DETERMINING COTTON LEAF CANOPY TEMPERATURE USING MULTISPECTRAL REMOTE SENSING

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Abstract

Previous studies at Shafter have demonstrated that differences in surface temperature associated with water stress can readily be observed in multispectral images of cotton *(Gossypium hirsutum* L.) fields. In 1999, remote sensing and field observations were made to develop a linear mixture modeling approach to extracting cotton leaf canopy temperature from measurements of surface temperature. In this approach, bare soil temperature within the field was found to be correlated with the amount of crop ground cover. With this information, the effects of incomplete ground cover could be accounted for in estimating the temperature of the cotton leaf canopy.

Introduction

Plant canopy temperature has been recognized as a sensitive indicator of plant water status, and has lead to the development of stress-related indices based on the difference between plant canopy and ambient air temperature (Jackson et al., 1981; Idso, 1982). This concept has been extended to remotely sensed measurements of canopy temperature under incomplete ground cover conditions (Moran et al., 1996). During the 1998 growing season, remote sensing data were collected at Shafter, CA, and analyzed to demonstrate the ability to detect the onset of water stress in cotton fields (Maas et al., 1999). Additional data were collected in 1999 to facilitate the development of a generalized procedure for estimating cotton leaf canopy temperature from remotely sensed surface temperature under conditions of incomplete ground cover. The objective of this presentation is to describe the development of this procedure.

Field Study

The field study was conducted on a 1.7-acre (0.7-ha) field at the Shafter Research and Extension Center, Shafter, CA, during 1998 and 1999. In 1998, the field was planted on April 17 with the Acala cotton variety 'MAXXA' in 30-in (0.76-m) rows. Row direction was oriented north-south. In 1999, the field was planted on May 6. Cotton variety, row spacing, and row orientation were the same as in 1998. The soil belonged to the Wasco series of sandy loams (coarse-loamy, mixed, nonacid, thermic Typic Torriothents).

The field was irrigated using subsurface drip irrigation, with one drip line located at a depth of 10 in (25.4 cm) below each row. The field was divided lengthwise into 6 plots, each plot being 16 rows wide. Irrigation could be controlled separately for each plot using an automated system capable of replacing each day's evapotranspiration (Phene et al., 1992). A strip of bare soil approximately 40 ft (12 m) wide was maintained weed-free along the north end of the field.

Plots were numbered 1 through 6 from west to east in the field. Two water stress treatments were used in each year of the study. The first, called the early stress treatment, involved withholding irrigation from two plots (plots 1 and 4 in 1998 and plots 2 and 5 in 1999) for approximately a week (between July 20 [day 201] and July 28 [day 209] in 1998, and between July 12 [day 193] and July 22 [day 203] in 1999). The second, called the late stress treatment, involved turning off the irrigation to two plots (plots 2 and 5 in 1998 and plots 1 and 4 in 1999) for approximately a week (between August 10 [day 222] and August 18 [day 230] in 1998, and between August 9 [day 221] and August 17 [day 229] in 1999). During both years, irrigation was maintained at levels sufficient to prevent water stress throughout the season in plots 3 and 6 and in the other plots before and after their respective stress treatments.

Imagery of the study field was obtained both years using the Shafter Airborne Multispectral Remote Sensing System (SAMRSS), which contains digital cameras capable of obtaining imagery in the visible, near-infrared, and thermal infrared wavebands. SAMRSS is flown aboard a light aircraft at approximately 3000 ft (910 m) AGL. Imagery of the study field was obtained daily during the two stress treatments. In both years, imagery was obtained in the red (550 nm) and near-infrared (850 nm) wavebands using Dalsa digital cameras (Dalsa, Inc., Waterloo, Ontario, Canada). During 1998, thermal imagery was obtained using an Inframetrics model 760 thermal imager (Inframetrics, Inc., North Billerica, MA). During 1999, thermal imagery was obtained using either a Raytheon ExplorIR thermal imager (Raytheon Systems, Goleta, CA) or an Indigo Merlin thermal imager (Indigo Systems, Santa Barbara, CA). All imagery was obtained at local solar noon (approximately 1:00 pm PDT).

SAMRSS imagery was calibrated using three large (32 ft on a side) targets located on the ground next to the study field. Each target was constructed of plywood and painted either white, black, or an intermediate shade of gray. The reflectance of each target was measured using a portable field spectroradiometer (Model LI-1800, LI-COR, Inc., Lincoln, NB). At the time of an aircraft overpass, the temperature of

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each target was measured using a hand-held infrared thermometer (Everest Interscience, Inc., Fullerton, CA). These data were used to convert image digital counts in the visible and near-infrared wavebands to surface reflectance, and image digital counts in the thermal waveband to surface temperature. Image data in the various wavebands were registered and resampled to a common pixel size using ENVI image processing software (RSI, Inc., Boulder, CO).

During 1998, ground-based measurements of plant canopy and bare soil temperature were made on most days with aircraft overflights using a handheld infrared thermometer. Measurements were made at the same time as the aircraft overflights. Bare soil temperature was measured at 10 random locations within the bare soil strip at the north end of the field. Plant canopy temperature was measured at 10 random locations within each plot. Plant canopy temperature was measured by pointing the infrared thermometer at an oblique angle to the surface of the crop so that leaves would obscure any bare soil surface between the rows of plants.

During 1999, ground-based measurements of plant canopy and bare soil temperature were continuously recorded from four arrays of miniature infrared thermometers (MIRTs). Up to July 29 (day 210), MIRT arrays were located in plots 2, 3, 5, and 6. After July 29, MIRT arrays were located in plots 1, 3, 4, and 6. A MIRT array consisted of five miniature infrared thermometers attached to a bar transversing two rows of cotton plants; the MIRTs were equally spaced, with the first and last located over the adjacent rows. Each MIRT pointed downward, and the bar could be moved upward to maintain a relatively constant distance (approximately 0.3 m) between the MIRTs and the cotton canopy over the course of the growing season. In addition to these four arrays, four separate MIRTs were positioned over the bare soil strip on the north end of the study field to measure bare soil temperature outside the field. All MIRTs were connected to a data logger which recorded 15-min averages of surface temperature from each sensor.

In both years, measurements of plant height and width were made weekly in each plot. Measurements were made on 10 randomly selected plants in each plot using a meter stick. Ground cover of cotton rows was estimated as plant width divided by row spacing.

Theoretical Analysis

There has been recent success (Maas, 1998) in using a linear mixture model (LMM) to estimate crop ground cover from remotely sensed measurements of surface reflectance in the red and near-infrared wavebands. In this presentation, a similar approach is proposed to "unmix" remotely sensed measurements of surface temperature to provide estimates leaf canopy temperature.

We can write a simple LMM for surface temperature (Tsurface):

$$\mathrm{Tsurface} = \mathrm{Tcanopy}\cdot\mathrm{GC} + \mathrm{Tsoil}\cdot(1-\mathrm{GC}) \qquad \text{Eq. 1}$$

in which Tcanopy and Tsoil are, respectively, the temperatures of the leaf canopy and bare soil visible between plants, and GC is ground cover. Equation 1 can be "unmixed" to provide a direct estimate of leaf canopy temperature:

$$\mathrm{Tcanopy} = (\ \mathrm{Tsurface} - \mathrm{Tsoil}\cdot(1-\mathrm{GC})\ )\ /\mathrm{GC} \quad \text{Eq. 2}$$

Tsurface is obtained from the remotely sensed thermal imagery. GC is estimated from the remotely sensed imagery in the red and NIR wavebands, using the LMM procedure of Maas (1998). With an estimate of Tsoil, Equation 2 can be solved for leaf canopy temperature.

Results and Discussion

Figure 1 shows values of bare soil temperature measured at solar noon over a 55-day period during 1999. Measurements outside the field were obtained from the MIRTs located on the bare soil strip at the north end of the field. Measurements inside the field were obtained from MIRTs in the field plots located such that they viewed the bare soil surface between rows of plants (typically the middle MIRT in each array). These data indicate that, while bare soil temperatures inside and outside the field were relatively equal at the start of the period, the difference between bare soil temperatures inside and outside the field increased with time thereafter.

The difference between bare soil temperatures inside and outside the field was calculated from the data in Figure 1 for each day with ground cover data, and is plotted versus the respective value of ground cover in Figure 2. The distribution of points in Figure 2 was fit with a linear regression,

$$\mathrm{Tsoil\ (outside)} - \mathrm{Tsoil\ (inside)} = 35.93\cdot\mathrm{GC} - 11.96 \quad \text{Eq. 3}$$

This relationship provides a reasonable fit ($R^2 = 0.90$) to the data, indicating that much of the difference in soil temperature inside and outside the field was associated with the amount of ground cover in the field. For values of GC less than 0.35, bare soil temperature inside the field could be greater than that observed outside the field. This is because the rows of cotton plants tended to reduce air circulation near the ground in the field, resulting in reduced convection of heat away from the soil surface. For values of GC greater than 0.35, shading of the soil surface by plants during part of the day resulted in reduced heat storage by the soil and cooler soil temperatures inside the field.

The implication of these findings is shown in Figure 3. Here, individual pixel values from imagery acquired on 13 August 1998 are plotted for a stressed plot (plot 1) and an unstressed control plot (plot 3) in the study field. The dashed diagonal line in the figure represents the LMM described by Equation 1 based on bare soil temperature measured outside the field; the circle on this line at GC=0 represents the bare soil temperature, while the circle at GC=1 represents the temperature of the unstressed leaf canopy measured with a handheld infrared thermometer. If this form of the LMM were correct, then the pixels from the unstressed plot should generally lie along the dashed line, while most of the pixels from the stressed plot should lie above the dashed line. This is not the case, suggesting that basing the LMM on bare soil temperature measured outside the field may not be appropriate. The curved solid line in Figure 3 represents the LMM based on estimates of bare soil temperature within the field derived from bare soil temperature measured outside the field adjusted using Equation 3. When compared to the pixel data, this form of the LMM appears to be more appropriate.

The ability of the unmixed LMM (Equation 2) to estimate Tcanopy from Tsurface was evaluated using remote sensing data and field observations from 1999. Values of surface temperature and surface reflectance in the red and NIR wavebands were extracted for several dates from areas within the imagery corresponding to the locations of the MIRT arrays. Bare soil temperatures were also extracted from the imagery for the strip of bare soil along the north edge of the study field. GC for each location within the field was estimated from the reflectance data. Tsoil for each location in the field was estimated using Equation 3 from observations of bare soil temperature outside the field and GC. Tcanopy was then calculated from the observations of Tsurface and the estimates of Tsoil using Equation 2. These estimates of Tcanopy are compared in Figure 4 to corresponding values of Tcanopy observed using the MIRTs located directly above the cotton rows (the first and last MIRT in an array). Results are presented for both stressed and unstressed plots. While there is considerable scatter in the points in Figure 4, the cluster of values tends to lie along the 1:1 line, suggesting that in general the procedure appears to provide reasonable estimates of leaf canopy temperature from remotely sensed surface temperature.

Conclusions

These preliminary results suggest that a linear mixture model (LMM) of the form of Equation 2 may be used to estimate leaf canopy temperature from remotely sensed surface temperature. For situations with incomplete ground cover, values of soil surface temperature used in the LMM must be appropriate for conditions inside the field. Results of this study suggest that the use of soil surface temperature values obtained from bare soil surfaces outside the field (like a nearby plowed field) in the LMM will likely lead to inaccurate estimates of leaf canopy temperature.

Current airborne remote sensing systems, with proper calibration, can measure surface temperature and estimate ground cover. Due to considerations involving spatial resolution, it is generally not possible to directly measure soil surface temperature within the field using an airborne remote sensing system. However, it might be possible to estimate this quantity using one of the following approaches.

1.) Soil surface temperature could be measured using remote sensing on a bare surface outside the field and adjusted using an empirical relationship such as Equation 3. Unfortunately, soil surface temperature inside a field is likely to be a dynamic quantity that can vary from day to day based on weather conditions (irradiance, air temperature, wind speed, wind direction). More study is needed to determine to what degree empirical procedures can be used in this application.
2.) A simple energy balance model could be used to estimate soil surface temperature in the field based on ambient weather conditions and remotely sensed ground cover. Soil thermal properties in the model might be calibrated using remotely sensed surface temperature measurements from a bare surface outside the field.

Disclaimer

Mention of trade names in this manuscript does not imply endorsement by the United States Department of Agriculture.

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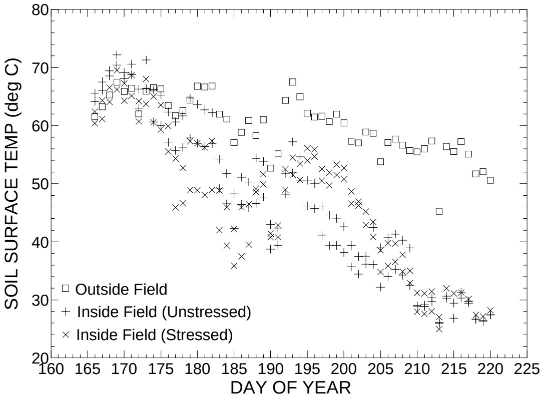

Figure 1. Measurements of bare soil temperature inside and outside the study field in 1999.

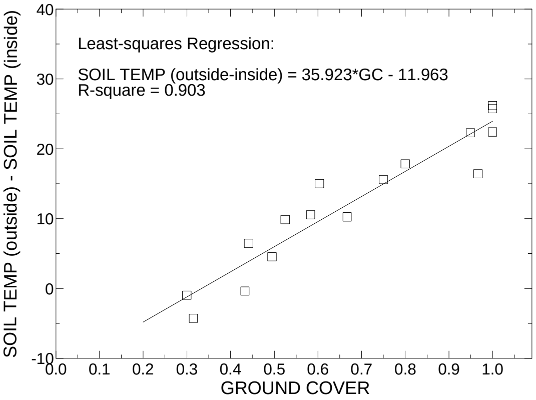

Figure 2. Relationship between the difference in bare soil temperature inside and outside the field and ground cover.

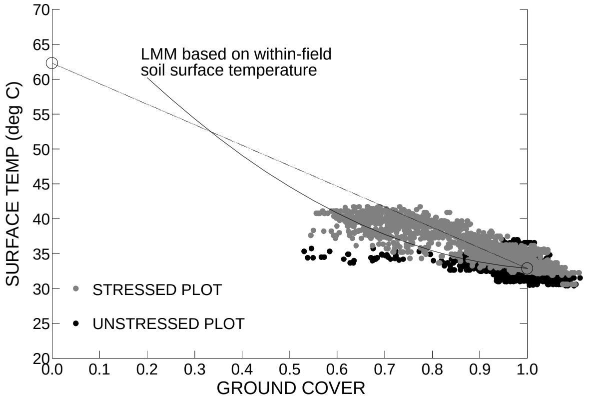

Figure 3. Plot of image pixel data from plot 1 (stressed) and plot 3 (unstressed) on 13 Aug 1998. Dashed diagonal line represents the LMM (Eq. 1) based on soil temperature measured outside the field; curved solid line represents the LMM based on soil temperature measured inside the field.

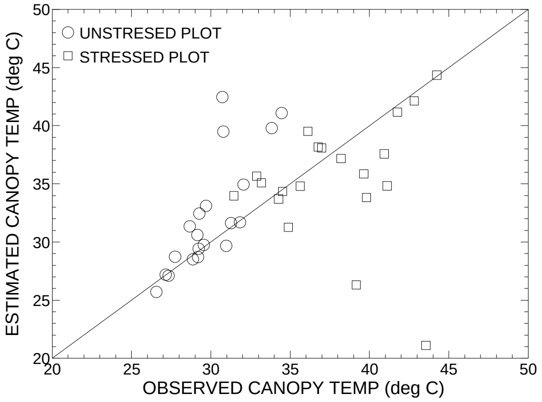

Figure 4. Estimated leaf canopy temperature versus observed leaf canopy temperature for 1999.