT's can be used by farmers. Thus far, as it appears techniques will be so complicated that the approach will be considered unpractical by farmers for the chores of irrigation scheduling.

My recommendation would be that if another study is to be done on this subject it should be very extensive. It should be one in which not a single parameter already known to be a factor in extracting canopy temperatures from composite scenes (such as soil temperature, composite temperature, aerodynamic resistances radiation loads, wind and others) will be left out. That way, the viability of the approach could be defined.

APPENDIX A

CALIBRATING IRT1 FOR NEGATIVE TEMPERATURES

IRT1 is factory calibrated to measure temperatures in the range of -30 to 100°C. However, in this experiment measurement of temperatures with magnitude less than negative 30°C was needed. It was necessary to measure sky temperature which was sometimes much smaller than that. Therefore, in order to make such measurements the thermometer should be calibrated for such temperatures.

A two point calibration was chosen, using dry ice and ice water. Ice water should have a temperature of 0.0°C while dry ice should have a temperature of -56.9°C (ASHRAE Handbook).

A small metal container with dimensions 15.5 × 15.5 × 10.2 cm, painted with flat black paint, was placed on top of a red brick inside a medium size styrofoam cooler and the lid put on. A hole with side dimensions equaling those of the infrared thermometer was cut through one of the smaller sides of the stryorfoam cooler so that the thermometer could be inserted through it and measure the temperature of the metal container. The metal container was placed such that it was about 10 cm from the infrared thermometer and its center about 8 cm from the bottom of the cooler. With an emissivity set at 0.99 (that of black body) the metal box was filled with one of the elements and allowed to stabilize. The temperature was monitored every five minutes and determined stable when no sensible change was noticed between readings. This procedure was first done with dry ice and then with ice water. The dry ice appeared to stabilize at -55.3°C, 130 minutes after it had been placed in the metal container, while ice water appeared to stabilize at -0.2°C, 39 minutes after it had been placed in the container. The time difference is probably because dry ice only had direct contact with the container in very small areas while ice water had total contact with the container.

The two pairs of points (0.0,-0.2) and (-56.9,-55.3) then defined a straight line from which temperatures could be extrapolated. That is, by measuring any negative temperature between -0.2 and -55.3°C, the "actual" temperature could then be extrapolated from this line ranging between 0.0 and -56.9°C. The mathematical parameters that define the line are:

slope = 1.0327
constant = 0.2065

with the equation taking the form:

$$T_a = 1.0327 \times T_m + 0.2065 \qquad \text{(A1)}$$

where T_m is actual temperature (°C) and T_m is the measured temperature (°C).

APPENDIX B

CALIBRATING IRT1 FOR AREA VERSUS DISTANCE

In spite of the fact that IRT1 is manufacturer calibrated for an angle of view of 3 degree solid angle, it was recalibrated not only as a check but also to get an area versus distance relationship.

A very simple procedure was used and is described herein. The infrared thermometer was mounted on a tripod looking vertically down. A sheet of plywood was placed under the tripod and the thermometer. A small level and a plumb were used to assure the vertical position of the thermometer and to get an approximation of the center point on the sheet of plywood. Lines were drawn through that point. Distances were measured from the tip of the thermometer. A small hot soldering iron was then moved on the plywood, over the lines, from the outside to determine the point where the thermometer would start "seeing" the soldering iron. The point was determined by quick jumps in the actual temperature reading of the thermometer. That point was marked and the procedure repeated 3 more times for each case. Table A2.1 gives the distance of the thermometer from the plywood and the average radius (distance from center to the point where IRT sensed the soldering iron) all in centimeters.

Table B1. IRT1 calibration data for distance versus area.

Distance cm	radius cm	Area cm
42.3	2.3	16.62
42.3	2.2	15.21
110.8	3.5	37.39
150.9	4.2	55.42

The distance was then regressed on the area to yield the following parameters:

constant = 0.50 cm
slope = 0.35 cm^2/cm
r = 0.996

defining the following equation,

$$A = 0.50 + 0.35 \times D \qquad (B1)$$

where A is area (cm^2) and D is distance from target (cm), measured from the end tip of IRT.

APPENDIX C

CALIBRATING IR1 AND IRT2

The need for using IRT2 at AETL implied that IRT1 and IRT2 had to be standardized, since temperatures were going to be monitored with both. It is possible that they will not read the same temperature from the same body.

A two point calibration was again chosen, with the references now being ice water and boiling water. The approach taken was somewhat different from that of calibrating IRT1 for negative temperatures. In this case there were two containers; one continually boiling water and another not too far away from that with ice water. By holding both thermometers at the same time, and pointing them at an angle of about 60 degrees with the horizontal, to avoid steam from condensing on the thermometer, the temperature of the boiling water was read with both thermometers. The measurements of the ice water were taken alternating with boiling water in the same fashion. A total of 10 pairs of data were collected for each case. Table C3.1 reports the data.

Table C1. IRT1 and IRT2 calibration data.

Temperatures are in degrees celsius.

Ice Water		Boiling Water	
IRT2	IRT1	IRT2	IRT1
-0.5	-0.5	92.2	92.2
-0.7	-0.4	92.0	92.3
-1.1	-0.3	93.9	93.4
-1.4	-0.3	91.7	91.5
-1.5	-0.4	92.6	91.7
-1.6	-0.4	93.0	92.4
-1.4	-0.5	91.9	91.5
-1.5	-0.4	94.0	92.5
-1.6	-0.4	94.5	93.4
-1.7	-0.5	94.7	93.8

IRT1 data was then regressed on IRT2 data yielding the following parameters:

constant = -0.8849 °C

slope = 1.0159 °C/°C

r = 0.99995

therefore defining an equation relating IRT1 measured temperature to an IRT2 temperature of the following form,

$$IRT2 = -0.8849 + 1.0159 \times IRT1 \qquad (C1)$$

where IRT1 is the measured temperature and IRT2 is the corresponding extrapolated temperature, both in celsius. The extrapolated temperature of IRT2 was then used in the calculations.

APPENDIX D

CALIBRATING THE DIGITAL CAMERA (DC) FOR AREA VERSUS DISTANCE

Like IRT1, the DC had to also be calibrated for area versus distance, since there was no manufacturers information available on the characteristics of the lens.

In this case, two small rectangles of area 3.95 and 20.70 square centimeters were drawn on a white sheet of paper and painted black. The paper was placed against a bright wall. The DC was mounted on a tripod with its center standing at the same height as that of the rectangle on the wall. At each measurement only one rectangle was used. To vary distances at which readings with the DC were taken, the tripod was moved perpendicularly to the wall and away from it. The data in Table D1 was obtained.

The way the camera "sees" each part is that the black rectangle is black and the rest is light, which is what is reported through the software. The total area seen by the camera is calculated by the equation,

$$A = a/(1 - x) \qquad \text{(D1)}$$

where A is the area in, cm^2, a is the rectangular black area, cm^2, and x is the light percentage reported.

Table D1. DC area versus distance calibration data.

Target Area cm^2	Distance cm (in)	Light %	Total area cm^2
3.95	20.32 (8)	77	17.7
	22.86 (9)	81	20.80
	25.40(10)	84	24.69
	27.94(11)	87	30.38
	30.48(12)	89	35.91
20.70	63.50(25)	85	138.00
	67.95(26.75)	88	172.50
	180.66(71.13)	91	230.00
	220.98(87)	93	295.71

The distance from DC to the target was then regressed on the area yielding the following parameters:

constant = 9.46 cm^2
slope = 1.33 cm^2/cm
r = 0.947

with the equation relating area and distance defined as,

$$A = 9.46 + 1.33 \times D \qquad \text{(D2)}$$

where A is as above and D is distance, cm.

APPENDIX E

NEUTRON PROBE CALIBRATION

The neutron probe was calibrated using the count ratio method to measure the soil water content for the first 90 centimeters. The bulk density of the soil was approximated to 1.47 gm/cm^3 and the standard count of the probe was measured to be 17,760. Table A5.1 gives the measuring sites, the neutron probe count, the ratio and the gravimetric water content of the same sites.

The water content, measured gravimetrically, was regressed on the count ratio to yield the following equation which relates depth of water per 30 cm to the count ratio of the neutron probe:

$$Y = 3.1379 + 8.7497 \times X \qquad \text{(E1)}$$

where Y is the water content in cm per 30 cm and X is count ratio. The data used in this regression does not include the top 30 cm data. The top 30 cm was monitored gravimetrically. The correlation coefficient for the above equation is 0.870.

Table E1. Neutron probe calibration data.

SE2.3 corresponds to the south-east plot, second site at 90 cm (3 foot) depth.

Site	Ratio	Water content cm/30 cm
SE1.1	0.8333	9.71
SE1.2	1.2246	6.89
SE2.3	1.1715	7.62
SE2.1	0.8777	10.19
SE2.2	1.2324	8.03
SE2.3	0.8089	2.59
SE3.1	0.6347	6.33
SE3.2	1.0322	7.21
SE3.3	0.5954	2.10
SW1.1	0.7230	8.67
SW1.2	1.2916	8.78
SW1.3	0.9814	2.37
SW2.1	0.6066	6.88
SW2.2	1.1562	6.88
SW2.3	0.6331	1.73
SW3.1	0.4146	4.85
SW3.2	0.9810	7.35
SW3.3	0.5859	2.44
NE1.1	0.5875	7.15
NE1.2	1.1996	6.99
NE1.3	1.0085	6.42
NE2.1	0.5843	7.88
NE2.2	1.2067	6.24
NE2.3	0.9396	6.76
NE3.1	0.3264	4.13
NE3.2	0.9092	4.00
NE3.3	0.6056	2.71

APPENDIX F

TABLES OF RESULTS

This Appendix contains tables of the analysis done in this study. Table F1 is a table of the sensitivity analysis according to the parameter being varied at that particular time. Tables F2 through F7 are tables from which plots of percent cover versus the absolute difference between projected and measured canopy temperature were developed, as well as plots of measured versus projected canopy temperatures. Tables F8 through F9 show the results of the CWSI analysis.

Table F1. Sensitivity analysis of equation (4) to its parameters.

The change studied on each parameter was of 10 percent.

Effect of Canopy Cover

No.	PROJ-C	PROJ.UP-C	PROJ.LO-C
1	30.1	32.8	26.8
2	27.1	29.2	24.5
3	27.9	29.9	25.3
4	28.5	28.9	28.0
5	33.2	34.6	31.6
6	31.6	32.2	30.9
7	26.1	26.5	25.5
8	25.8	26.3	25.1
9	24.0	24.5	23.4
10	28.8	29.1	28.4
11	28.3	28.5	27.9
12	29.6	29.8	29.4
13	28.7	28.2	29.2
14	28.2	28.4	28.0
15	25.7	26.2	25.2
16	26.4	26.6	26.0
17	22.9	23.4	22.3

Table F1. Sensitivity analysis of equation (4) to its parameters. The change studied on each parameter was of 10 percent.

Effect of Emissivity of Soil

No.	PROJ-C	PROJ.UP-C	PROJ.LO-C
1	30.1	30.1	30.1
2	27.1	27.1	27.1
3	27.9	27.9	27.9
4	28.5	28.5	28.5
5	33.2	33.2	33.2
6	31.6	31.6	31.6
7	26.1	26.1	26.1
8	25.8	25.8	25.8
9	24.0	24.0	24.0
10	28.8	28.8	28.8
11	28.3	28.3	28.3
12	29.6	29.6	29.6
13	28.7	28.7	28.7
14	28.2	28.2	28.2
15	25.7	25.7	25.7
16	26.4	26.4	26.4
17	22.9	22.9	22.9

Table F1. Sensitivity analysis of equation (4) to its parameters. The change studied on each parameter was of 10 percent.

Effect of Soil Temperature

No.	PROJ-C	PROJ.UP-C	PROJ.LO-C
1	30.1	26.7	33.2
2	27.1	27.1	27.2
3	27.9	27.9	27.9
4	28.5	-4.3	52.4
5	33,2	6.4	53.6
6	31.6	24.7	37.9
7	26.1	14.5	36.1
8	25.8	16.1	34.3
9	24.0	15.2	31.8
10	28.8	20.6	36.2
11	28.3	19.5	36.1
12	29.6	21.8	36.7
13	28.7	21.6	35.1
14	28.2	17.2	37.9
15	25.7	17.0	33.5
16	26.4	15.6	35.8
17	22.9	14.5	30.5

Table F1. Sensitivity analysis of equation (4) to its parameters. The change studied on each parameter was of 10 percent.

Effect of Sky Temperature (BSTAR)

No.	PROJ-C	PROJ.UP-C	PROJ.LO-C
1	30.1	30.1	30.1
2	27.1	27.1	27.1
3	27.9	27.9	27.8
4	28.5	28.5	28.4
5	33.2	33.3	33.2
6	31.6	31.7	31.6
7	26.1	26.1	26.0
8	25.8	25.8	25.7
9	24.0	24.0	23.9
10	28.8	28.8	28.8
11	28.3	28.3	28.2
12	29.6	29.6	29.6
13	28.7	28.7	28.6
14	28.2	28.3	28.2
15	25.7	25.8	25.7
16	16.4	26.4	26.3
17	22.9	23.0	22.9

Table F1. Sensitivity analysis of equation (4) to its parameters. The change studied on each parameter was of 10 percent.

Effect of Composite Temperature (Total Radiation)

No.	PROJ-C	PROJ.UP-C	PROJ.LO-C
1	30.1	36.2	23.9
2	27.1	29.9	24.4
3	27.9	30.6	25.1
4	28.5	54.9	-6.2
5	33.2	56.8	4.0
6	31.6	40.9	21.8
7	26.1	38.5	12.3
8	25.8	36.6	13.9
9	24.0	34.0	13.2
10	28.8	38.9	18.0
11	28.3	38.7	17.0
12	29.6	39.4	19.1
13	28.7	37.7	19.0
14	28.2	40.5	14.8
15	25.7	35.9	14.7
16	26.4	38.1	13.4
17	22.9	32.5	12.6

Table F1. Sensitivity analysis of equation (4) to its parameters. The change studied on each parameter was of 10 percent.

Effect of Canopy Emissivity

No.	PROJ-C	PROJ.UP-C	PROJ.LO-C
1	30.1	29.5	32.8
2	27.1	26.4	30.1
3	27.9	27.2	30.9
4	28.5	27.5	32.8
5	33.2	32.2	37.8
6	31.6	30.5	36.3
7	26.1	25.0	30.7
8	25.8	24.7	30.4
9	24.0	22.9	28.5
10	28.8	27.7	33.6
11	28.3	27.2	33.0
12	29.6	28.5	34.4
13	28.7	27.6	33.3
14	28.2	27.2	32.9
15	25.7	24.6	30.4
16	26.4	25.3	31.0
17	22.9	21.8	27.7

Table F2. Analysis of field data, FARM.SE.1

No.	cover %	Measured °C	Projected °C
1	40	32.1	42.7
2	52	34.6	40.1
3	51	30.7	51.8
4	44	28.8	18.2
5	61	28.8	24.0
6	38	29.9	24.3
7	74	30.4	26.4
8	79	28.5	22.2
9	69	29.3	30.1
10	82	28.8	27.5
11	94	30.1	28.5
12	84	30.6	33.1
13	99	27.9	27.1
14	100	27.6	27.9
15	86	29.6	25.1
16	51	28.2	14.3
17	50	31.6	4.6
18	68	29.0	24.2
19	62	29.4	27.1
20	68	30.4	15.9
21	63	29.5	23.5
22	64	28.7	18.4
23	64	31.0	15.7
24	66	30.6	29.2
25	61	30.6	22.2
26	58	30.0	16.9

Table F3. Analysis of laboratory data, AETL.1

No.	cover %	Measured °C	Projected °C
1	23	31/6	39.0
2	27	35.4	39.1
3	9	29.5	13.7
4	7	27.5	23.5
5	9	26.3	18.6
6	8	27.5	14.5
7	9	28.1	10.2
8	22	28.7	25.9
9	14	33.7	23.5
10	11	29.1	28.5
11	13	32.4	18.9
12	10	33.1	18.4
13	19	33.3	33.2
14	11	36.2	14.7
15	9	29.9	5.7

Table F4. Analysis of laboratory data, AETL.4

No.	cover %	Measured °C	Projected °C
1	28	31.7	26.3
2	45	30.2	33.7
3	18	29.9	22.5
4	28	28.7	25.7
5	45	28.7	31.5
6	18	26.7	19.4
7	38	20.0	22.0
8	22	31.1	29.7
9	30	29.2	34.3
10	38	31.8	31.6
11	22	29.1	32.7
12	30	32.0	36.5

Table F5. Analysis of laboratory data, AETL.8A1.

No.	cover %	Measured °C	Projected °C
1	25	28.9	30.3
2	24	27.2	26.1
3	25	27.7	28.7
4	24	26.0	28.3
5	23	27.8	28.2
6	23	26.4	21.3
7	27	25.5	22.8
8	25	27.2	31.2
9	23	24.0	22.5
10	27	24.5	20.2
11	25	24.8	22.4
12	23	25.9	24.6
13	28	25.7	25.7
14	30	29.3	27.1
15	23	26.9	26.4
16	28	28.2	25.8
17	30	29.5	25.7
18	24	21.4	18.4
19	27	22.9	22.9
20	29	24.1	22.9

Table F6. Analysis of laboratory data, AETL.COMP

No.	cover %	Measured °C	Projected °C
1	25	28.9	30.9
2	24	27.2	28.8
3	23	26.1	16.4
4	25	28.8	35.3
5	24	26.0	30.8
6	23	27.8	31.3
7	25	26.4	26.1
8	27	25.5	25.8
9	25	27.2	23.7
10	23	24.0	21.1
11	27	24.5	24.0
12	25	24.8	21.8
13	23	25.9	28.0
14	28	25.7	27.6
15	30	29.3	28.8
16	23	26.9	25.7
17	28	28.2	28.3
18	30	29.5	29.6
19	24	21.4	23.4
20	27	22.9	25.7
21	29	24.1	26.6

Table F7. CWSE values for field data (FARM.8E.1).

Date	$T_C - T_A$ (°C)	VPD(KP_a)	CWSI
7/25/85	-15.1	10.12	0.13
	-12.6		0.24
	-16.5		0.06
7/30/85	-12.1	6.12	-0.16
	-12.1		-0.16
	-11.1		-0.09
8/5/85	-13.0	6.71	-0.13
	-14.9		-0.26
	-14.1		-0.20
8/8/85	-11.1	4.92	-0.32
	- 9.8		-0.20
	- 9.3		-0.16
8/12/85	-12.4	5.39	-0.32
	-12.7		-0.35
	-10.7		-0.18
8/15/85	- 9.4	5.66	-0.03
	- 7.9		0.08
	- 6.0		0.23
8/19/85	- 9.3	4.62	-0.22
	- 8.9		-0.19
	- 7.9		-0.09
8/23/85	- 1.1	4.88	0.56
	- 1.9		0.49
	- 0.4		0.69
8/29/85	- 4.4	4.12	0.15
	- 4.4		0.15
	- 5.0		0.09

Table F8. CWSI values for laboratory data (AETL.8A1).

Date	$T_C - T_A$ (°C)	VPD(KP_a)	CWSI
12/4/85	1.1	3.03	0.64
	0.0	2.96	0.48
	-1.5	3.00	0.28
	2.1	2.88	0.62
	-0.4	2.85	0.41
	1.0	2.93	0.61
12/6/85	-0.8	2.80	0.35
	-0.7	2.64	0.33
	-0.0	2.56	0.28
12/7/85	0.5	2.69	0.51
	0.0	2.68	0.44
	3.8	2.68	0.99
	1.2	2.77	0.62
	2.0	2.83	0.74
	3.2	2.81	0.91
12/10/85	2.6	1.83	0.75
	4.4	1.80	1.11
	5.6	1.81	1.34

Table F9. CWSI values for field data FARM.SE.1 using Idso et al. (1982) relationship for cotton at full cover: intercept = 1.49, slope = 2.09.

Date	$T_C - T_A$ (°C)	VPD(KP_a)	CWSI
8/15/85	- 7.2	5.66	0.24
	- 4.4		0.46
	- 2.4		0.61
8/19/85	-11.6	4.62	-0.32
	-12.0		-0.36
	- 5.4		0.26
8/23/85	- 6.1	4.88	0.23
	- 5.1		0.32
	- 0.9		0.69
8/29/85	- 8.5	4.12	-0.14
	- 8.1		-0.10
	- 5.2		0.00
9/3/85	- 4.3	3.69	-0.21
	- 4.2		-0.22
	- 1.5		0.24

APPENDIX G

TABLES OF RAW DATA

Table G1. Field data for FARM.NE.1, cotton at full cover.

Date	Site	Canopy Temp. (°C)	RH %*	DBT (°C)**	RN*** W/m^2	Soil Moisture cm/30cm
8/15/85	1	30.2	11.8	37.4	591.8	10.0
	2	33.0				9.3
	3	35.0				6.5
8/19/85	1	26.8	31.8	38.4	565.0	9.1
PC	2	26.4				8.6
	3	33.0				5.7
8/23/85	1	33.0	30.7	39.1	583.7	5.8
	2	34.0				6.4
	3	38.2				3.8
8/29/85	1	27.8	35.0	37.2	590.4	9.0
	2	29.1				9.8
	3	32.1				4.5
9/3/85	1	26.6	33.3	34.7	571.4	7.1
	2	26.5				16.3
	3	30.6				8.4

*RH = relative humidity

**DBT = dry bulb temperature

***RN = net radiation

Table G2. Field data for FARM.SE.1, AETL.1, AETL.4, AETL.8A1, and AETL.COMP, cotton at partial cover.

Date	Site	Composite Temp. (°C)	Canopy Temp. (°C)	Soil Temp. (°C)	Cover (%)	TCT (°C)	IRTT (°C)	Sky Temp. (°C)	RH (%)	DBT (°C)	RN W/m^2	Soil Moisture cm/30cm
7/25	1	42.5	32.0	43.8	40	49.5	52.0	-28.0	5.5	47.9	628.1	16.3
	2	42.0	34.5	45.8	52							13.0
	3	50.0	30.6	50.0	51							12.6
7/30	1	29.4	29.2	38.3	44	36.9	36.4	+ 2.9	22.6	41.3	626.4	18.4
	2	30.0	29.2	40.0	61							14.7
	3	38.9	30.2	47.9	38							12.5
8/5	1	31.8	30.6	47.8	74	46.4	50.0	- 6.1	24.8	43.6	584.2	14.9
	2	30.1	28.7	57.4	79							12.5
	3	38.2	29.5	56.0	69							10.5
8/8	1	28.6	29.0	36.5	82	37.7	37.6	[illegible] 5.6	33.8	40.1	695.3	17.6
	2	28.6	30.3	38.2	94							14.3
	3	33.9	30.8	41.5	84							11.5
8/12	1	26.7	28.0	48.2	99	39.2	42.2	-15.6	28.2	40.4	603.5	13.7
	2	27.2	27.7	48.0	100							11.2
	3	28.7	29.7	5.20	86							9.4

Table G2. Field data for FARM.SE.1, AETL.1, AETL.4, AETL.8A1, and AETL.COMP, cotton at partial cover.

Date	Site	Composite Temp. (°C)	Canopy Temp. (°C)	Soil Temp. (°C)	Cover (%)	TCT (°C)	IRTT (°C)	Sky Temp. (°C)	RH (%)	DBT (°C)	RN W/m^2	Soil Moisture cm/30cm
8/15	1	30.3	28.0	46.0	51	40.9	40.6	-37.8	11.8	37.4	591.8	11.1
	2	31.3	29.5	56.3	45							9.6
	3	34.0	31.4	58.0	50							8.0
8/19	1	30.7	29.1	45.0	68	39.8	40.6	-12.5	31.8	38.4	565.0	8.9
	2	28.7	29.5	46.5	62							7.6
	3	30.8	30.5	58.2	68							6.3
8/23	1	32.6	29.7	48.1	63	46.2	48.0	- 7.6	30.7	39.1	583.7	10.7
	2	32.1	28.9	54.0	64							8.0
	3	33.8	31.2	61.0	64							5.8
8/29	1	32.0	30.6	39.3	66	40.4	40.7	-19.0	35.0	37.2	590.4	10.9
	2	31.3	30.6	45.7	61							9.3
	3	32.5	30.0	52.1	58							6.1
	AETL.1											
10/15	1	36.4	31.4	37.0	23	32.4	37.0	-38.9	13.8	32.8	584.2	----
	2	38.6	35.2	39.6	27	33.3	39.6	-39.6	12.9	32.6	580.4	----

Table G2. Field data for FARM.SE.1, AETL.1, AETL.4, AETL.8A1, and AETL.COMP, cotton at partial cover.

Date	Site	Composite Temp. (°C)	Canopy Temp. (°C)	Soil Temp. (°C)	Cover (%)	TCT (°C)	IRTT (°C)	Sky Temp. (°C)	RH (%)	DBT (°C)	RN W/m^2	Soil Moisture cm/30cm
10/18	1	30.0	29.3	32.3	9	29.0	32.4	-36.9	16.3	38.3	478.2	6/0
	2	28.7	27.3	29.9	7	35.7	32.4	-39.5	19.5	36.2	513.6	12/6
	3	28.9	26.1	30.7	9	40.6	30.7	-40.0	20.6	34.8	530.1	10/2
10/22A	1	33.3	29.0	38.8	10	33.1	34.9	-39.9	28.1	29.3	466.2	29/8
	2	31.8	27.3	34.0	8	34.2	35.4	-40.7	26.1	29.8	471.8	17/16
	3	29.0	27.9	31.5	9	29.5	29.5	-41.4	25.3	30.2	596.3	15/8
P	1	36.0	28.5	39.7	22	36.1	40.5	-41.5	20.5	31.7	454.6	30/0
	2	35.2	33.5	37.9	14	35.6	38.6	-41.1	19.7	32.3	488.3	18/17
	3	31.1	28.9	32.3	11	31.0	31.7	-42.2	18.7	33.5	442.8	17/8
10/24A	1	37.5	31.2	40.9	13	37.8	41.3	-43.4	17.6	34.1	434.4	40/0
	2	38.1	32.5	43.5	10	40.8	45.1	-43.5	27.0	34.8	536.8	24/18
	3	35.6	32.9	38.2	10	35.9	36.5	-43.9	16.8	34.1	567.3	20/11
P	1	43.6	33.9	46.9	19	42.5	48.1	-42.1	16.1	34.0	420.8	40/0
	2	43.1	35.9	47.0	11	43.7	48.0	-42.8	13.9	34.8	451.1	26/19
	3	37.5	29.7	41.0	9	38.3	39.1	-42.2	13.1	35.7	406.5	24/12

Table G2. Field data for FARM.SE.1, AETL.1, AETL.4, AETL.8A1, and AETL.COMP, cotton at partial cover.

Date	Site	Composite Temp. (°C)	Canopy Temp. (°C)	Soil Temp. (°C)	Cover (%)	TCT (°C)	IRTT (°C)	Sky Temp. (°C)	RH (%)	DBT (°C)	RN W/m^2	Soil Moisture cm/30cm
AETL.4												
10/30A	1	32.7	31.5	36.2	28	35.1	39.7	-43.1	15.6	32.7	435.6	20/0
	2	34.2	30.0	36.2	45	34.1	38.3	-39.6	14.4	33.7	529.8	26/19
	3	37.7	29.7	41.7	14	35.0	39.7	-40.3	13.6	34.1	551.4	42/24
P	1	33.0	28.5	36.8	28	35.3	41.7	-44.1	12.1	34.2	483.3	20/0
	2	33.9	28.5	37.4	45	35.5	37.9	-45.0	11.7	35.0	504.2	26/19
	3	35.2	26.5	39.3	14	36.9	38.2	-45.8	12.0	34.9	463.9	42/24
11/2 A	1	19.2	19.8	18.8	38	26.5	24.5	-50.8	19.3	27.0	447.2	39/0
	2	30.2	30.8	31.4	22	31.9	31.8	-50.6	27.6	27.4	447.2	40/33
	3	32.8	28.9	33.4	30	29.2	32.5	-50.8	16.7	27.4	508.0	55/40
P	1	34.5	31.5	37.6	38	31.2	40.3	-47.7	16.8	28.3	465.7	39/0
	2	36.1	28.8	38.1	22	30.6	37.0	-48.8	14.1	30.2	477.9	40/33
	3	38.3	31.7	40.3	80	37.7	37.7	-48.4	13.7	31.7	469.1	55/40

Table G2. Field data for FARM.SE.1, AETL.1, AETL.4, AETL.8A1, and AETL.COMP, cotton at partial cover.

Date	Site	Composite Temp. (°C)	Canopy Temp. (°C)	Soil Temp. (°C)	Cover (%)	TCT (°C)	IRTT (°C)	Sky Temp. (°C)	RH (%)	DBT (°C)	RN W/m^2	Soil Moisture cm/30cm
	AET.8A1 + AETL.COMP			8A1/comp								
12/4	1	27.3	29.0	27.4/27.2	25	20.6	31.5	-52.9	19.3	27.9	362.8	30/0
	2	28.8	27.4	30.7/29.9	24	30.6	29.2	-52.5	19.0	27.4	394.0	25/24
	3	26.8	26.3	31.6/30.7	23	31.5	33.1	-52.1	19.7	27.8	395.9	34/18
	P 1	24.0	27.4	23.5/21.1	25	32.1	32.7	-50.6	18.1	26.8	327.7	39/0
	2	27.7	26.2	28.6/27.8	24	29.5	30.8	-51.4	18.2	26.6	307.8	25/24
	3	28.7	28.0	28.8/29.0	23	30.8	32.4	-51.4	17.8	27.0	313.8	34/18

Table G2. Field data for FARM.SE.1, AETL.1, AETL.4, AETL.8A1, and AETL.COMP, cotton at partial cover.

Date	Site	Composite Temp. (°C)	Canopy Temp. (°C)	Soil Temp. (°C)	Cover (%)	TCT (°C)	IRTT (°C)	Sky Temp. (°C)	RH (%)	DBT (°C)	RN W/m^2	Soil Moisture cm/30cm
12/6 A	1	28.6	26.6	31.7/31.3	23	29.5	30.0	-53.4	23.3	27.4	317.0	36/0
	2	29.0	25.7	32.3/31.3	27	29.1	33.3	-53.2	23.3	26.4	399.4	33/28
	3	29.1	27.4	29.5/31.9	25	31.6	33.7	-53.1	25.9	26.5	357.1	41/22
12/6 P	1	25.1	24.2	26.9/27.3	23	31.7	30.0	-52.3	22.4	25.4	316.1	36/0
	2	26.7	24.7	30.1/28.8	27	31.1	31.0	-52.7	22.4	25.2	315.5	33/28
	3	27.8	25.0	30.6/30.8	25	31.8	31.9	-52.5	23.3	25.5	333.0	41/22

Table G2. Field data for FARM.SE.1, AETL.1, AETL.4, AETL.8A1, and AETL.COMP, cotton at partial cover.

Date	Site	Composite Temp. (°C)	Canopy Temp. (°C)	Soil Temp. (°C)	Cover (%)	TCT (°C)	IRTT (°C)	Sky Temp. (°C)	RH (%)	DBT (°C)	RN W/m^2	Soil Moisture cm/30cm
12/7 A	1	26.4	26.1	28.0/27.0	23	28.4	26.7	-56.3	18.1	25.6	414.8	40/0
	2	28.2	25.9	30.3/29.6	28	27.2	29.4	-55.8	19.8	25.9	401.1	36/26
	3	30.2	29.4	32.7/32.0	30	28.1	35.5	-54.5	18.25	25.6	408.0	42/22
P	1	27.5	27.1	28.9/29.1	23	33.3	31.8	-53.6	17.0	25.9	339.9	40/0
	2	29.4	28.3	31.9/31.0	28	31.3	35.2	-53.4	17.2	26.3	388.0	36/26
	3	29.8	29.6	32.7/31.1	30	33.8	36.3	-53.8	18.2	26.4	417.9	42/22

Table G2. Field data for FARM.SE.1, AETL.1, AETL.4, AETL.8A1, and AETL.COMP, cotton at partial cover.

Date	Site	Composite Temp. (°C)	Canopy Temp. (°C)	Soil Temp. (°C)	Cover (%)	TCT (°C)	IRTT (°C)	Sky Temp. (°C)	RH (%)	DBT (°C)	RN W/m^2	Soil Moisture cm/30cm
12/10A VC	1	22.8	21.6	25.2/23.7	24	22.1	27.9	-59.9	16.7	19.0	306.3	38/34
	2	25.6	23.1	27.7/26.7	27	17.2	28.4	-59.8	16.5	18.7	354.3	55/40
	3	25.2	24.3	27.3/25.8	29	21.9	28.9	-59.5	16.1	18.7	316.8	56/0

A = before noon

C = cloudy

P = after noon

PC = partly cloudy

VC = very cloudy

W = Windy

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