Corn Canopy Temperatures Measured with a Moving Infrared Thermometer Array

E. J. Sadler, C. R. Camp, D. E. Evans, J. A. Millen

Abstract. *Measurement of water stress and scheduling of irrigation are both enabled by non–contact infrared thermometers (IRTs). Technological advances have miniaturized IRTs and reduced power requirements so that inexpensive self–powered units are now commercially available. The objective of this work was to test a linear array of IRT sensors mounted on a center–pivot irrigation machine, and to use this IRT array to examine spatial variation in water stress of corn under four irrigation treatments imposed on a highly variable field with a center pivot equipped for site–specific irrigation and agrochemical application. An array of 26 IRTs was mounted on the pivot, which was run dry for a full circle on 7 days during the 1999 corn growing season. Procedures were developed to adjust for time lag during the 3.5–hr measurement period. Significant differences were obtained among the varying water treatments, as expected, but also among plots within the same soil map unit and among soil map unit means. Distinct spatial patterns, not necessarily related to the 1:1200–scale soil map, were observed. These results emphasize the necessity to consider soil water relations during the development of management recommendations for site–specific agriculture.*

Keywords. *Site–specific agriculture, Irrigation, Infrared thermometer, Water stress, Corn,* Zea mays.

Advances in infrared thermometers (IRTs) have increased the options available to irrigation managers wishing to obtain canopy temperatures as an indicator of crop water stress. Where initial IRTs were bulky and depended on external power supplies (e.g., Conaway and Van Bavel, 1967), battery–powered handheld IRTs have been available for some years, and self–powered IRTs are now available. As the power requirements and size have been reduced, so has the cost, meaning it is now economically feasible to use multiple dedicated sensors to obtain spatial patterns of canopy temperatures.

Uses to which IRTs have been applied in water management include obtaining canopy temperatures critical to calculation of the energy balance (Conaway and Van Bavel, 1967; Tanner and Pelton, 1960), determining initial onset of water stress in susceptible areas via an increase in variance of spatial canopy temperature (Aston and Van Bavel, 1972; Clawson and Blad, 1982), quantifying stress via the crop water stress index, or CWSI (Idso et al., 1981; Jackson et al., 1981), and directly controlling irrigation machines (Upchurch et al., 1998). In some of these cases, individual point measurements were considered representative of an entire area; in others, transects or spatial patterns were obtained.

Accuracy and repeatability of commercial IRTs have been improved by several research groups who have employed several refinements in sensor calibration, construction, and data analysis. Sadler and Van Bavel (1982) demonstrated an automated calibration procedure that significantly improved the factory calibration. Kalma et al. (1988) showed the potential to correct the output of a datalogger–compatible IRT using a separate measurement of the sensor temperature and the Stephan–Boltzmann equation. Bugbee et al. (1996) demonstrated the improvements possible with minor changes in data collection or circuit design for a small, inexpensive, self–powered IRT. Baker et al. (2001) showed the improvement in IRT accuracy possible if applied in a differential mode.

Bugbee et al. (1996) also documented the field of view of small thermocouple IRTs. The degree to which vegetation covers the field of view can affect temperature measurements. For most applications during the traditionally stated critical periods of corn tasseling, pollination, and grain fill, leaf area index is high, and viewing an appreciable fraction of soil through the leaves is not considered likely. However, with sparse canopies, such as with early season crops grown in wide rows, field of view would be a concern.

Given the possibilities for reasonably accurate IRT measurements, placing a sensor in a position to obtain the desired data remains a challenge, especially when one desires spatial measurements. Scanning instruments in satellite and aircraft platforms would appear to be one option, although timeliness and availability of data remain problematic (Kustas and Norman, 1996; Moran and Jackson, 1991).

Article was submitted for review in December 2000; approved for publication by the Soil & Water Division of ASAE in February 2002.

Contribution of the USDA Agricultural Research Service, Coastal Plains Soil, Water, and Plant Research Center, Florence, S.C., in cooperation with the South Carolina Agricultural Experiment Station, Clemson, S.C. Mention of trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product by the USDA and does not imply its approval to the exclusion of other products or vendors that may also be suitable.

The authors are: **E. John Sadler, ASAE Member,** Soil Scientist; **Carl R. Camp, ASAE Member Engineer,** Agricultural Engineer; **Dean E. Evans,** Agricultural Engineer; and **Joseph A. Millen, ASAE Member Engineer,** Agricultural Engineer; USDA Agricultural Research Service, Coastal Plains Soil, Water, and Plant Research Center, Florence, South Carolina. **Corresponding author:** E. John Sadler, USDA–ARS, Coastal Plains Soil, Water, and Plant Research Center, 2611 West Lucas Street, Florence, SC 29501–1242; phone: 843–669–5203 ext. 112; fax: 843–669–6970; e–mail: sadler@florence.ars.usda.gov.

Carrying an IRT by hand (e.g., Sadler et al., 1995, 2000) or on a handheld mast has been used for transect measurements, but time lag in the data creates a problem under some conditions. Automatically moving a single IRT sensor on a track has been used for small–scale applications and on larger scales, such as the 100–m application of Barnes et al. (2000) and Martin et al. (2000). In other applications, multiple sensors have been used to take an essentially simultaneous transect of temperature (Evans et al., 2000; Upchurch et al., 1998).

Several compromises must be made regarding the choice of data collection method. Aircraft and satellite scanning systems use a single sensor and obtain 2–dimensional spatial data with nearly negligible time lag in the data itself, but with sometimes significant delay in delivery of results. Single–sensor moving transect applications also eliminate the possibility of sensor–to–sensor calibration differences, but cannot make a 1–dimensional transect without possibly significant lag, which becomes a critical limitation under varying conditions. Multiple–sensor linear arrays can make measurements at discrete points along a 1–dimensional transect. However, spatial resolution is achieved by increasing the number of sensors (and cost), and sensor–to–sensor differences must be tolerated or overcome via calibration. Using a moving linear array to obtain a 2–dimensional spatial pattern retains these latter challenges and adds the time lag difficulty mentioned above for moving–sensor applications.

The issue of time lag is merely troublesome with smaller systems, but may effectively prevent whole–circle measurements with large systems in which the pivot makes a complete circle in a period of 10 hours or more. Although smaller systems are becoming more common as irrigation expands in areas with smaller fields, and small–format pivots are increasing in popularity, the system described here could not be used on pivots that take longer than approximately 6 hours to complete a circle. However, the information obtained using the devices is expected to be incorporated into real–time sensor–based irrigation control, which would detect water stress and instruct the machine to apply water as needed at that time.

The long history of IRT use in irrigation management, combined with the obvious availability of center–pivot and linear–move irrigation machines as a frame from which to hang sensors, has led to several research applications that employ either a moving sensor or multiple–sensor linear array mounted on irrigation machines. In this article, we describe a linear array of IRTs on a site–specific center–pivot irrigation machine and describe possible solutions to the measurement challenges mentioned above. The objectives of this research are to determine spatial canopy temperature dependence on soil map unit and varying irrigation water treatments.

Material and Methods

The data presented here were collected during the 1999 corn growing season on an area used to conduct an irrigation × N–fertilizer × soil map unit experiment. The experimental design included four irrigation treatments and two N–fertilizer treatments placed on 12 soil map units. These treatments were imposed using a 3–tower, 137–m center–pivot irrigation system that had been modified for site–specific application of water and nutrients in 13 segments, each 9.1 m in length. Details of the center pivot modifications can be found in Camp et al. (1998) and Omary et al. (1997). A linear array of 26 IRTs was mounted along the pivot, two in each of the 13 segments. The methods will be described in the following order: field study, IRT mounting hardware, IRT sensor, data logger and collection, and data analysis.

Field Study

Conventional surface tillage culture was used, including in–row subsoiling to a depth of 40 cm at planting. Granular fertilizer (31 kg/ha N, 53 kg/ha P_2O_5, and 53 kg/ha K_2O) was applied broadcast prior to planting. Corn (Pioneer 3163) was planted 3 April 1999 in 0.76–m rows to a final plant population of about 64,000 plants/ha. Pre–plant, pre–emergence, and post–emergence herbicides and a banded insecticide were applied as recommended by South Carolina Cooperative Extension Service.

Irrigation treatments were 0%, 50%, 100%, and 150% of an irrigation base rate (IBR) determined by soil water potential values (measured by tensiometers) and meteorological conditions. The IBR varied during the growing season (4 to 13 mm/application) depending upon crop growth stage and weather conditions. Irrigation was initiated in all irrigation treatments when soil water potential at the 30–cm depth in the 100% base rate treatment was < –30 kPa. Standard meteorological variables were measured at an automated weather station adjacent to the experimental site. The two N–fertilizer treatments were the recommended rainfed and irrigated rates (135 and 225 kg/ha). Urea ammonium nitrate with sulfur (UAN 24S) was applied according to the treatment plan via the irrigation system during the period 2–4 June 1999.

This site had been mapped on a 1:1200 scale by USDA–SCS staff in 1984 (USDA–SCS, 1986). Brief descriptions of the 12 soil map units under the center pivot are given in table 1. Further descriptions of the soil map units and other details of this agronomic experiment can be found in Karlen et al. (1990) and Camp et al. (2000). The experimental plot sizes were nominally 9.1 × 9.1 m (6.1 × 6.1 m control areas) and were organized into randomized complete blocks (RCBs) where there was sufficient area within the soil map unit boundaries; where there was not enough area, randomized incomplete blocks (RICBs) were used. On the larger soil map areas, multiple RCBs were used. The plot diagram for this experiment, including the soils map, is shown in figure 1.

The 1999 crop year included a moderately severe drought, which provided a great deal of contrast in canopy temperatures across plot treatments and soils. A timeline of rainfall, irrigations, and temperature measurements is shown in table 2. IRT measurements were conducted with the center pivot running dry at full speed, which required approximately 3.5 hours for a full circle.

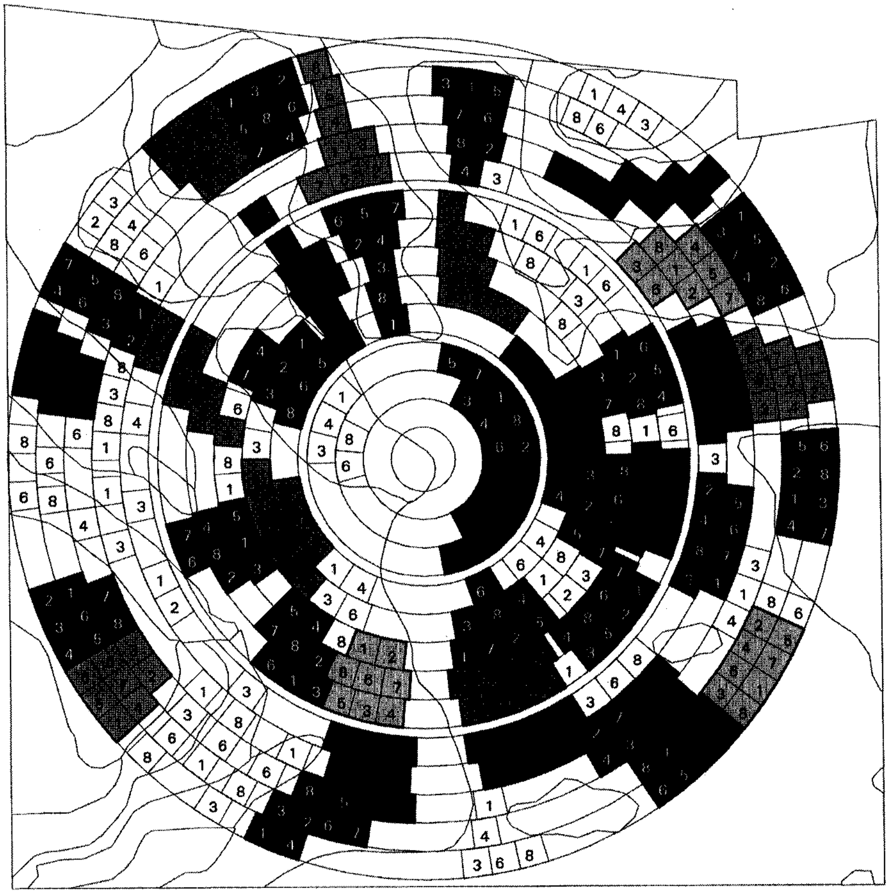
IRT Mounting Hardware

Two IRTs were placed in each of the 13 segments. The IRTs were mounted on adjustable booms and masts made of 25–mm aluminum pipe. The 4–m booms were connected to the manifold braces using connecting clamps, and the 1.5–m masts were attached using aluminum pipe connectors. A shield was constructed of 37–mm PVC pipe and attached on the mast so that it could be rotated and tilted as desired. The

Table 1. Classification of twelve soil map units within the 24–ha area at the Coastal Plains Research Center where the 8–ha experimental field was located (USDA–SCS, 1986).

Symbol	Soil Description	Soil Classification
BnA	Bonneau loamy fine sand (lfs), 0% to 2% slopes	Loamy, siliceous, thermic Grossarenic Paleudult[a]
Cx	Coxville loam	Clayey, kaolinitic, thermic Typic Paleaquult
Dn	Dunbar lfs	Clayey, kaolinitic, thermic Aeric Paleaquult
Do	Dunbar lfs, overwash	Clayey, kaolinitic, thermic Aeric Paleaquult
ErA	Emporia fine sandy loam (fsl), 1% to 2% slopes	Fine–loamy, siliceous, thermic Typic Hapludult
GoA	Goldsboro lfs, 0% to 2% slopes	Fine–loamy, siliceous, thermic Aquic Paleudult
NbA	Noboco lfs, moderately thick surface, 0% to 2% slopes	Fine–loamy, siliceous, thermic Tyic Paleudult
NcA	Noboco lfs, thick surface, 0% to 2% slopes	Fine–loamy, siliceous, thermic Typic Paleudult
NfA	Noboco fsl, 1% to 2% slopes	Fine–loamy, siliceous, thermic Typic Paleudult
NkA	Norfolk lfs, moderately thick surface, deep water table, 0% to 2% slopes	Fine–loamy, siliceous, thermic Typic Paleudult[b]
NoA	Norfolk lfs, thick surface, 0% to 2% slopes	Fine–loamy, siliceous, thermic Typic Paleudult[b]
NrA	Norfolk fsl, 1% to 2% slopes	Fine–loamy, siliceous, thermic Typic Paleudult[b]

[a] Reclassified in March 1990 to loamy, siliceous, thermic Arenic Paleudult.
[b] Reclassified in March 1988 to fine–loamy, siliceous, thermic Typic Kandiudult.



Treatment Codes		
	Nitrogen (kg/ha)	
%BR	135	225
0	1	5
50	2	6
100	3	7
150	4	8

Figure 1. Diagram of the 1999 corn plot layout for an irrigation × N–fertilizer × soil map unit experiment. Soil map unit outlines and codes are indicated on the diagram. Shading indicates plots within single RCB or RICB blocks.

boom was located approximately 3 m above ground level. The mast could be extended to its full length above or below the boom. For this study, the IRTs were placed approximately 3 m forward of the center–pivot main structure and approximately 1.5 m above the crop. The booms were placed near the opposite ends of each segment, with each IRT aimed approximately 45° downward and 45° inward toward the center of the segment. This positioning resulted in a canopy temperature "footprint" centered approximately 2.5 m from each side of the 9.1–m segment. The resulting canopy temperature at the center of each 6–row planter pass avoided any plot–edge effects.

IRT Sensors

The IRTs used were Exergen Irt/c .3X with a 3:1 field of view and type K thermocouple leads (Exergen Corp., Newton, Mass.). These IRTs had a published accuracy of ±2% and cost approximately $210 U.S. per unit in 1996. In the work described here, the IRTs were used as supplied by the manufacturer, except that the 26 IRTs were calibrated in the laboratory prior to use in the field. For further work, steps

Table 2. Timeline of irrigation, rainfall, and IRT measurements during the 1999 corn growing season.

Date	AM	Midday	PM
02 July	—	Irrigation: 13 mm	—
06 July	Irrigation: 13 mm	—	Rain: 17 mm
07 July	—	—	Rain: 8 mm
08 July	—	—	Rain: 5 mm
09 July	—	—	Irrigation: 4 mm
13 July	—	—	Rain: 3 mm
14 July	—	—	Rain: 2 mm
15 July	—	—	Rain: 15 mm
19 July	—	IRT data collection	Irrigation: 5 mm
20 July	Irrigation: 6 mm	IRT data collection	—
21 July	Irrigation: 10 mm	—	—
22 July	Irrigation: 5 mm	IRT data collection	—
23 July	Irrigation: 6 mm	IRT data collection	—
24 July	—	—	Rain: 42 mm
26 July	—	IRT data collection	—
29 July	—	—	Rain: 2 mm
30 July	—	—	Rain: trace
01 Aug	—	—	Rain: 7 mm
02 Aug	Irrigation: 9 mm	—	—
03 Aug	—	IRT data collection	—
04 Aug	Irrigation: 6 mm	—	—
05 Aug	Irrigation: 6 mm	—	—
06 Aug	Irrigation: 9 mm	—	—
09 Aug	Irrigation: 9 mm	—	—
11 Aug	—	IRT data collection	—

suggested by Bugbee et al. (1996) to improve the accuracy of the IRTs would be useful.

Datalogger and Collection

The IRT data were collected using a CR21X datalogger (Campbell Scientific, Logan, Utah) mounted on the last tower of the center pivot. Data signal multiplexers (CSI AM416) were mounted at the two inner towers to decrease the amount of thermocouple cable needed. Data were collected at 15–sec intervals, which provided a canopy temperature "snapshot" at approximately every 0.45° of center–pivot movement, or approximately 800 records during a complete circle.

After each set of canopy temperatures was collected, the data were downloaded via a short–haul modem to a 386–MHz PC module integrated into a PLC (programmable logic controller, GE Fanuc model 90–30, Charlottesville, Va.) mounted on the center–pivot truss to control the application of water and nutrients. As part of the normal operation of the pivot, the PC software interrogated the center–pivot control system (C:A:M:S, Valmont Industries, Valley, Neb.) to obtain the angular position of the center pivot. This information was stored in a file along with a time stamp for later determination of the ground position for each of the canopy temperature values.

Crop canopy temperature data were collected starting at approximately 1100 hr EDT on days that had a high probability of clear skies. Seven days during the grain–fill period were chosen to acquire canopy temperature data. Of these seven, only two days (19 July and 11 August) had any significant cloud cover for brief periods (approximately 5 to 15 minutes). Data were collected for the complete center–pivot travel circle, which required approximately 3.5 hours.

The ground position of each canopy temperature data point was determined from the angle of the center pivot. The angle reported by the resolver was corrected using a ground position survey done before the season and built into the center–pivot controller. This corrected value with its associated time stamp was then interpolated using the time stamp of the IRT data to get the angle of the center pivot at the time of each measurement. This angle was then corrected for the geometric offsets of the IRT footprint forward, inward, and down from the point where the boom was attached to the center–pivot structure. The polar coordinates were then converted to Cartesian coordinates in the local coordinate system.

Data Analysis

Before performing any analysis of the data, the raw temperature values were corrected for individual calibrations and time lag. After correction for calibration, the temperature values were adjusted to account for environmental changes during 3+ hours of runtime. Because a rise in canopy temperature usually corresponds with a rise in air temperature, the usual normalization is to compute the canopy minus air temperature difference (T_{diff}). Where air temperatures are not available, the adjustment used by Evans et al. (2000) can be used, which entail the regression of temperature against time, subtracting the trend, and adding back the average (T_{adj}). Both the method of Evans et al. (2000) and the subtraction of air temperature method were computed and compared.

The T_{diff} and T_{adj} values were assigned attributes based upon their ground position. The soil map unit, irrigation and N–fertilizer treatments, and plot number for each data point were determined using ARC/Info GIS software (ESRI, Redlands, Cal.). ARC/Info was also used to determine whether the data point was within the center 6.1 × 6.1–m control zone to avoid edge effects. Once those attributes were assigned to the data points, the dataset was statistically analyzed to determine relationships between crop canopy temperature and soil map units and irrigation rates.

All values attributed to the center 6.1 × 6.1–m area of a treatment plot were used in these analyses. The number of plots was 396 inclusive of all RICB replications. Where no significant differences occurred between N treatments, the values for low and high N treatments were considered as two observations for the same water treatments and soils. Analyses of variance and regression analyses were conducted using SAS (SAS, 1990). One final analysis conducted was to approximate the spatially variable water stress that occurred on this field for one representative day. This was done by assuming that the fully irrigated plots (treatment 150% IBR) were not stressed. For each of the 59 blocks (both RCB and RICB), this surrogate unstressed temperature was subtracted from the unirrigated plot temperature (treatment 0% IBR). The differences were assigned positions based on the corresponding midpoints of the blocks, and the values were interpolated using kriging in SURFER software (Golden Software, Inc., Golden, Colo.).

Results

A timeline of rain, irrigation, and temperature measurements is given in table 2, and summary information on the

Table 3. Summary values of weather conditions during the measurement periods.

Date	Air Temperature (°C) Mean	Min	Max	Solar Radiation (W/m^2) Mean	Min	Max	Dew–Point Temp. (°C) Mean
19 July	32.6	30.6	34.2	895	785	1030	21.3
20 July	34.4	32.4	36.1	885	822	943	22.1
22 July	38.1	36.1	40.6	824	778	883	23.7
23 July	39.7	38.5	41.2	846	729	956	22.8
26 July	34.6	32.9	36.2	893	750	1008	22.1
03 Aug	33.5	31.4	34.8	943	912	997	15.7
11 Aug	37.0	34.6	38.8	711	522	862	23.3

weather conditions during the seven measurement periods is given in table 3. Together, these results illustrate the conditions before and during the measurements. In general, irrigation was applied in the morning, a measurement run was done near midday, and sometimes an irrigation or rainfall occurred in the late afternoon or evening.

The effectiveness of the time lag adjustment was examined by simply subtracting the initial from the final means of the entire 26–IRT array. These values, measured approximately 3.5 hours apart, represent the full effect of the diurnal increase in air temperature. Therefore, any adjustment must minimize this increase. The unadjusted canopy temperature (T_c), air temperature (T_a), T_{diff}, and T_{adj} (Evans et al., 2000) are shown in table 4. The mean rise in canopy temperature for all seven days was 5.5° C ±1.5° C, and the mean rise in air temperature was 2.9° C ±1.6° C. Therefore, the mean T_{diff} was 2.5° C ±1.5° C. This accounted for 55% of the temperature rise, which was considered sufficient for this analysis. The linear regression–based method of Evans et al. (2000) resulted in somewhat more adjustment and therefore smaller rise (1.8° C ±1.2° C), but theoretical and practical reasons suggest that the canopy–air temperature difference method should be used where possible. It is widely used in other research and is available in real time, while the regression–based method must be applied afterwards. For all results

Table 4. Examination of adjustment for temperature rise during 3.5–hour measurement period. Values are differences between the last point and the first point measured. T_{diff} is canopy (T_c) minus air (T_a) temperature, and T_{adj} is obtained using the method of Evans et al. (2000).

Date	T_c (°C)	T_a (°C)	T_{adj} (°C)	T_{diff} (°C)
19 July	6.3	2.9	1.9	3.3
20 July	3.5	2.6	0.7	0.9
22 July	7.2	2.7	2.6	4.5
23 July	4.7	0.8	1.1	3.9
26 July	4.8	3.8	1.4	1.1
03 Aug	4.7	2.2	1.1	2.5
11 Aug	7.0	5.5	3.8	1.5
Mean	5.5	2.9	1.8	2.5
Std. Dev.	1.5	1.6	1.2	1.5

shown below, the temporal adjustment method used the canopy–air temperature difference (T_{diff}).

An indication of the dramatic temperature differences obtained as a result of contrasting irrigation treatments can be seen in figure 2. A small subset of data was extracted for 15° of pivot travel from one ring on one day. The values shown are averages of the two IRTs in ring 10, and start in an unirrigated border, continue through 100%, 0%, 0%, and 150% IBR treatments, and finish in an unirrigated border. Of the four plots shown, only the third is a high–N treatment. Where the irrigation treatment switched from none (0%) to full (100% or 150%) or back, the canopy temperature responded within a few meters in each case, and the magnitudes of the effect were easily detectable by these inexpensive IRTs. Similar results were obtained in most similar transition zones. Not shown here, but strikingly apparent in all our scans, was a high–temperature zone along the unirrigated field road. These observations indicate that abrupt differences in water application, such as caused by a clogged sprinkler or treatment border, could be detected by IRTs.

Spatial maps of T_{diff} values from two contrasting days illustrate the spatially variable response of the crop to water

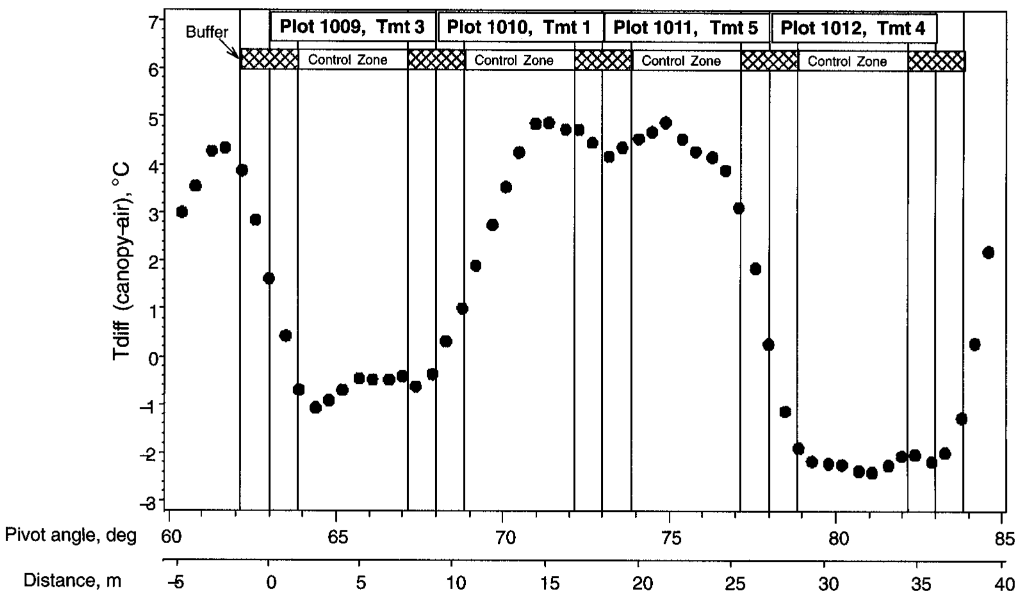


Figure 2. Canopy minus air temperature (T_{diff}) values in a 45–m transect along the arc of travel for plots 9 through 12 of ring 10 on 23 July 1999. Points are the mean of the two IRTs within the plot.

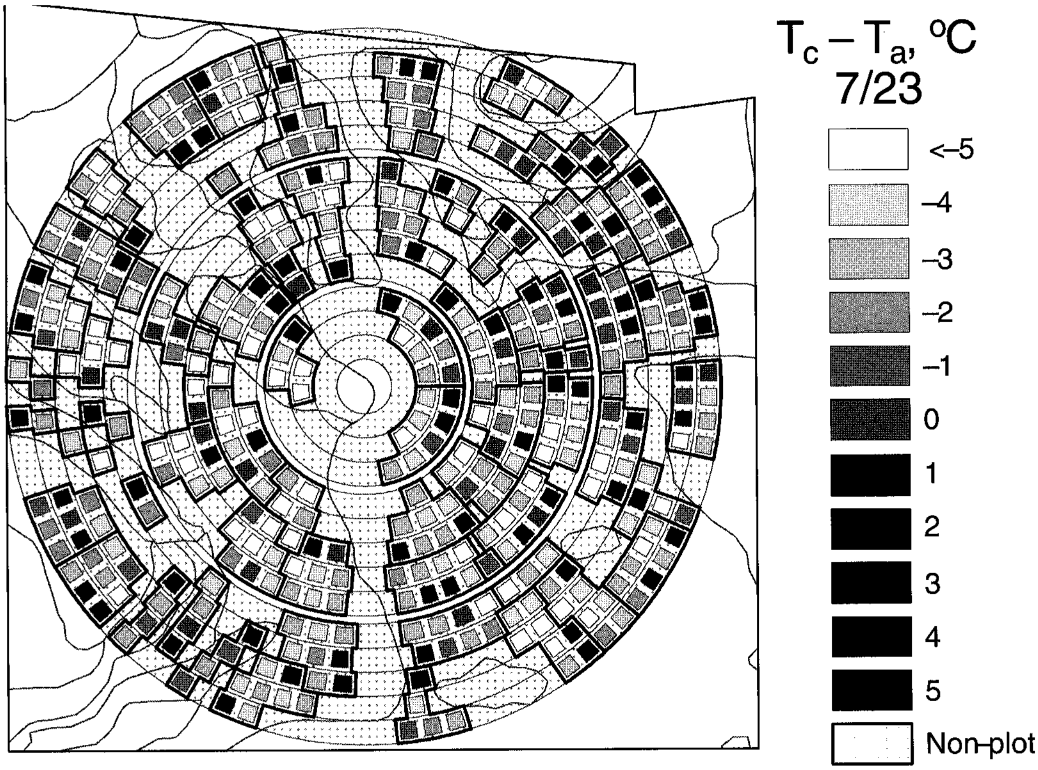


Figure 3. Canopy–air temperature difference (T_{diff}) values on 23 July 1999, a warm, dry day. Soil map units are superimposed on the map.

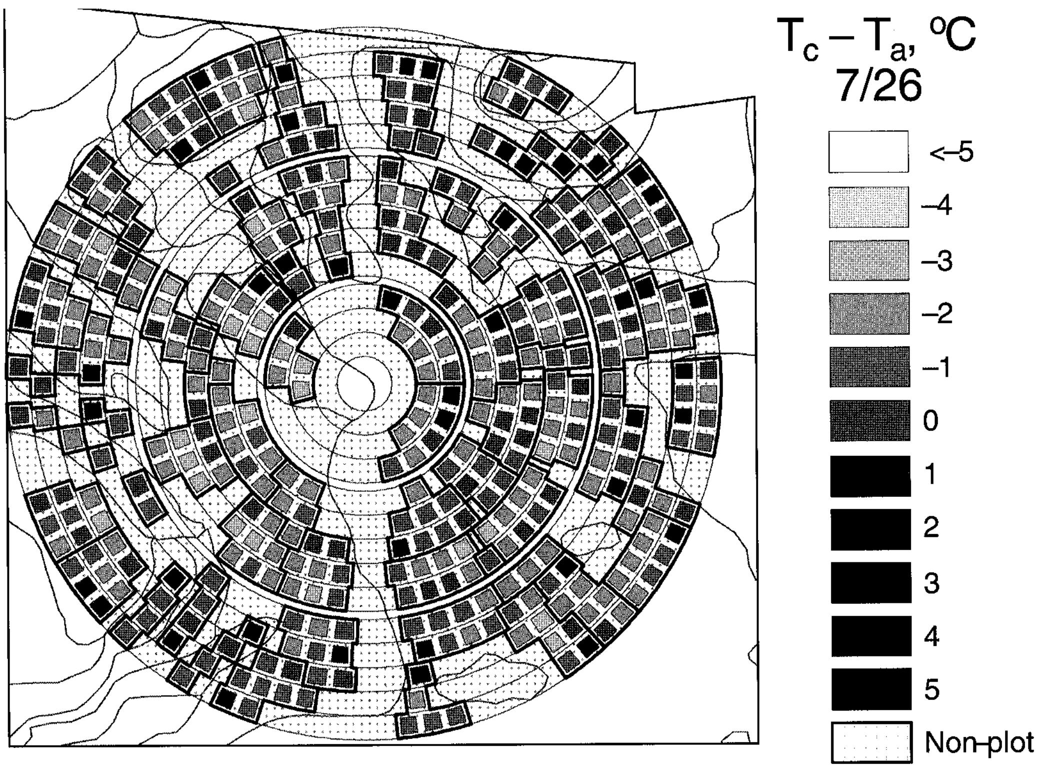


Figure 4. Canopy–air temperature difference (T_{diff}) values on 26 July 1999, two days after a 42–mm rain. Soil map units are superimposed on the map.

stress. The first day was 23 July 1999 (fig. 3), on which the non–irrigated treatments were under considerable water and heat stress. Eight days had passed since rainfall, and the air temperatures were 38.5° C to 41° C. The second day was 26 July 1999 (fig. 4), two days after a 42–mm rainfall with air temperatures of 33° C to 37° C. The 26 July data indicate lower crop stress than the 23 July data. It is obvious from the 26 July data that the rain on 24 July reduced the variability across the plot areas. It can also be seen that the well–watered treatments in different areas of the field had different temperatures on the same day.

The primary relationships of interest are the canopy temperatures as affected by the different irrigation treatments on the different soils. Results of the analysis of variance performed on the T_{diff} values are shown in table 5. For each day, there are two main significant effects, and for four of the seven days, there is a third. To no surprise, the largest effect is the irrigation treatment. The orthogonal contrasts indicate that there is a significant linear effect and a smaller but still significant quadratic effect. The third contrast, the deviation from the quadratic effect, is significant only on 1 of the 7 days. We conclude that a quadratic equation is appropriate for empirical description of the relationship, as illustrated below. The second significant main effect is the replication within soil, indicating substantial variation within any given map unit. The third significant main effect on four days is for the soil map unit, indicating that significant differences existed among map unit means. The mean square for rep(soil) increased faster than the mean square for the soil main effect after a rain event on 24 July (table 5). This suggests that within–soil variability increases faster than across–soil variability for crop water stress. Whether or not irrigation had been applied the morning of the IRT measurements did not appear to affect the results.

Parallel to the analysis of variance, but more easily visualized, is the empirical description of the relationships using regression analysis and graphical representation. In the following figures, the primary relationship is plotted, and variation existing within plots, within blocks, within soils, and among soils is examined. Each figure illustrates some significant element of the analysis of variance shown in table 5.

Variation within individual plots is not tested in the analysis of variance but is important in building confidence in the results. Figure 5 presents graphically the regression results for one block of one of the soil map units (NkA block 31) for two contrasting days. Shown are the individual data points, the plot means, and the corresponding fitted quadratic equations. The effect of the rainfall on 24 July was to flatten the response curve, lowering the apparent stress for the unirrigated plots. While the temperature difference was reduced for the well–watered plots, the differences in solar irradiance, temperature, and humidity between the two days hampered the interpretation of that change. The regression lines through the individual points and the plot means are both plotted, but they are so nearly coincident that one cannot distinguish them. They are both provided so that the reader can contrast how much variation was explained by the regression of individual points with how much was explained by regression of plot means. As suggested by orthogonal contrast, the general shape of the quadratic curve appears appropriate. More than 90% of the variation in plot mean temperature difference was explained by irrigation amount as coded by IBR.

Variation from day to day was not tested with analysis of variance, as climatic conditions differed and a complete evaluation of the energy balance is beyond the scope of this article. However, it is worthwhile to visualize the seven sets of responses for one block. The regression lines obtained through plot means on all 7 days for the same block (block 31 of the NkA soil map unit) are shown in figure 6. For 7 of the 8 days, 90% of the variation was explained with the quadratic equations. July 23 provided the most extreme data, as judged by the difference between the well–watered and water–stressed values. The other July dates were intermediate, while the two August dates had generally higher temperatures relative to that of the air. The corn crop was nearing physiological maturity; most non–irrigated plots had reached black layer by 3 August and many irrigated plots had reached it by 11 August. Onset of maturity could explain some of this elevation in temperature. However, fully explaining that observation will not be possible until a more thorough examination can be made of the theoretical effects of the energy balance of the corn crop under these contrasting water treatments.

The variation in crop response for all RCB blocks within the predominant soil map unit (NkA) on 23 July is shown in figure 7. While individual curves are difficult to distinguish in the graph, the message is not contained in any individual curve. Rather, the similarities and differences among the curves are what is important. Generally parallel curves were

Table 5. Analysis of variance results for the seven datasets of canopy minus air temperature.

		Mean Square						
Source[a]	DF	July 19	July 20	July 22	July 23	July 26	Aug 3	Aug 11
Error	268	0.60	0.61	1.14	1.02	0.24	0.61	1.39
Soil	11	8.08**	8.10*	8.67	9.90*	2.66*	5.37	11.02
Rep(Soil)	45	1.94**	3.05**	4.98**	3.75**	1.08**	4.81**	6.50**
UAN	1	0.36	0.39	0.23	2.91	0.03	0.02	0.04
Water	3	53.21**	93.01**	143.98**	244.74**	32.66**	77.67**	106.18**
Soil*UAN	9	0.41	0.78	1.47	0.97	0.43	0.86	0.95
Soil*Water	31	0.67	0.73	1.26	1.33	0.36	0.55	2.17*
Water*UAN	3	0.38	0.37	1.78	0.39	0.25	0.02	0.55
Soil*Water*UAN	22	0.44	0.63	0.99	0.76	0.32	0.37	0.80
Orthogonal contrasts								
Water, linear	1	88.01**	135.28**	234.09**	388.95**	49.29**	124.95**	184.13**
Water, quadratic	1	6.70**	31.30**	46.80**	74.38**	4.39**	9.65**	6.41*
Water, deviation	1	0.33	0.99	11.81**	3.03	0.00	0.26	0.57

[a] Soil = soil map unit; Rep(Soil) = replication within soil map unit; UAN = nitrogen fertilizer treatment; Water = irrigation treatment.
Significance for the soil effect was computed using Rep(Soil) as an error term.
* = Results significant at the 0.05 level.
** = Results significant at the 0.01 level.

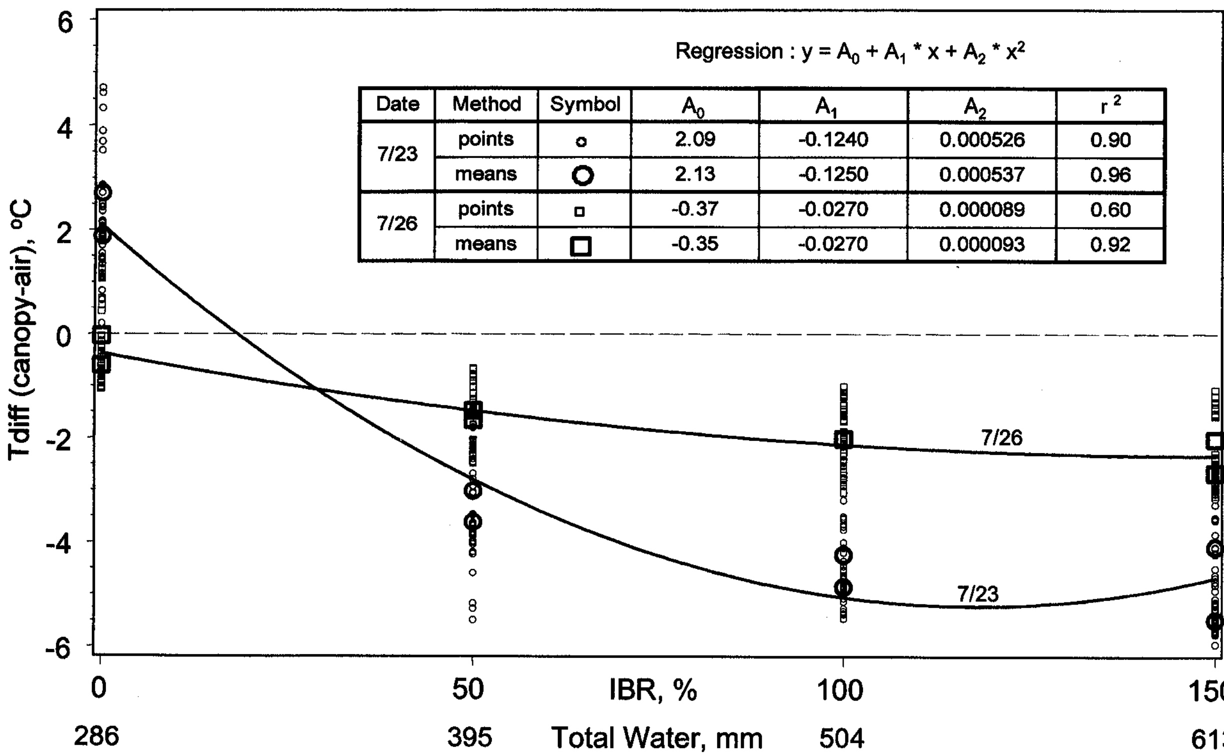


Figure 5. Fitted quadratic curves and data points for canopy–air temperature difference (T_{diff}) versus irrigation base rate (IBR) and total water applied on two contrasting days (23 and 26 July 1999). Shown are data from one RCB (block 31) in the NkA soil map unit. The *x* value in the equation is IBR.

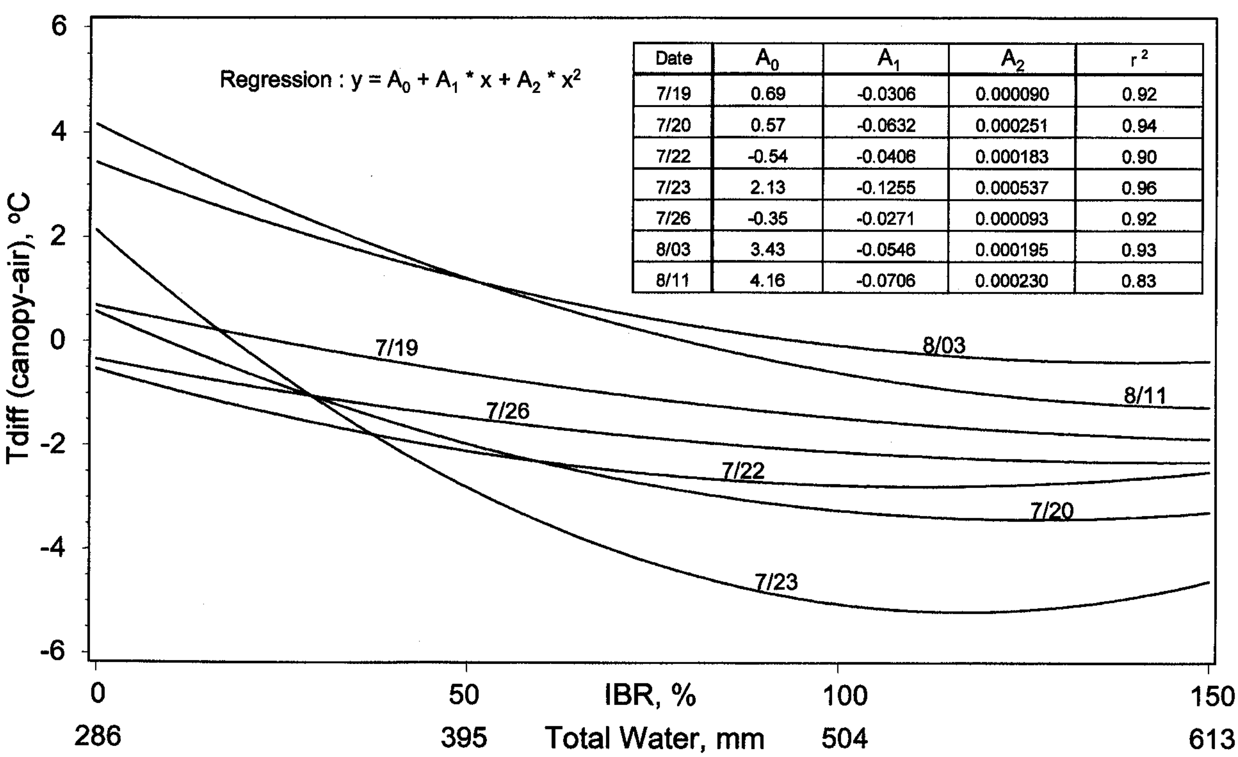


Figure 6. Fitted quadratic curves for canopy–air temperature difference (T_{diff}) versus irrigation base rate (IBR) on all days. Shown are data from one RCB (block 31) in the NkA soil map unit. The *x* value in the equation is IBR.

obtained on the 18 RCB treatment blocks, with a variation of approximately 3.5° C in the unirrigated cases and 2° C in the well–watered cases. The differences between the curves, seen here for the NkA soil map unit, were significant for the entire experiment on all 7 days.

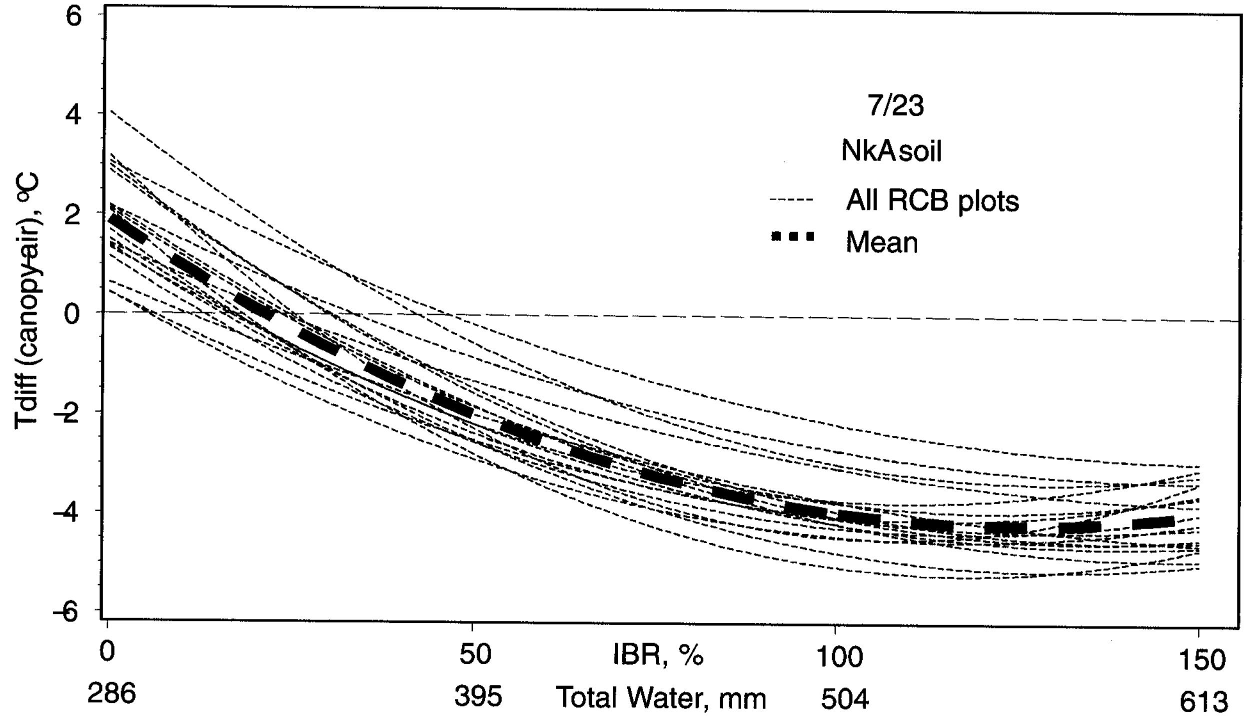


Figure 7. Fitted quadratic curves for canopy–air temperature difference (T_{diff}) versus irrigation base rate (IBR) on 23 July 1999. Shown are data from all the RCBs in the NkA soil map unit. The heavy line indicates the regression curve for all data.

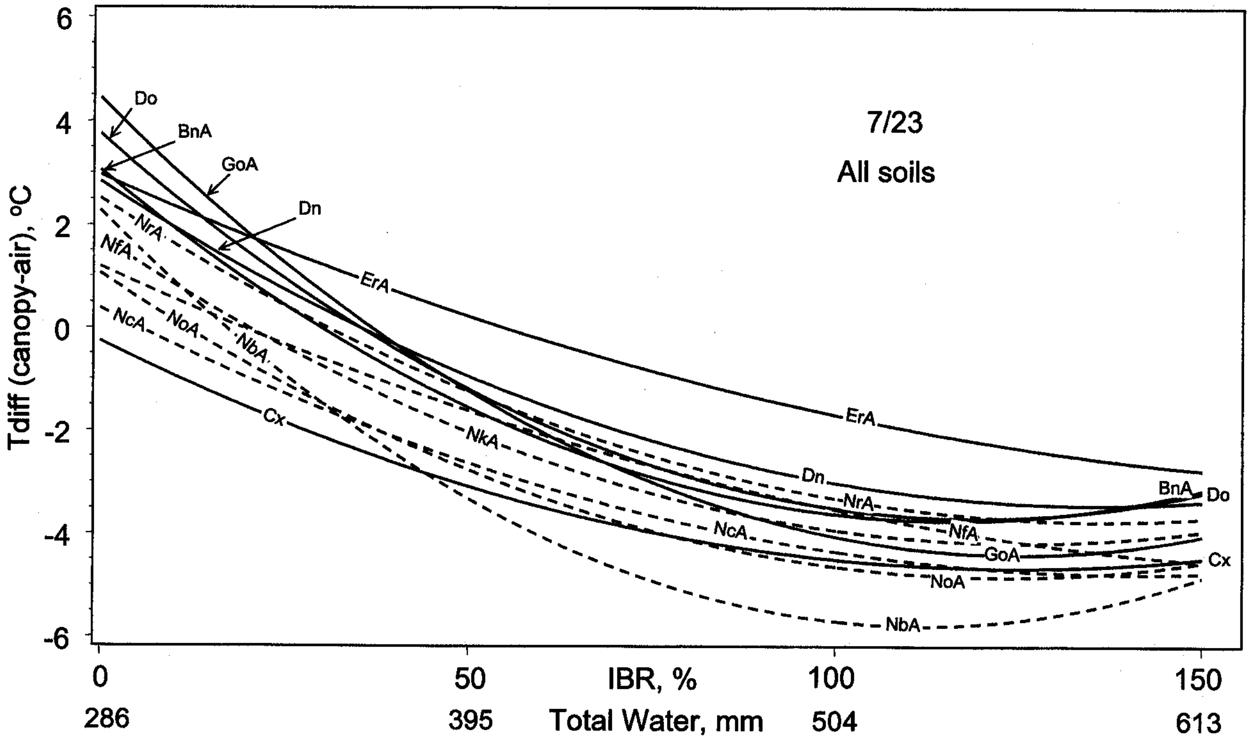


Figure 8. Fitted quadratic curves for canopy–air temperature difference versus irrigation base rate (IBR) on 23 July 1999 for all soil map units.

The heavy black line in figure 7 represents the mean for all NkA RCB blocks. Similar map–unit–mean lines are shown in figure 8 for all 12 soils on 23 July. Here, one can see clearly the significant variation in response among soils that was detected in the analysis of variance. It is interesting that the mean curves are quite similar for the NkA and NcA soils, which are the two most common types (18 and 8 RCB blocks, respectively). The typical pedon descriptions for these soils indicate very little physical difference between them from the surface to 1.2–m depth.

The spatial water stress as indicated by the temperature difference between water stressed and well–watered plots is shown in figure 9. It is apparent that variation exists across and within soil map units. It is also clear that there are distinct

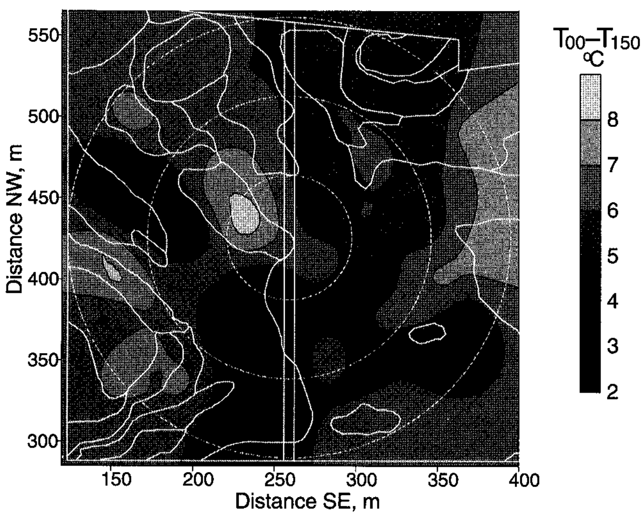


Figure 9. Contour map showing the difference between the mean canopy temperature for the dry plots (0% IBR, T_{00}) and the wet plots (150% IBR, T_{150}) on 23 July 1999.

spatial patterns in the stress detected, which means that there are significant spatial patterns in the ability of the corn crop to withdraw water from the soil at various places in the field.

Summary and Conclusions

This study has shown that crop canopy temperature can be measured on a spatial scale of several meters using inexpensive IRTs mounted on an existing center–pivot irrigation system. With modern dataloggers and computer equipment, it was easy to collect the data and take action on the results with little delay. Such real–time access to the data suggests that it could be used for irrigation system control, either independently or in concert with soil–based measurements and models or forecasts.

An IRT array as described here could be used as a post–irrigation check mechanism, such as for determining the uniformity of irrigation applications, especially when using precision application equipment. Variations in canopy temperature could indicate a lack of application uniformity or could indicate problems in the water delivery system. The ease with which we were able to detect plot areas with no irrigation leads us to conclude that detecting major water application problems should be possible.

The results obtained with the linear array of IRTs indicate that significant variation in corn response to irrigation water levels existed within and among soil map units on this field. This supports the assertion that soil water relations can be a major cause of yield variation on sandy Coastal Plain soils. Therefore, it is important to examine all possible management techniques that affect infiltration, rooting volume, and water–holding capacity if one is to develop recommendations for site–specific agriculture on these and similar soils.

References

Aston, A. R., and C. H. M. Van Bavel. 1972. Soil surface water depletion and leaf temperature. *Agronomy J.* 64(3): 368–373.

Baker, J. M., J. M. Norman, and A. Kano. 2001. A new approach to infrared thermometry. *Agric. and Forest Meteorology* 108(4): 281–292.

Barnes, E. M., P. J. Pinter, B. A. Kimball, D. J. Hunsaker, G. W. Wall, and R. L. LaMorte. 2000. Precision irrigation management using modeling and remote sensing approaches. In *Proc. 4th Decennial National Irrigation Symposium*, 332–337. R. G. Evans, B. L. Benham, and T. P. Trooien, eds. November 14–16. Phoenix, Ariz. St. Joseph, Mich.: ASAE.

Bugbee, B., M. Droter, O. Monje, and B. Tanner. 1996. Evaluation and modification of commercial infrared transducers for leaf temperature measurement. Available at: www.apogee–inst.com/irtspaperhtm.

Camp C. R., E. J. Sadler, D. E. Evans, L. J. Usrey, and M. Omary. 1998. Modified center–pivot system for precision management of water and nutrients. *Applied Eng. in Agric.* 14(1): 23–31.

Camp, C. R., E. J. Sadler, D. E. Evans, and J. A. Millen. 2000. Corn yield response to N–fertilizer for a range of water regimes and soil mapping. In *Proc. 5th International Conference on Precision Agriculture*, CD–ROM. P. C. Robert, R. H. Rust, and W. E. Larson, eds. Bloomington, Minn. July 16–19. Madison, Wisc.: ASA/CSSA/SSSA.

Clawson, K. L., and B. L. Blad. 1982. Infrared thermometry for scheduling irrigation of corn. *Agronomy J.* 74(2): 311–316.

Conaway, J., and C. H. M. Van Bavel. 1967. Evaporation from a wet soil surface calculated from radiometrically determined surface temperatures. *J. Applied Meteorology* 6(4): 650–655.

Evans, D. E., E. J. Sadler, C. R. Camp, and J. A. Millen. 2000. Spatial canopy temperature measurements using center pivot mounted IRTs. In *Proc. 5th International Conference on Precision Agriculture*, CD–ROM. P. C. Robert, R. H. Rust, and W. E. Larson, eds. Bloomington, Minn. July 16–19. Madison, Wisc.: ASA/CSSA/SSSA.

Idso, S. B., R. D. Jackson, P. J. Pinter Jr., R. J. Reginato, and J. L. Hatfield. 1981. Normalizing the stress–degree–day parameter for environmental variability. *Agric. and Forest Meteorology* 24(4): 45–55.

Jackson, R. D., S. B. Idso, R. J. Reginato, and P. J. Pinter Jr. 1981. Canopy temperature as a crop water stress indicator. *Water Resources Research* 17(4): 1133–1138.

Kalma J. D., H. Alksnis, and G. P. Laughlin. 1988. Calibration of small infrared surface temperature transducers. *Agric. and Forest Meteorology* 43(1): 83–98.

Karlen, D. L., E. J. Sadler, and W. J. Busscher. 1990. Crop yield variation associated with Coastal Plain soil map units. *Soil Science Society of America J.* 54(3): 859–865.

Kustas, W. P., and J. M. Norman. 1996. Use of remote sensing for evapotranspiration monitoring over land surfaces. *Hydrological Sciences* 41(4): 495–516.

Martin, E. C., D. J. Hunsaker, E. M. Barnes, and P. M. Waller. 2000. Growing crops in the desert. *Resource Eng. and Technology for a Sustainable World* 7(11): 7–9.

Moran, M. S., and R. D. Jackson. 1991. Assessing the spatial distribution of evapotranspiration using remotely sensed inputs. *J. Environmental Quality* 20(4): 725–737.

Omary, M., C. R. Camp, and E. J. Sadler. 1997. Center–pivot irrigation system modification to provide variable water application depths. *Applied Eng. in Agric.* 13(2): 235–239.

Sadler, E. J., and C. H. M. Van Bavel. 1982. A simple method to calibrate an infrared thermometer. *Agronomy J.* 74(6): 1096–1098.

Sadler, E. J., P. J. Bauer, and W. J. Busscher. 1995. Spatial corn yield during drought in the SE Coastal Plain. In *Site–Specific Management for Agricultural Systems: 2nd International Conference*, 153–166. P. C. Robert, R. H. Rust, and W. E. Larson, eds. Madison, Wisc.: ASA/CSSA/SSSA.

Sadler, E. J., P. J. Bauer, W. J. Busscher, and J. A. Millen. 2000. Site–specific analysis of a droughted corn crop: II. Water use and stress. *Agronomy J.* 92(3): 403–410. 2000.

SAS. 1990. *SAS/GRAPH Software: Reference.* Version 6, 1st ed. Vols. 1–2. Cary, N.C.: SAS Institute.

Tanner, C. B., and W. L. Pelton. 1960. Potential evapotranspiration estimates by the approximate energy balance method of Penman. *J. Geophysical Research* 65(10): 3391–3413.
Upchurch, D. R., D. F. Wanjura, J. R. Mahan, J. J. Burke, and J. A. Chapman. 1998. Irrigation system having sensor arrays for field mapping. U.S. Patent Application SN 09/153,652.
USDA–SCS. 1986. Classification and correlation of the soils of Coastal Plains Research Center, ARS, Florence, South Carolina. Ft. Worth, Texas: South National Technical Center.