THERMAL CHARACTERIZATION AND SPATIAL ANALYSIS OF WATER STRESS IN COTTON (*GOSSYPIUM HIRSUTUM* L.) AND PHYTOCHEMICAL COMPOSITION RELATED TO WATER STRESS IN SOYBEAN (*GLYCINE MAX*)

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ABSTRACT

Studies were designed to explore spatial relationships of water and/or heat stress in cotton and soybeans and to assess factors that may influence yield potential. Investigations focused on detecting the onset of water/heat stress in row crops using thermal and multispectral imagery with ancillary physicochemical data such as soil moisture status and photosynthetic pigment concentrations. One cotton field with gradations in soil texture showed distinct patterns in thermal imagery, matching patterns measured by the VERIS 3100 soil EC mapping system. Yield of cotton obtained from 2003 to 2007 also followed mapped soil textures, and this depended to an extent on timing and amounts of precipitation. Thermal images were obtained of a soybean canopy in irrigated and non-irrigated fields, and samples were taken from three leaves at four locations of both fields for pigment analysis using high performance liquid chromatography (HPLC). Although leaf sample size for this preliminary study was rather small, significant differences between leaves sampled from irrigated vs. non-irrigated soybean plants were seen for three pigments at the 0.10 level. For another cotton field, several thermal images acquired over a five-week time interval (July-August 2006) were composited to produce a cumulative thermal map. Changes in canopy cover (derived from intensity-normalized color infrared imagery) were also mapped. Composited thermal imagery combined with tracking canopy cover change at key phenological stages could serve as a useful alternative to vegetative indices (VIs) for the in-season prediction of production potential as well as early senescence promoted by heat/water stress in highly heterogeneous fields, and foster the development of site-specific applications of insecticides to protect high-yielding areas and cost-effective application of defoliants/harvest aids for cotton. Thermal mapping was seen as a useful tool for characterizing soils to predict yield depending on temporal precipitation patterns and thus could be useful for determining supplemental irrigation needs.

Keywords. Remote sensing, thermal imaging, spatial image analysis, autocorrelation, HPLC, pigment analysis

INTRODUCTION[1]

Water stress can have profound impacts on yield in row-crop production (Idso et al., 1977). A study was designed to map water stressed areas indicating production potential and to indicate relationships between soil texture, weather, and yield in cotton and soybeans. Use of image sensors on aerial platforms to infer soil variability and to map areas of crop water use and heat/temperature stress has been well documented (Bartholic et al., 1972; Blad and Rosenberg, 1976; Heilman et al., 1976; Smith et al., 1989). Thomson et al. (2005) used a Raytheon Palm-IR camera, which indicated visible differences in canopy temperature before and after irrigation. However, varying cloud cover altered image contrast and relative temperature representations within a field for other image pairs. Observations of cloud cover effects were consistent with those of Pennington and Heatherly (1989). Thomson and Sullivan (2006) used an Electrophysics PV-320T thermal imaging camera over a 3-ha field planted in soybeans. Over a full canopy, canopy temperature represented by the camera was 4 to 6 C cooler than temperatures measured over leaf clusters using Apogee precision Infrared Thermometers (IRTs). This difference was smaller when the ground IRTs measured a single plant later in the season, taking care not to include soil background. Linear influence of altitude was documented to account for a portion of this attenuation effect.

For early detection of the onset of water/heat stress, ancillary data such as phytochemical concentration, soil moisture status, and hyperspectral reflectance may be useful to augment data from thermal imaging sensors. These data could also help determine spectral resolution limitations of thermal imaging for delineation of features. A series of studies were designed to explore spatial relationships governing the onset of heat/water stress in cotton and soybeans and to determine soil and weather factors that may have an influence on yield.

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MATERIALS AND METHODS

Studies reported on herein were conducted at the Stoneville, MS, USA research farms (33.42°N, 90.93°W, USDA-ARS and Mississippi State University cooperating). Two fields were planted in cotton; two in soybeans. The two cotton fields were characterized by highly variable soils, and one cotton field was chosen for its gradations in soil texture as verified by the VERIS 3100 soil electrical conductivity (EC) mapping system. By its easily delineated heterogeneity, this field was a good one to study soil-water-yield relationships. The soybean fields were planted in Sharkey series soils; one was irrigated using center pivot and one was non-irrigated. Flights were made over all fields for this study once per week.

Thermal Mapping of Soil Texture and Temporal Yield Trends in Cotton

A 2.5-ha non-irrigated field with gradations in soil texture (hereafter called F11) was used to determine relationships between soil texture inferred by EC, precipitation, and spatial yield distribution over a five-year period from 2003 to 2007. The potential for thermal imagery to map soil texture was also determined from aerial data taken in 2007. Imagery was obtained about every seven days from mid-July through the end of August using an Electrophysics PV-320T camera mounted in an Air Tractor 402B agricultural aircraft (flown at an altitude of 460 m). Although this field was also instrumented with Watermark soil water sensors, data on soil water potential are not considered in this study. Temporal soil water sensor responses have been reported on in previous studies (Thomson and Sullivan, 2006), but poor correlation has been noted between soil water sensor readings and canopy temperature data indicating crop water stress (Thomson et al., 2005).

Phytochemical Composition Differences between Irrigated and Non-Irrigated Soybean Leaves

Two 3-ha soybean fields (hereafter called F13 (irrigated) and F14 (non-irrigated)) were flown with the thermal imaging camera in 2007, and yield was obtained at harvest. Leaf pigment data were obtained for both irrigated (F13) vs. non-irrigated (F14) fields for association with water stress differences that may be observed in thermal imagery. Hyperspectral reflectance data from individual leaf samples were taken using a dual-channel Ocean Optics SD-2000 fiber optic spectroradiometer monitoring wavelengths ranging from 250-850 nm for each leaf sampled. Downwelling radiation was acquired simultaneously for conversion of upwelling leaf radiance to reflectance. Three leaves were chosen at each of four sensor stations in each field for pigment sampling on July 26, 2007 and August 7, 2007. On July 26, conditions were sunny; ambient air temperature was 30 C (86 F) at the 10:00 AM sampling time; nominal windspeed was 1.5 m/s (3.5 mph). On August 7th, conditions were sunny; ambient air temperature was 36 C (97 F) at the 2:00 PM sampling time; nominal windspeed was 0.7 m/s (1.5 mph). Each plant was marked and waypoints were programmed into a Garmin 76S WAAS GPS receiver to assist in locating the plants for subsequent sampling. Samples were taken from leaves at the top of the canopy to reduce interference from other leaves;

thus, leaves were exposed to sunlight. Leaf samples were analyzed using an Agilent Technologies HP1100 HPLC for the pigment constituents of interest (chlorophylls a and b, and the carotenoids neoxanthin, violaxanthin, lutein, antheraxanthin, and *beta*-carotene).

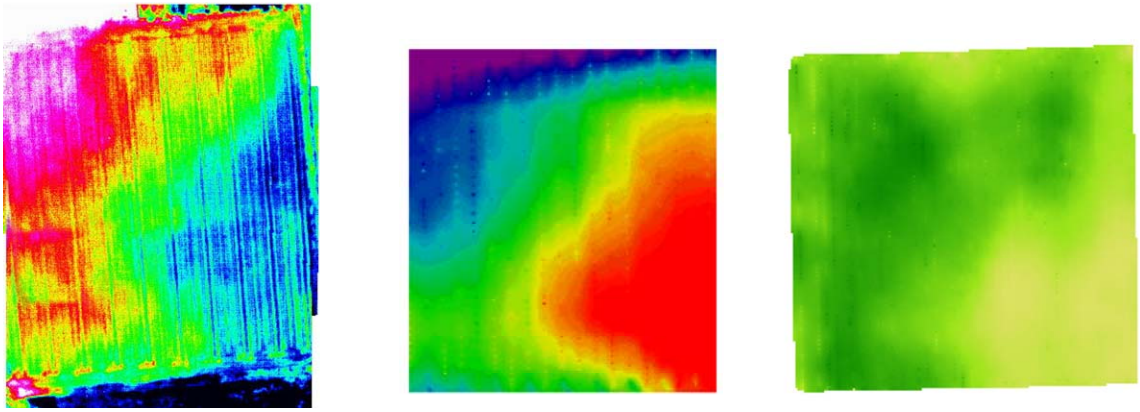
Water and Heat Stress in Cotton using Thermal and Multispectral Imagery

The thermal imaging camera was flown over a field planted in cotton (DPL 555) that showed sharp contrasts in soils. Imagery was obtained about every seven days from July 25 through August 31 2006. This year was also characterized by relatively dry conditions during the test period. Maximum air temperatures during the study ranged from 29-39°C (85-102°F) with a mean of 36°C (97°F); minimum air temperatures ranged from 17-25°C (63-77°F) with a mean of 23°C (73°F). Total cumulative precipitation for the months of July and August 2006 amounted to only 84.8 mm (3.34 in) and was 64.5 mm (2.54 in) below the 30-year average. Cotton canopy closure in this field is typically incomplete from year-to-year which necessitated the integration of additional multispectral data.

RESULTS

Thermal Mapping of Soil Texture and Temporal Yield Trends in Cotton

The yield map for 2007 “matched” visual trends from both thermal and VERIS soil texture maps (Fig. 1). The VERIS map indicates a Dundee fine sandy loam (southeast corner) to a Sharkey series clay soil (northwest corner). As a comparison between early-season and mid-season precipitation patterns, cumulative rainfall from planting (April 22) until June 17 totaled only 56 mm (2.2 in). However, numerous rainfall events occurred between June 18 and July 20 totaling 290 mm (11.3 in).

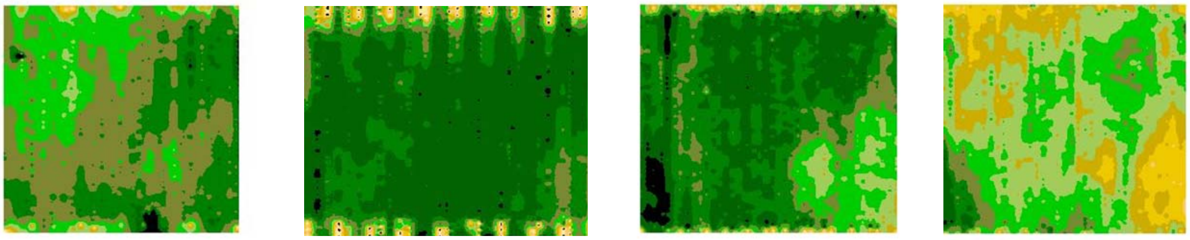


(A) **(B)** **(C)**

Figure 1. Soil maps and relative yield of cotton for 2007. The thermal soil map (A) shows excellent equivalence to the VERIS soil EC map (B). A cooler canopy (southeast corner) in the thermal image (A) corresponds to the coarser Dundee fine sandy loam near the creek bed (red zone in the VERIS image). Yield was also lower for cotton grown in the Dundee soil (C).

Yield maps are presented for years 2003 through 2006 (Fig. 2). Many comparative trends can be observed, which can be explained to a degree by timing and intensity of rainfall. In 2003, 260 mm (10.1 in) of cumulative precipitation was recorded from planting (April 22) to June 17. This is a similar amount to that recorded mid-season for 2007 (June 18 through July 20, Fig. 1). Cumulative rainfall was 66 mm (2.6 in) between June 18 and July 20 for 2003. The crop was more vigorous and final yield was higher in the coarser textured soils compared to the clay-rich areas (2003 map, Fig. 2), which is opposite the 2007 result. It can be seen that yield at the center of the southeast quadrant (2003 yield map) appears to be lower than the surrounding areas. This is not consistent with subjective observations at ground-level. Final yield in this portion was probably higher than indicated by the yield monitor, because the operator used this field section to calibrate the yield monitor. This probably led to inaccurate yield results within this small area.

Year 2004 was characterized by high precipitation; the cumulative amount from April 22 to July 20 was 580 mm (23 in). Yield of cotton was consistently high throughout the field (Fig. 2). Precipitation for 2005 was characterized by several small rain events throughout the season. Cumulative rainfall was 100 mm (4 in) between April 22 and June 17 and only 69 mm (2.7 in) between June 18 and July 20. Another 165 mm (6.5 in) of rainfall was recorded between July 20 and August 31. Spatial yield patterns for 2005 are very similar to that observed for 2007 (Fig. 1). The yield plot for 2006 indicates the effects of water stress, as only 152 mm (6 in) of rain was recorded between May 11 and August 31. Cotton grown in the transitional portion of the field, related to soil texture (diagonal, SW to NE) seemed to show higher drought tolerance than cotton grown in the coarser or finer textural extremes. As discussion herein only indicates visual observation, spatial analysis is continuing to further quantify these trends.



2003 2004 2005 2006

Figure 2. Relative yield of cotton for years 2003 through 2006. Color ramp representing yield is the same for all maps. Higher yield is represented by dark green, intermediate yield by gray, lower yield by light green and yellow zones.

Phytochemical Composition Differences between Irrigated and Non-Irrigated Soybean Leaves

Differences in pigment concentrations were observed between leaves sampled from irrigated (F13) and non-irrigated (F14) soybean fields for July 26, 2007. Leaves were also sampled on August 7, but field observations (and data confirmed) that differences between fields would be small because both canopies were yellowing uniformly. So, only results from July 26, 2007 are reported herein.

Table 1 illustrates statistical results for several phytochemical constituents. Both chlorophyll constituents show noticeable differences between fields, as did the carotenoid, Antheraxanthin.

Table 1. Statistical differences in pigment concentration between Fields 13 and 14.

Constituent	**LSMeans (F13)**	**LSMeans (F14)**	**p-value**
Chla*	72.30	35.49	0.0595
Chlb*	14.01	6.91	0.0694
Neoxanthin	2.17	1.47	0.2054
Violaxanthin	1.69	1.61	0.8553
Lutein	5.23	3.43	0.1633
Antheraxanthin*	40.50	23.67	0.0932
***Beta*-carotene**	11.04	9.67	0.5888

* indicates significance at the 0.10 level. Antheraxanthin LSMeans values shown are raw data (before conversion to ng)

Figures 3 and 4 illustrate spectroradiometer plots (% reflectance) of six representative leaves from each field. These are coded by field (F13 or F14), station (S), and sample (R). Leaf spectral differences between fields are not readily apparent for either wavelength range shown; no apparent patterns are visually evident. Thermal imagery for July 26, 2007 was also inconclusive for canopy temperature differences between fields. The pilot flew off-line while obtaining thermal images, but differences should have been picked up for field portions that were imaged.

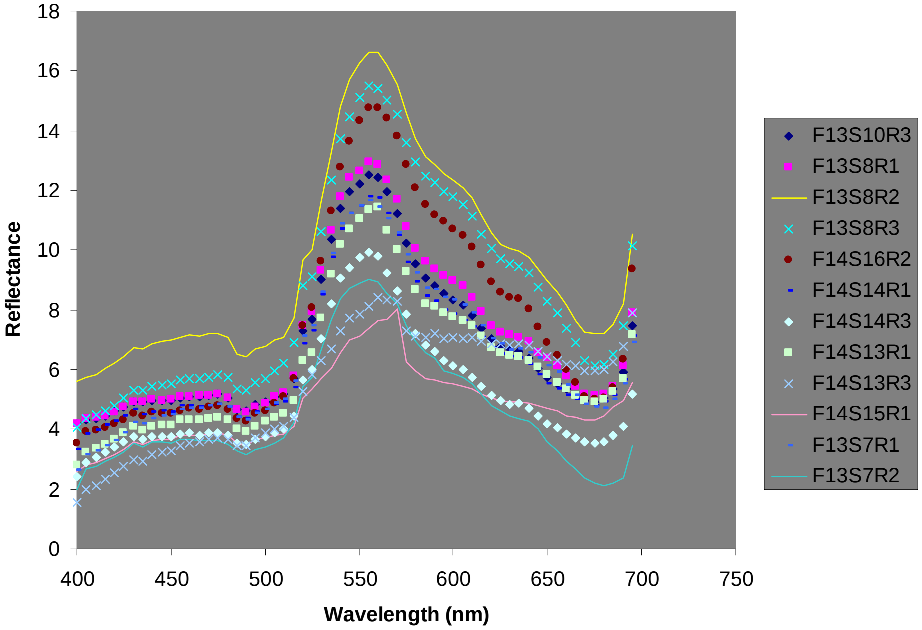


Figure 3. Soybean leaf spectra highlighting visible wavelengths

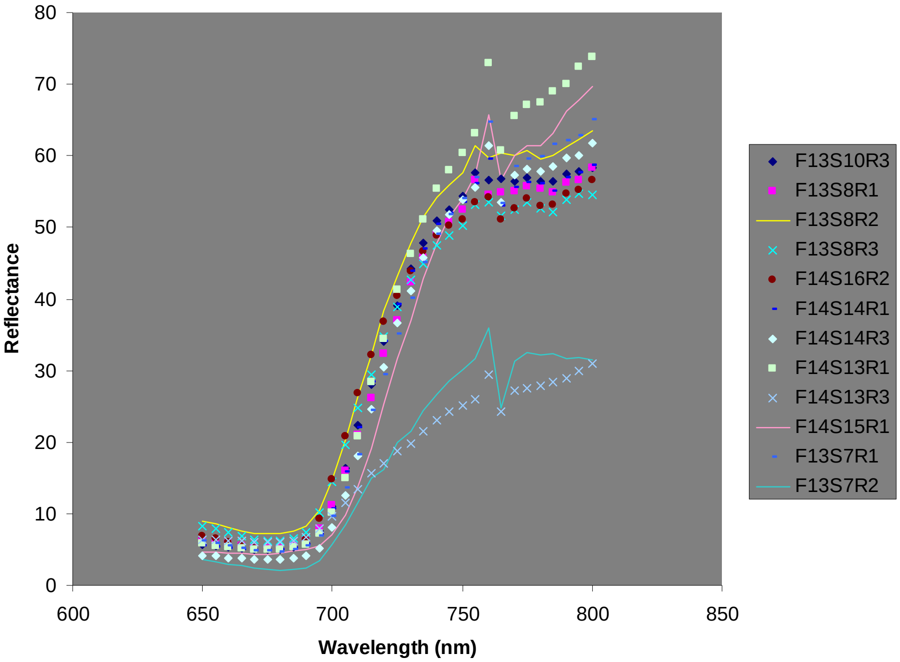


Figure 4. Soybean leaf spectra highlighting red and near-infrared wavelengths

Water and Heat Stress in Cotton using Thermal and Multispectral Imagery

Several thermal images (12-bit, 1 m spatial resolution) acquired over a five-week time interval were composited to produce a cumulative thermal map (Fig. 5A - Thomson et al., 2007). In addition, two CIR images (12-bit, 0.15 m resolution - obtained using an Emerge camera, flown at an altitude of 600 m, on July 10 and August 24) were processed using an intensity normalization method (Bajwa and Tian, 2002), and then Normalized Difference Vegetation Indices (NDVIs) were calculated. Each three-band image was constructed using the NDVI, near infrared (NIR), and green bands. These two images were then processed through unsupervised classification (isodata) establishing two classes (coded 0=no vegetation and 1=vegetation); zonal means were subsequently calculated for each image (i.e., resampled to 1 m resolution) resulting in assessments of percent cover. Canopy cover change was determined by subtracting the classified July image from the vegetation mapped in late August (Fig. 5B).

Thomson et al. (2007) compared the cumulative thermal map with a normalized yield map using a bivariate geostatistical analysis (Local Moran's I Spatial Autocorrelation or LISA), and reported tightly-coupled linkages of low yield zones with areas of the field subjected to the highest temperatures ($P \leq 0.01$) and significant reciprocal associations of high yield areas with the lowest canopy temperatures ($P \leq 0.01$). For the current study, a supplementary bivariate LISA map (using GeoDa 0.9.5-i5, Spatial Analysis Laboratory, University of Illinois, Urbana-Champaign, IL) was produced to chart significant autocorrelations ($P \leq 0.05$) between cotton canopy cover change and the cumulative thermal maps (Fig. 5C). Note the associations of low canopy cover change coupled with the lowest cumulative canopy temperatures (depicted in dark blue) as well as the adjacent areas of the field (portrayed in pink) displaying relatively high canopy cover change paired with relatively low canopy temperatures. Another bivariate LISA map, used to examine patterns of yield and in-season canopy cover change (Fig. 5D), resolved four field-scale production zones including: (1) a high yielding (low canopy cover change) "core" (pink); (2) a scattered assemblage of high yielding areas paired with relatively high canopy cover change (red); (3) the most "stressed" portions of the field with the lowest yield and lowest canopy cover change (dark blue); and (4) low yield areas coupled with relatively high canopy cover change (cyan).

Ground-truthing demonstrated that from mid to late August cotton plants subjected to consistently high temperatures (mapped in yellow, orange, and red – Fig. 5A) had 50-90% open boll. Thus, composited thermal imagery combined with tracking canopy cover change at key phenological stages could be useful for the in-season prediction of yield potential as well as early senescence promoted by heat/water stress in highly heterogeneous cotton fields, and foster the development of site-specific applications of insecticides to protect high-yielding areas and cost-effective application of defoliants/harvest aids.

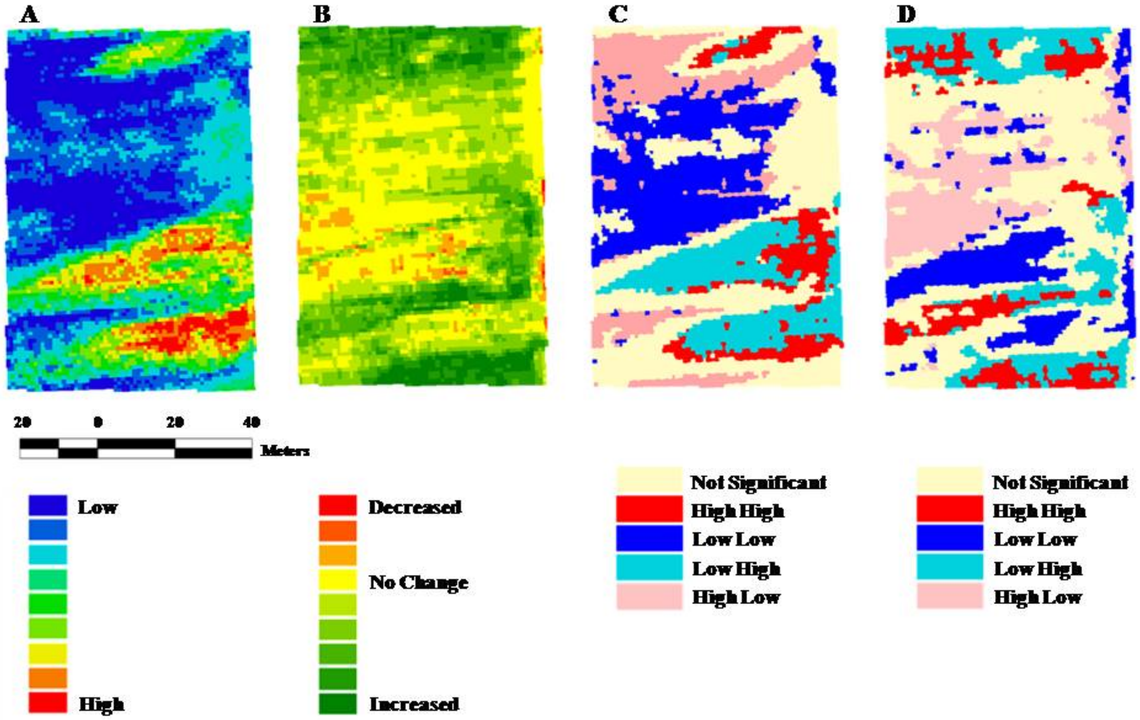


Figure 5. Maps summarizing heat/water stress in an irrigated cotton field: (A) cumulative thermal map; (B) canopy cover difference map (derived from normalized-classified CIR imagery obtained on July 10 and August 24, 2006); (C) bivariate LISA depicting significant autocorrelations between the canopy cover change and cumulative thermal maps; and (D) bivariate LISA highlighting significant relationships between yield and in-season canopy cover change.

SUMMARY AND DISCUSSION

Three investigations were conducted to assess the value of using thermal imagery, hyperspectral data, and multispectral imagery in the assessment of soil and plant factors governing water and heat stress in cotton and soybeans. One study showed good potential for mapping soil texture using thermal imagery. Soil and weather factors were also related to relative yield in a cotton field over a five-year period. It should be noted that this field has not been placed into alternate crop rotation for several years, and this may affect future yield potential. However, significant overall reductions in yield from year to year have not been noticed as yet. A second investigation found good potential for using pigment analysis to spatially map the crop canopy for relative levels of water stress. Statistically significant differences were observed between leaf pigments sampled from irrigated vs. non-irrigated soybean fields with greater concentrations of chlorophyll a, chlorophyll b, and antheraxanthin detected in the irrigated field. Spectroradiometer data did not appear to pick up differences consistent with pigment analysis differences determined using HPLC, but statistical analyses will proceed on spectroradiometer data to either confirm or negate this preliminary observation. Sampling and leaf viewing protocol will be reviewed for subsequent experiments. Data have not yet been correlated between the spectroradiometer and pigment analyses.

A complementary investigation of heat/water stress in irrigated cotton was conducted in a field with sharp contrasts in soils using the Electrophysics PV-320T camera mounted in an agricultural aircraft. Several thermal images acquired over a five-week time interval (July-August 2006) were composited to produce a cumulative thermal map. Changes in canopy cover (derived from intensity-normalized color infrared imagery) were also mapped. A bivariate LISA map depicted significant autocorrelations ($P \leq 0.05$) between percentage canopy cover and the cumulative thermal map. Another bivariate analysis of spatial autocorrelation using canopy cover change and yield maps resolved four field-scale production zones including: (1) a high yielding (low canopy cover change) "core"; (2) a scattered assemblage of high yielding zones paired with relatively high canopy cover change; (3) the most "stressed" portions of the field with the lowest yield and lowest canopy cover change; and (4) low yield areas coupled with relatively high canopy cover change. Thus, composited thermal imagery combined with tracking canopy cover change at key phenological stages could serve as a useful alternative to vegetative indices (VIs) for the in-season prediction of production potential as well as early senescence promoted by heat/water stress in highly heterogeneous cotton fields, and foster the development of site-specific applications of insecticides to protect high-yielding areas and cost-effective application of defoliants/harvest aids.

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