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Spatial and Temporal Analysis of Crop Conditions Using Multiple Canopy Temperature Maps Created with Center-Pivot-Mounted Infrared Thermometers

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Abstract. *A lack of real-time soil or plant status feedback and decision support systems has been a major stumbling block to the practical use of precision or site-specific irrigation and chemigation technologies. Data are needed on both a spatial and a temporal scale. It was hypothesized that an array of infrared thermometers, mounted on a center pivot, could provide this missing spatial and temporal feedback as they move over the entire field at regular intervals throughout the season. This was tested in a field of soybeans with varying degrees of induced water stresses in 2004 and 2005. Infrared thermometers were used to create canopy temperature maps of the underlying field every time the pivot moved over the field. These maps were standardized and combined into a single map for each year using an algorithm modeled after that used to combine multiple years of yield maps. These end-of-year maps for each year clearly showed* *stressed areas of the field. The combined, averaged, and standardized temperatures from the end-of-year maps were correlated with the end-of-year yield, biomass, and total water use in the different stressed plots for both years, resulting in* r^2 *values close to 0.8. These average, standardized temperatures were also significantly different across irrigation treatments in 2004. This demonstrates the method's ability to show spatial stress patterns in a field. To capture temporal variation and to highlight when temperature differences were caused by more than natural variation, statistical process control (SPC) charts were used to evaluate each point on the standardized temperature maps over time. Stress was deliberately introduced to a particular area of the field late in the 2005 season, and although the stress was not visible to the eye, this stressed area was clearly apparent in the SPC charts. These data demonstrate the ability of an array of infrared thermometers mounted on a center pivot to provide producers with feedback on both the spatial and temporal variability of a field during a growing season.*

Keywords. Canopy temperature, Center pivot, Infrared, Precision control, Precision irrigation, Remote sensing, Yield map.

Efficient and effective use of agricultural inputs is important for grower profitability as well as environmental sustainability. These inputs include seeding density and applications of fertilizer, herbicide, insecticide, and/or irrigation water. Precision agriculture promises to be the next major improvement to the use-efficiency of these crop-production inputs. Because conditions across a field can be highly variable, varying the application of these inputs for the spatially variable soil and/or growing conditions within a field can decrease input costs and increase yields for the field as a whole while helping to protect our environment. A major challenge in this effort is defining useful management zones within a field based on this spatial variability and monitoring the changes in those management zones over time. Some methods that have been used to do this include soil sampling, aerial photography, satellite imaging, and yield mapping. Problems with these methods include high costs and/or infrequent applicability. Even where soil properties are quite non-uniform across center-pivot irrigation systems, soil maps alone are not sufficient and there is a need to sense plant water stress. The interaction between soil properties and plant growth is not easily predicted, and it is plant growth that determines water use. In addition, spatial variability of precipitation and runoff or runon will lead to variability of available water even in uniform soils, and thus will require that plant water stress be spatially sensed and responded to.

In an overview of current precision irrigation technologies, Evans et al. (2000) concluded that in order for site-specific irrigation to be practical on a large scale, inexpensive, real-time sensing of the soil and/or plant status integrated with communications networks and control and decision support systems needed to be developed. McBratney et al. (2005), in a look at the present progress of and future directions for precision agriculture, stated that the development of proper decision support systems for implementing precision agriculture remains a major stumbling block to adoption. They also concluded that there was insufficient recognition of temporal variation as well as spatial variation.

A method that has shown promise for remotely assessing crop stress is measuring crop canopy temperatures (e.g., Jackson, 1982; Wanjura et al., 1995; Evett et al., 2000). The canopy temperatures of stressed plants tend to be comparatively warmer than those of non-stressed plants. A center pivot or lateral move provides an ideal platform for mounting canopy temperature sensing equipment. Not only are these self-propelled irrigation systems used extensively by irrigators around the world, they have the added advantage that they travel over a field regularly throughout the season in their irrigation cycles. An array of canopy temperature sensors mounted on one of these irrigation platforms could be used to regularly create canopy temperature maps, thus providing less expensive, real-time feedback of the crop status for the entire field. Early work on the concept of creating canopy temperature maps using an array of infrared thermometers mounted on a center pivot was done by Sadler et al. (2002).

A common problem in creating maps using data acquired from sensors mounted on a moving system is that such maps reflect whatever variation in microclimate occurred between the start and end of the measurement period, which may be several hours or days. Creation of a time-independent map requires a method for correcting for temperature changes due to such changing micro-climatic conditions. Peters and Evett (2004a, 2004b) presented a method of doing this by scaling canopy temperatures sensed at one time of day to accurately estimate temperature at another time of day. Their method used a reference diurnal canopy temperature curve sensed from the living canopy at a stationary location in the field. They also found that the degree of water stress of the reference canopy in the stationary location had little effect on the accuracy of the scaling method.

All of these developments have enabled the creation of time-of-day independent canopy temperature maps at regular intervals throughout the season using an array of infrared thermometers mounted on a moving irrigation system. Two objectives of this research were to combine a series of canopy temperature maps created on a center-pivot-irrigated field with varying water stress treatments into a single map for the whole season, and to determine the relationship, if any, of this map to the induced water stresses in the various areas of a field and to the yields obtained from these areas. A third objective was to do preliminary testing of the use of statistical process (Shewart) control (SPC) charts for capturing temporal variability and using these charts to monitor changes and watch for problem areas in a field during a growing season. These methods will place tools in the hands of producers and researchers that can be used to evaluate a field's performance on a spatial scale similar to yield maps. However, these regularly created maps can also be used during the season as well as at the end of the season. This information could help growers to maximize yields while minimizing inputs for improved profitability and environmental quality.

Materials and Methods

This study is part of a broader experiment in center pivot automation based on the time-temperature-threshold (TTT) method of irrigation scheduling in 2004 and 2005. The experimental site was a three-tower, 127 m long research center pivot located at the USDA-ARS Conservation and Production Research Laboratory at Bushland, Texas (35? 11' N, 102? 06' W, 1170 m elev. above MSL). Only half of the field was used each year to allow the other half to be planted to a cover crop to even up the residual soil water differences from previous year's irrigation treatments (fig. 1). Soybean rows were planted in concentric circles spaced at 0.76 m beginning at 20 m from the center point. Agronomic practices common in the region for high yields were used. The soil is a Pullman clay loam (fine, superactive, mixed, thermic torrertic Paleustoll; USDA-NRCS, 2005) with slow permeability due to a dense B21t layer that is 0.15 to 0.40 m below the surface. A calcic horizon begins about 1.2 m below the surface and somewhat limits rooting and water extraction below this depth (Tolk et al., 1999). The plant-available water holding capacity within the top 2.0 m of the profile is approximately 240 mm (~200 mm to 1.5 m) depth. This soil is common to more than 1.2 million ha of land in this region and about 1/3 of the sprinkler-irrigated area in the Texas High Plains (Musick et al., 1988; 1990).

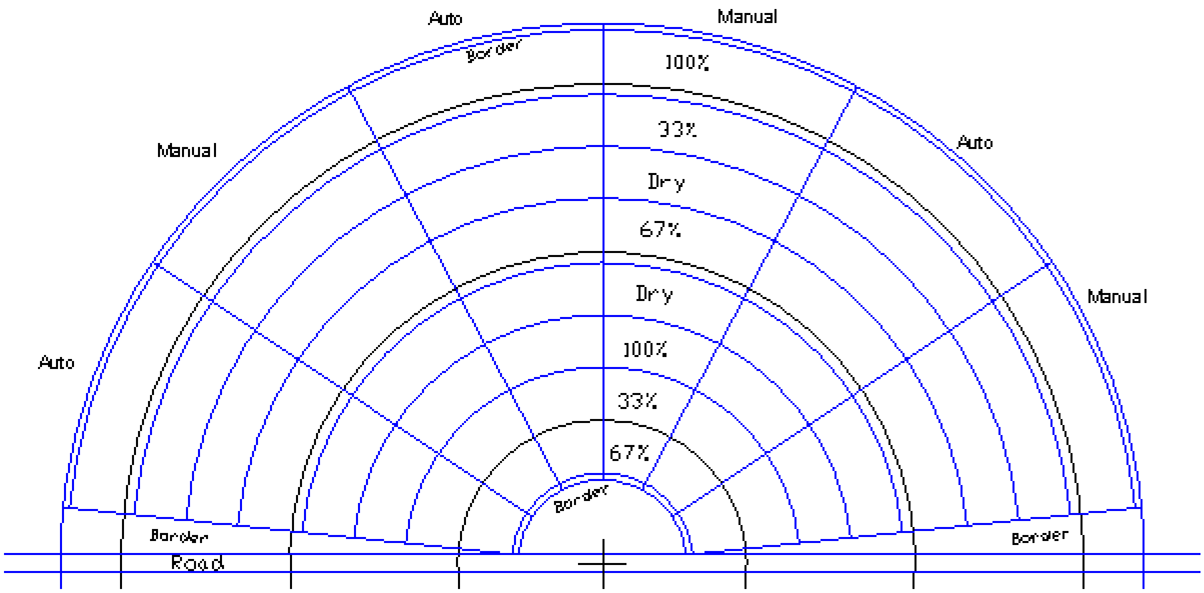

Figure 1. Center pivot plot plan for 2004. The automatic and manual irrigation management treatments, and the dry (no irrigation), 33%, 67%, and 100% of required irrigation treatment areas are shown.

Four different water level treatments were applied radially from the pivot center in two randomized complete blocks, providing varying levels of plant stress throughout the field (fig. 1). Treatments were 100%, 66%, and 33% of projected irrigation needs, and a dry-land (no irrigation) treatment. Drops were spaced every other row (1.52 m) and fitted with low-energy precision application (LEPA) drag socks. Each drop was pressure regulated to 41 kPa. The irrigation amount was controlled by nozzle sizes and pivot rotation speed as appropriate. The furrows were dammed/diked to limit water movement in the furrows. The randomization in 2005 was slightly different, with irrigation treatments starting from the centermost treatment being: 67%, dry, 33%, 100%, 67%, 100%, dry, and 33%.

Each year there were three arc-wise blocks each of an automatically controlled (via the TTT method) irrigation scheduling treatment and of a treatment for which the irrigations were manually scheduled using soil water deficiency as determined by neutron probe soil moisture meter. These blocks were applied in alternate wedge shapes around the pivot. Two additional rows of soybeans were planted around the outside and inside edges of the pivot to help minimize border effects. Neutron probe access tubes were installed near the center of each plot for initial and end-of-season soil moisture determinations. Additional soil moisture determinations were made in the 100% treatment plots for irrigation scheduling on a weekly basis. Methods used, including use of a depth control stand to improve accuracy of near-surface soil moisture and calibration to accuracy of <0.01 $m^3 m^{-3}$, are given in Hignett and Evett (2002), Evett and Steiner (1995), and Evett et al. (2003).

End-of-season yield and total biomass were obtained from each plot by hand-harvesting two adjacent rows 2.29 m long near the center of each plot (3.48 m^2). Total seasonal crop water use was also calculated for each plot by the soil water balance method. Soil water measurements were taken to 2.3 m depth, well below the depth to which irrigation and precipitation infiltration events penetrate. Soil water content at 2.3 m was small so that hydraulic conductivity was very small, and the hydraulic gradient at that depth was also quite small, leading to no appreciable deep percolation loss in the soil water balance equation. The plots were large enough that loss or gain of water due to lateral movement of water was likewise unimportant. Rainfall data were collected at a weather station located adjacent to the field.

A datalogger (CR10X, Campbell Scientific, Logan, Utah) mounted on the center pivot collected data from

16 infrared thermocouple thermometers (IRTCs) attached to the trusses of the pivot. The IRTCs were mounted on the leading side of the pivot, and the pivot was only allowed to irrigate in one direction so that the sensors would not view wet canopy. In 2004, the IRTCs were narrow field-of-view (ratio of distance to view spot size was 10:1) and were oriented so that they pointed parallel to the center pivot arm (perpendicular to crop rows) towards a spot in the middle of each concentric irrigation treatment plot. The sensors were oriented at about a 45? angle so that the canopy could be viewed earlier in the season without the soil background in the field-of-view. In order to minimize sensor angle related effects, two IRTCs were aimed at approximately the same spot from opposite sides of each plot (Wanjura et al., 1995). The average of these two readings for each plot was used. In 2005, broader field-of-view IRTCs (model IRt/c.2-T-80, Exergen Corp., Watertown, Mass.) were used (ratio of distance to view spot size was 2:1). These sensors were mounted much closer to the canopy, at about 1 m from the soil surface, using mounting arms made of angle iron attached to the pivot trusses, and oriented at 45? towards the center of the plot and perpendicular to the crop rows, similar to what was done in 2004. The height of these sensors was adjusted upward throughout the season to accommodate the growing canopy height. Again, two different IRTCs were pointed at the same plot from different angles, and the average of the two was used in the data analysis. Data were not used in the season until the sensors at 45? did not view soil background information.

The IRTCs on the pivot were connected to a multiplexer (Campbell Scientific AM25T) at the second tower, and the results were conveyed to the datalogger at the third and last tower. Readings were taken on 10 s intervals, and 1 min averages were logged. Pivot position estimates were obtained from the pivot control panel on 1 min intervals. These position estimates were corrected for errors (Peters and Evett, 2004c) and were adjusted for the speed and direction of the pivot so that the recorded position was in the center of the arc across which the 1 min average temperatures were sensed. All measurements taken within a 4? arc were grouped together and averaged. A collection of spatially oriented temperature point data (temperature maps) was created for each day that the pivot moved throughout the season. Canopy temperature, like many other crop stress indicators such as leaf water potential, is very limited at night. Therefore, all pivot movements were scheduled such that all of the plots could be mapped during daylight hours. Each IRTC was separately calibrated (second-order polynomial) using a black body (model BB701, Omega Engineering, Inc., Stamford, Conn.) before the season began.

In order to scale the individual temperature measurements to a common time of day, the diurnal canopy temperature dynamics were captured by two IRTCs (Exergen IRt/c.2-T-80) mounted in stationary locations in two of the 100%, manual irrigation treatments. Each IRTC was mounted in the nadir position over the crop row, close enough to the canopy that soil was not included in the field of view. These IRTCs were adjusted upward throughout the season with the changing height of the canopy. They were connected through a multiplexer (Campbell Scientific AM25T) to a datalogger (Campbell Scientific CR21X). The datalogger recorded the 5 min averages of each of the IRTC readings collected on 10 s intervals.

Peters and Evett (2004a) showed that canopy temperatures at other times of day and in other parts of a field, which may be under different stresses, could be modeled relative to such a reference using only a one-time-of-day temperature measurement (as in fig. 2) by:

$$T_{rmt} = T_e + \frac{(T_{rmt,t} - T_e)(T_{ref} - T_e)}{T_{ref,t} - T_e} \quad (1)$$

where T_{rmt} is the calculated canopy temperature at the remote location, T_e is the early morning (pre-dawn) canopy temperature, T_{ref} is the canopy temperature from the reference location at the same time interval as T_{rmt} , $T_{rmt,t}$ is the one-time-of-day canopy temperature measurement at the remote location at any daylight time t , and $T_{ref,t}$ is the measured reference temperature from the time that the remote temperature measurement was taken (t). Equation 1 was used to standardize all temperature measurements taken from the moving center pivot to 12:00 h CST, effectively creating a canopy temperature map of the field and compensating for time lag.

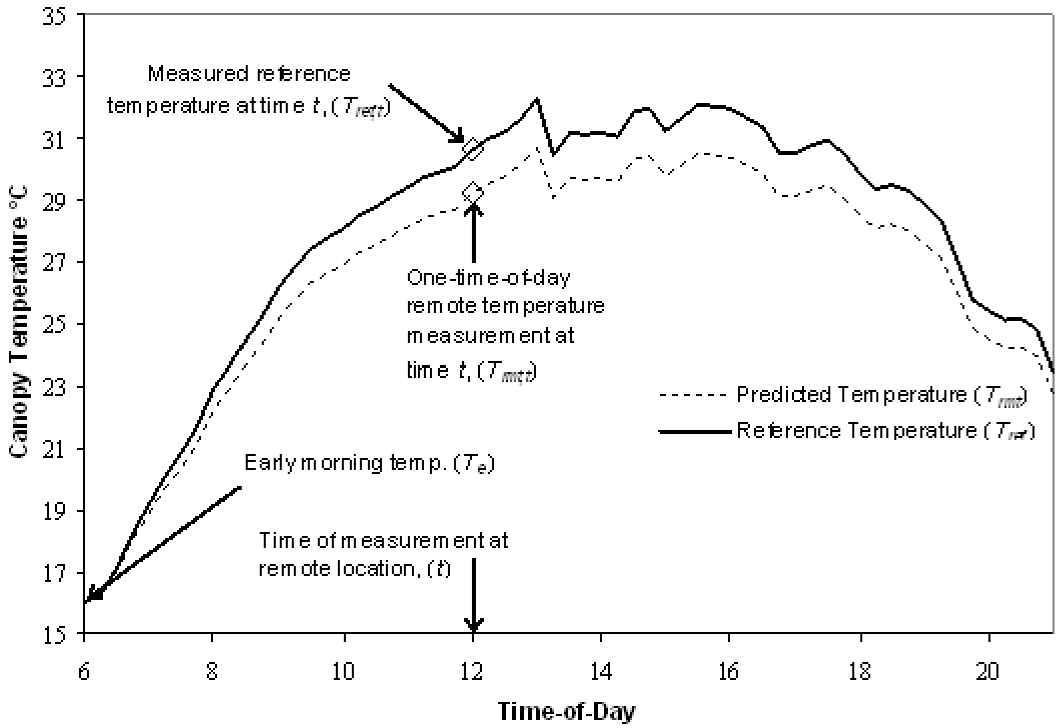

Figure 2. Diagram demonstrating the terms used in the scaled method (eq. 1). Time *t* might be any daylight time at which a canopy temperature ($T_{rmt,t}$) was measured at a remote location in the field. A contemporaneous temperature ($T_{ref,t}$) from the reference temperature data is then used in equation 1 along with the common pre-dawn minimum temperature (T_e) and each value in the reference temperature data (T_{ref}) to predict corresponding temperatures at the remote location throughout the daylight hours (T_{rmt}).

Canopy temperature maps created throughout the season are influenced by daily weather conditions. A method of standardizing these maps was needed so that comparisons could be made between maps taken on different days. This problem is similar to comparing multiple years of yield map data. Methods for standardizing yield maps include dividing the individual yield points by the field-average yield (Moore and Wolcott, 2000; Taylor and Whitney, 2005), using a binary system for above- or below-average yield (Diker et al., 2005), and using the relative value between maximum and minimum yield (Carlson et al., 2005). The latter method was used for standardizing individual canopy temperature measurements (T_{std}) in the field for each day a map was created:

$$T_{std} = \frac{T_i - T_{min}}{T_{max} - T_{min}} \quad (2)$$

where T_{max} is the maximum measured canopy temperature in a particular map, T_{min} is the minimum measured canopy temperature in the map, and T_i is the individual canopy temperature measurement. The value of T_{std} is between 0 and 1, with 0 being the coolest temperature in the field and 1 being the warmest. Once each day's temperature map had been standardized, the average and standard deviation of *T* *std* for all maps in the season were calculated for each field position. Visual maps were created using ArcMap (ESRI Corp., Redlands, Cal.).

Manufacturers use statistical process control (SPC) to determine when the variability in their product measurements is no longer due to natural variation but due to some special cause. Product measurements are plotted on control charts, and a number of different tests can be applied to statistically determine when the variability between measurements is no longer due to natural variation. When this happens, the process is termed out of control. This same procedure was applied to each point on the temperature maps that were created throughout the growing season to capture and examine temporal variability as well as spatial variability. A separate control chart was created for each point on the scaled and standardized temperature map for the whole growing season. Individual measurement and moving-range control charts were used (Proc Shewart, IRCHART statement; SAS Institute, Inc., Cary, N.C.) with only test 1 (one or more points outside the 3-sigma control limits) and test 3 (six points in a row steadily increasing or steadily decreasing) enabled. Discussion of the creation and use of statistical process control is outside the scope of this article. Very good documentation on the use of Shewart control charts is available online in the SAS/QC (quality control) documentation (SAS, 2005).

Results and Discussion

The resultant map of the averaged *T std* for each field position is given in figure 3 for 2004 and figure 4 for 2005. The differences between the irrigation treatments are visible in the maps. These differences were also visible in the field to the eye. In 2004, the differences between the automatic and manual treatments were difficult to perceive by eye in the field. However, some of these differences are visible in figure 3. The averaged values of *T std* in each treatment were analyzed for both years to determine whether there were statistical differences at the 0.05 level between the various water stress treatments (table 1). The statistics for the end-of-year yield and total biomass for the various treatments are also given for comparison. The analysis was done using SAS (SAS Institute, Inc., Cary, N.C.) with a procedure for mixed models (Proc Mixed) employing the Tukey-Kramer method to adjust for multiplicity. The standard deviations of *T std* were also analyzed since these are often of interest to those comparing multiple years of yield maps. No significant differences were found in the standard deviation data between irrigation treatments, and it is difficult to gain any useful information from end-of-year average maps of these standard deviations.

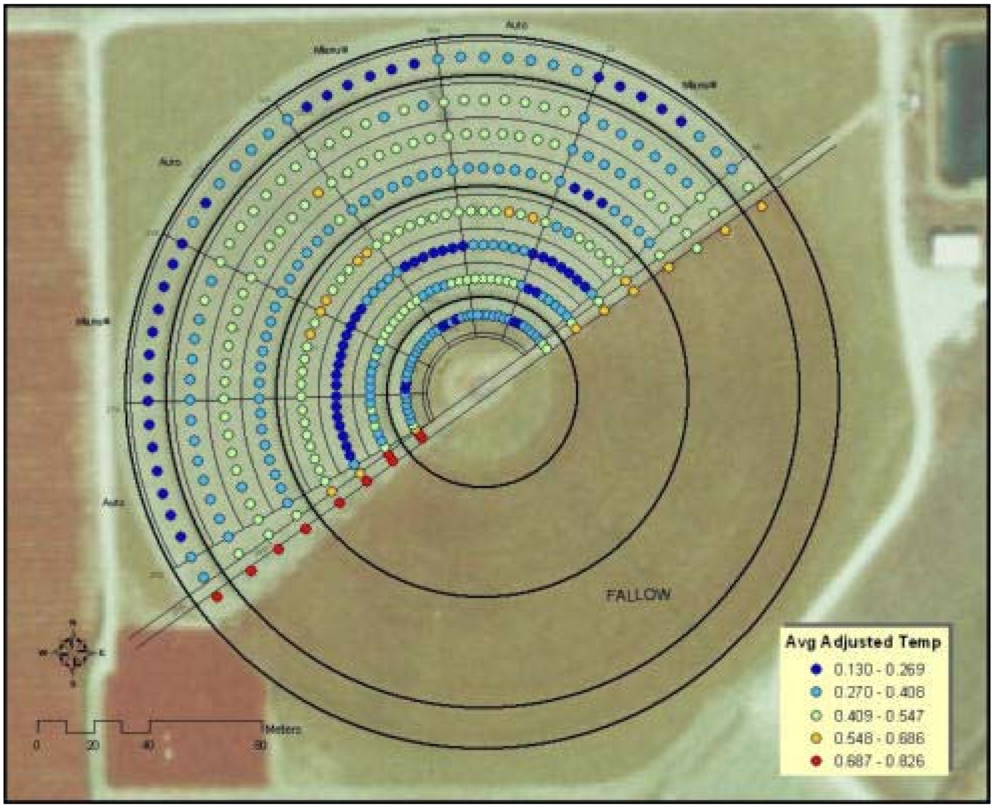

Figure 3. Temperature map of average, adjusted, scaled canopy temperatures for 2004.

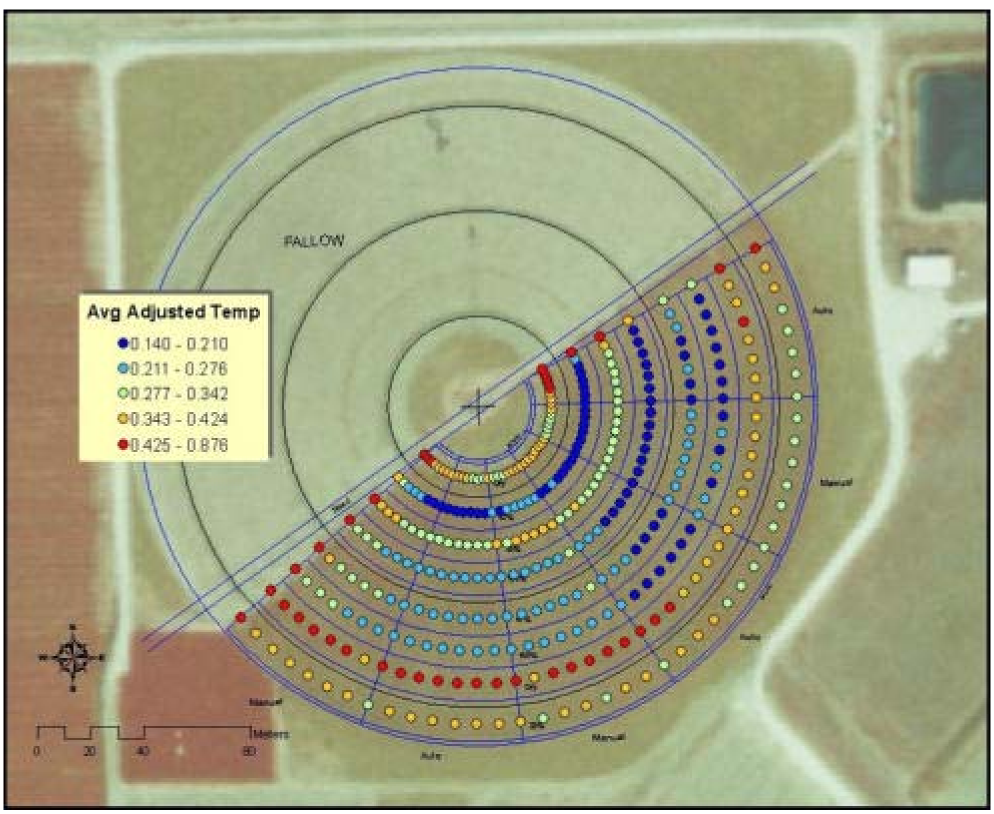

Figure 4. Temperature map of average, adjusted, scaled canopy temperatures for 2005.

Table 1. Response of the scaled canopy temperature measurements (*T std*) and the end-of-year dry yield and biomass measurements in 2004 and 2005. Treatments were manual vs. automatic, and the irrigation levels (100%, 67%, 33%, and dry). Values in the same column followed by the same letter are not significantly different at the 0.05 level.

	2004			2005		
Treatments	Mean *T std* [a] (?C)	Dry Yield (kg m^{-2})	Biomass (kg m^{-2})	Mean *T std* (?C)	Dry Yield (kg m^{-2})	Biomass (kg m^{-2})
Manual [b]	0.343 a	0.295 a	2.20 a	0.305 a	0.272 a	1.22 a
Automatic	0.391 a	0.270 b	2.01 b	0.286 a	0.289 a	1.31 a
100% [c]	0.250 a	0.400 a	2.96 a	0.222 a	0.383 a	1.63 a
67%	0.326 b	0.345 b	2.45 b	0.220 a	0.321 b	1.38 b
33%	0.397 b	0.256 c	1.86 c	0.337 b	0.239 c	1.11 c
Dry	0.495 c	0.130 d	1.13 d	0.402 b	0.178 d	9.34 d

[a] Mean of the standardized canopy temperature measurements.

[b] Values for manual and automatic treatments are means across all irrigation levels.

[c] Values for irrigation levels are means across both manual and automatic treatments.

Significant differences in the averaged *T std* were found between all of the irrigation-induced water-stress treatments except the 33% and 66% levels in 2004. However, in 2005, the only significant differences were between the two drier treatments and the two wetter treatments. These results resemble the differences in the end-of-year measured yield and total biomass results. Although the difference in *T std* between the manual and automatic irrigation treatments in 2004 was not significantly different at the 0.05 level, similar to the yield and dry matter data, it was fairly close, with a Pr > F = 0.15. The averaged *T std* from each treatment was also plotted against the yield from the corresponding treatment (fig. 5), and an r^2 value of 0.783 was obtained for a linear regression in 2004 and 0.780 in 2005. Similar r^2 values were obtained for the regression of the averaged *T std* from each treatment with the total plant biomass and total water used, as shown in figure 5. The root mean squared errors (RMSE) of regression for the predicted yield, biomass, and total water used were 0.049 kg/m^2, 0.086 kg/m^2, and 49.7 mm, respectively, for 2004 and 0.038 kg/m^2, 0.135 kg/m^2, and 43.3 mm, respectively, for 2005. These r^2 and RMSE values demonstrate the ability of this method to identify stressed areas in a field and thereby identify management zones for precision agriculture under self-propelled irrigation systems. They also demonstrate this method's potential to predict yield, total biomass accumulation, and total water use.

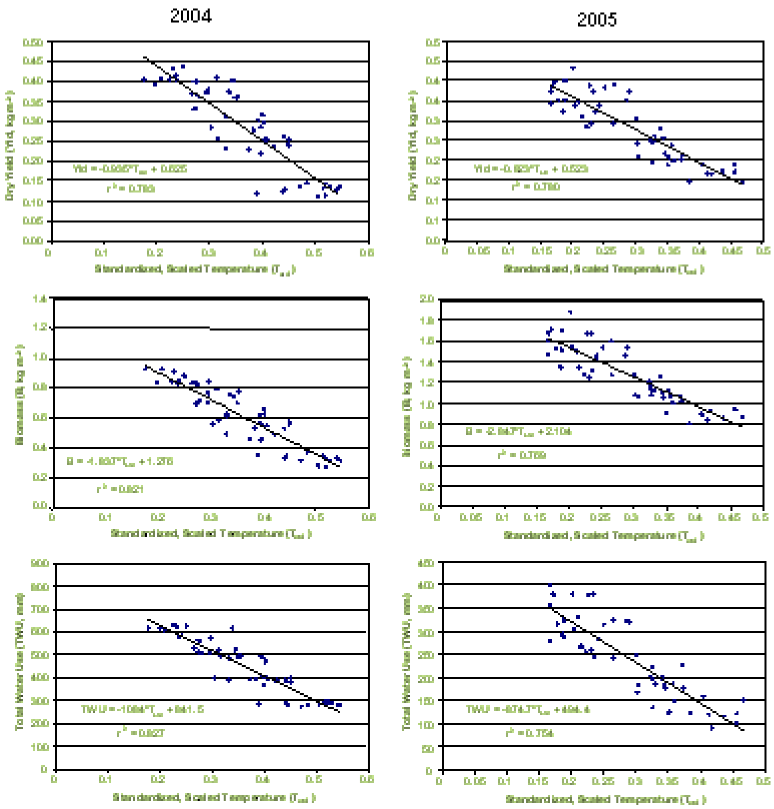

Figure 5. Scatter plots of the standardized, scaled canopy temperatures (*T std*) over the season with year-end yield, total biomass, and total water use in 2004 and 2005.

Figure 6 gives an example of the statistical process (Shewart) control, individual measurement, and moving range charts for just one of the many points in the temperature map over the growing season. Although in this example no points go beyond the upper control limit (UCL), one point goes out of control by exceeding the lower control limit (LCL) on 29 July (DOY 211). Out-of-control instances were categorized into five different values: 0 = in control, 1 = exceeded the LCL (violates SPC standard test 1), 2 = exceeded the UCL (violates test 1), 3 = six points or more steadily increasing or decreasing, and 4 = exceeds either the UCL or LCL of the moving range chart. The out-of-control points from each time the moving irrigation system mapped the field canopy temperatures could then be shown in a separate out-of-control map for that day. An example for DOY 211 is given in figure 7. The out-of-control point from figure 6 can be seen in figure 7 as the second irrigation treatment out from the center (33% irrigation) between the middle manual and automatic irrigation treatments. Data sufficient to track down each out-of-control point were not collected in either year. However, figure 7 shows a typical pattern of the out-of-control points lying between the automatic and manual irrigation treatments. This area of the field is where the pivot stopped to drain or pressure-up so as to not influence the next treatment. This would cause erratic behavior in the amount of water received in these areas, causing them to possibly receive more water than was previously typical and cause out-of-control points.

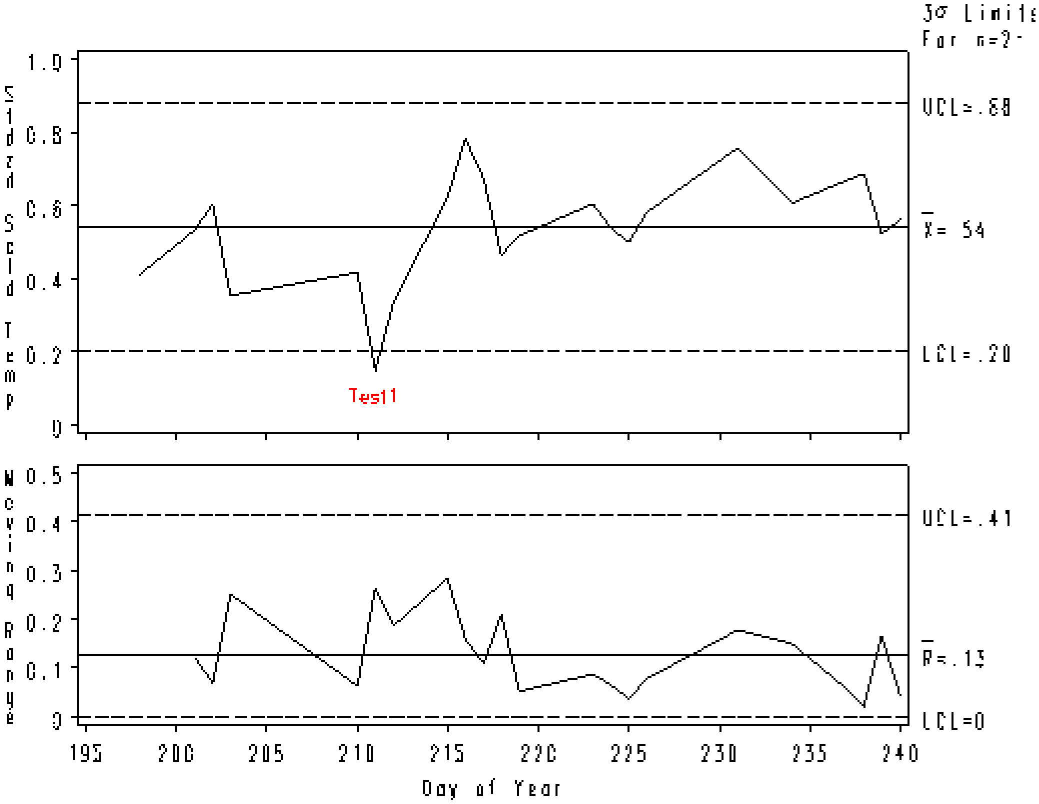

Figure 6. Example of the SAS individual measurement and range charts for a particular point (3262 in the second plot out from the center point, which is a 33% irrigation plot) showing one out-of-control point exceeding the lower control limit (LCL) on DOY 211.

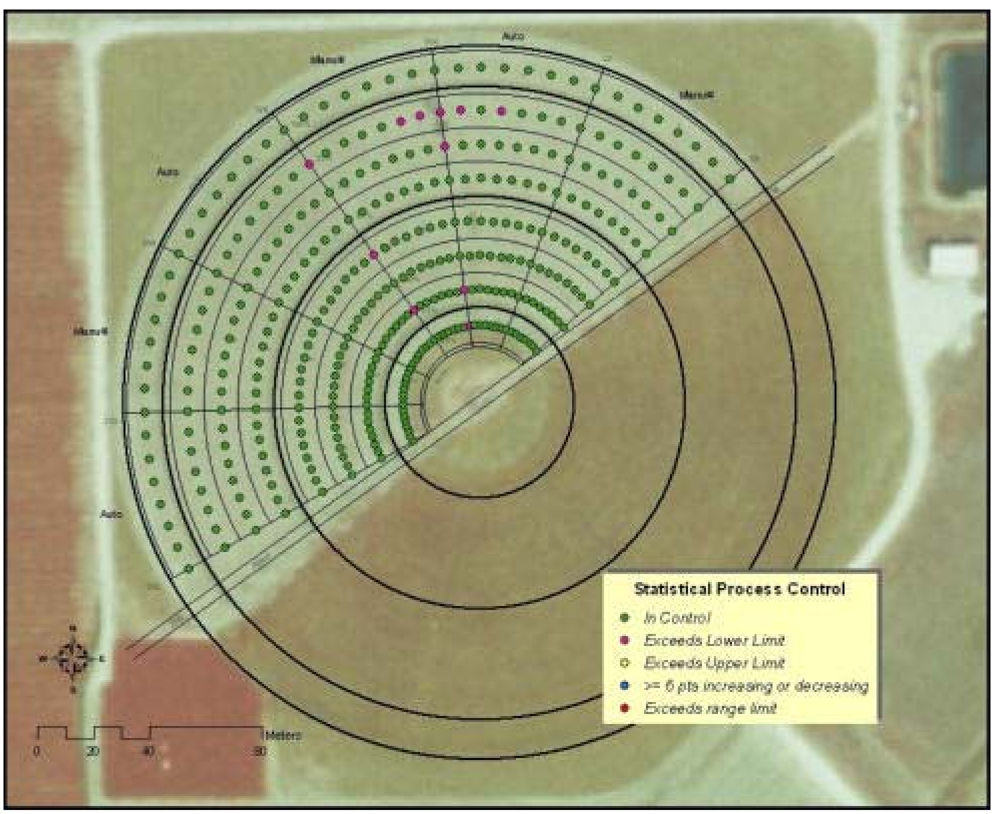

Figure 7. Field map for DOY 211 showing out-of-control points for this day. On this particular day, the only out-of-control points were those where the lower control limit was exceeded on the individual measurements chart.

To test the SPC method's ability to monitor temporal variations in a field, a slice of the field was deliberately stressed in 2005 to see if the temporal changes could be highlighted by these maps. This was done on 14 September (DOY 257) by applying two times the maximum recommended amount of Roundup (to the Roundup-ready soybeans) and at a much later time of year than recommended to a thin pie-slice shaped wedge in the northeast corner of the field in such a way that the area where the yield and biomass samples were taken would not be affected. No change to the canopy was visible to the eye, yet it can be clearly seen in the out-of-control map created the following day on DOY 258 (fig. 8). Although this demonstration is preliminary and additional research needs to be done, this method shows the potential of being able to graphically display areas of fields where problems arise due to pest infestations, plant disease, or problematic irrigation systems. These problems would be special causes of variability and could be graphically shown on the out-of-control maps. A key advantage of the method is its ability to highlight problems during the growing season, when something might be done about them, instead of after the growing season.

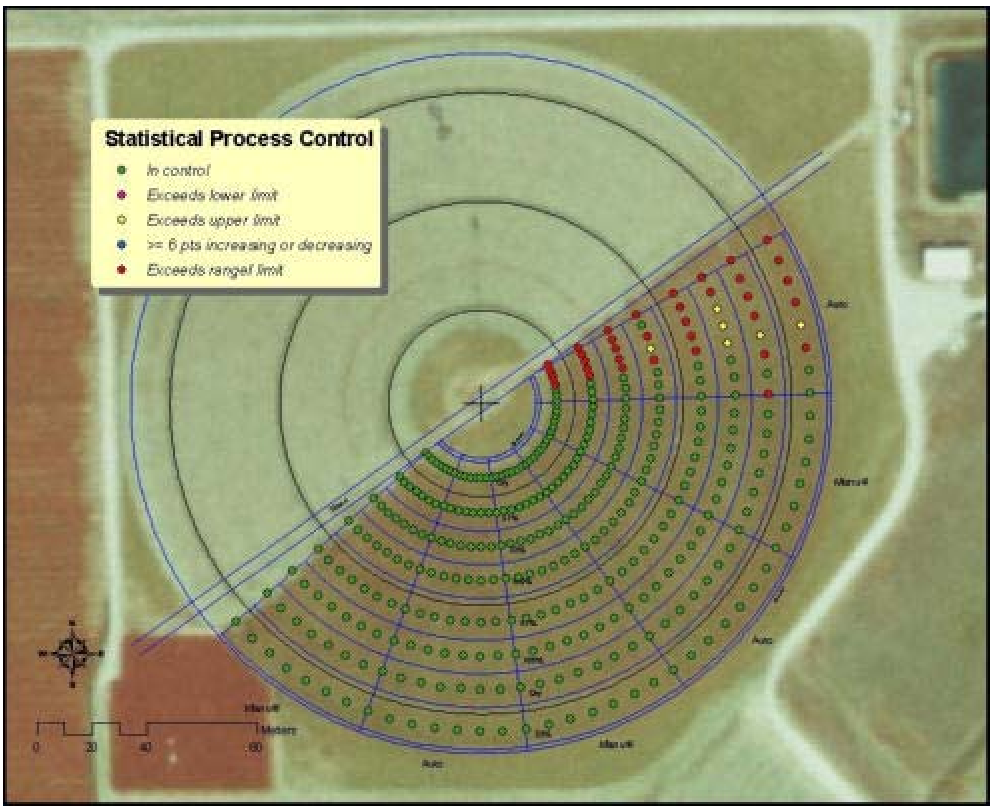

Figure 8. Field map for DOY 258 showing out-of-control points for this day. Although the effects were not visible to the naked eye, the out-of-control points highlight the region where the additional herbicide was sprayed.

Summary and Conclusions

The advancement of precision irrigation requires a less expensive system for spatially monitoring crop status over time. Canopy temperature maps were created by an array of infrared thermometers mounted on a center pivot in a field with varying degrees of irrigation stress treatments in 2004 and 2005. To account for time lag, the individual canopy temperature measurements were scaled to 12:00 h. These maps were then standardized and combined into a single map similar to what is commonly done with multiple years of yield map data. The standardized temperatures from this map showed statistical differences consistent with the significant differences found in the end-of-year yields and total biomass. The average standardized canopy temperatures from the combined map were also found to be highly correlated with yield, biomass, and total water use, with r^2 values close to 0.8 for each year. This demonstrates the capability of this method to help identify stressed areas of a field. The use of statistical process (Shewart) control charts for each point in a field was demonstrated as a potential method for monitoring temporal variation in a field. This was demonstrated in 2005 by deliberately stressing a part of the field. Although the stressed area was not visible to the eye, it showed up in the out-of-control map. The methods and technology presented here demonstrate a method for sensing plant water status on a spatial and temporal scale. These data may be useful for identifying precision irrigation/chemigation management zones and for monitoring fields during the season, while the grower still can respond to issues causing crop stress.

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