EVALUATING THE SENSITIVITY OF AN UNMANNED THERMAL INFRARED AERIAL SYSTEM TO DETECT WATER STRESS IN A COTTON CANOPY

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ABSTRACT. *Airborne thermal infrared (TIR) imagery is a promising and innovative tool for assessing canopy response to a range of stressors. However, the expense associated with acquiring imagery for agricultural management is often cost-prohibitive. The objective of this study was to evaluate a less expensive system, an unmanned airvehicle (UAV) equipped with a TIR sensor, for detecting cotton (*Gossypium hirsutum *L.)response to irrigation and crop residue management. The experimental site was located on a 6.1 ha field in the Tennessee Valley Research and Extension Center located in Belle Mina, Alabama, where landscapes are gently rolling and soils are highly weathered Rhodic Paleudults. Treatments consisted of irrigation (dryland or subsurface drip irrigation) and crop residue cover (no cover or winter wheat (*Triticum aestivum *L.)). TIR (7 to 14 μm) imagery was acquired on 18 July 2006 at an altitude of 90 m and spatial resolution of 0.5 m. Coincident with image acquisition, ground truth data consisting of soil water content (0-25 cm), stomatal conductance, and canopy cover were measured within a 1 m radius of each sample location. All sample locations were georeferenced using a real-time kinematic (RTK) GPS survey unit. Analysis of sample locations acquired in multiple flight lines was used to assess the stability and repeatability of the UAV system during an acquisition. Compared to field measurements of stomatal conductance with CVs ranging from 2% to 75%, variability in TIR emittance (CV < 40%) was within the observed tolerance of ground truth measurements of stomatal conductance. Significant differences in canopy cover and stomatal conductance across irrigation treatments allowed testing of the sensitivity of the UAV system. A negative correlation was observed between TIR emittance and stomatal conductance (r = -0.48) and canopy closure (r = -0.44), indicating increasing canopy stress as stomatal conductance and canopy closure decreased. TIR emittance exhibited greater sensitivity to canopy response compared to ground truth measurements, differentiating between irrigation and crop residue cover treatments. TIR imagery acquired with a low-altitude UAV can be used as a tool to manage within-season canopy stress.*

Keywords. *Cotton, Crop residue management, Irrigation, Thermal infrared, Unmanned airvehicle.*

For nearly 40 years, researchers have evaluated innovative agricultural solutions centered on remote sensing. Most studies have indicated that reflectance and emittance spectra can be used to evaluate *in situ* crop stress (Colwell, 1956; Jackson et al., 1983; Penuelas et al., 1993; Shanahan et al., 2001). With the advent of high spatial and spectral resolution sensors (handheld, airborne, and satellite), remote sensing applications for precision agriculture, irrigation management, soil sampling, and identification of high-risk areas for pests are currently being investigated. However, the expense and timeliness of obtaining high-resolution remotely sensed imagery has limited the adoption of this technology by crop producers. Recent advances in unmanned airvehicles (UAVs) equipped with visible (VIS), near-infrared (NIR), and/or thermal infrared (TIR) sensors offer promise as new remote sensing tools that can deliver high-resolution imagery quickly, accurately, and at a reduced cost.

The cumulative effect of energy exchange is characteristic of a plant's ability to utilize incoming energy and dissipate heat (Idso et al., 1981; Jackson et al., 1977; Myers and Allen, 1968; Millard et al., 1978; Monteith and Szeicz, 1962). As plants transpire, water evaporates and cools the leaf surface; however, external stresses such as drought, nutrient deficiencies, pests, and extreme temperatures cause transpiration rates to decrease and canopy temperatures to rise. Capitalizing on these studies, more than 25 years ago, Jackson et al. (1983) developed a crop water stress index (CWSI) relating canopy temperatures to crop water stress. The CWSI was based on principles of the crop energy balance given by Monteith and Szeicz (1962):

$$R_n = G + H + \lambda E_r \quad (1)$$

where R_n is the net radiant heat flux density, G is the soil heat flux density, H is the sensible heat flux density, and λE_r is the latent heat flux density.

The CWSI application was widely applied and well correlated with soil water content, photosynthesis, and plant water

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potential. However, a number of variables complicated the application of CWSI in practice: canopy cover, aerodynamic resistance, vapor pressure deficit (VPD), and accurate estimates of net radiation. Idso et al. (1981) showed that for most crops, less than 3°C separates a well-watered plant from a water-stressed plant at VPDs less than 1.5 kPa. Investigating the utility of several temperature-based canopy stress indices in a sub-humid climate, Keener and Kircher (1983) demonstrated that the addition of a vapor pressure deficit and/or net radiation term was important. Vapor pressure deficit and net radiation terms strengthened the relationship between canopy stress indices and crop response indicators (yield, kernel weight).

As the expense of various TIR sensors declines, researchers have investigated new platforms to allow for field-scale acquisitions of TIR emittance. Barnes et al. (2000) evaluated a prototype sensor (VIS, NIR, and TIR) mounted on an irrigation system to assess nitrogen and water stress within an Arizona cotton field. Results showed a linear relationship existed between CWSI and soil water depletion when the CWSI was greater than 0. The CWSI was calculated based on the relationship between leaf area index (LAI) and canopy cover as well as the canopy-air temperature differential. However, the overall correlation between CWSI and soil water depletion was only 30%. This low correlation was likely a function of low and negative CWSI values, where the crop was actively transpiring under moderate decreases in soil water content. More recently, Kostrzewski et al. (2003) used the same linear pivot to evaluate canopy temperature measurements as an indicator of water and nitrogen stress. Results from their study showed that a measure of the coefficient of variability in the temperature minus air differential was a better indicator of increasing water stress compared to using mean values. The coefficients of variation were sensitive to a 6% to 10% change in soil water status when soil water contents were within the 20% to 30% depletion range.

Sadler et al. (2002) used a similar system for measuring canopy temperature along a linear move system over a corn crop in South Carolina. Temperature data were adjusted to account for changes in climate during the 3.5 h required for full field coverage. Differences in canopy temperature were observed within and among soil map units, providing evidence of spatial patterns in the ability of the crop to obtain water.

Thomson and Sullivan (2006) used an agricultural aircraft and Electrophysics PV-320T thermal imaging camera to quantify spatio-temporal variability in temperature signatures of a soybean canopy. Results indicated that spatial differences could be easily quantified, and that temporal measurements of canopy temperature could be improved by careful resolution of (1) small canopy-air temperature differences, (2) instantaneous weather effects, and (3) altitude. Sensors mounted on piloted agricultural aircraft can provide beneficial information in areas where aerial spraying is a prevalent activity.

The utility of low-altitude UAVs for acquiring imagery over agricultural fields is an innovative technique that has not been thoroughly investigated to date. UAVs offer the benefit of near-instantaneous measurements of crop canopies, frequent data acquisition, and rapid data delivery. Simpson et al. (2003) designed a low-cost UAV equipped with a 2 megapixel, commercial digital camera for rapid imaging of agricultural fields. As a test of the system, Simpson et al. (2003) acquired imagery over a corn canopy receiving variable nitrogen and irrigation amounts. Differences in canopy reflectance were noted between most N rates within a given irrigation regime. However, separation among N treatments was best between plots receiving 0, 45, and 90 kg N ha^{-1}. Data depicted a plateau in crop response to N rates exceeding 118 kg ha^{-1}.

Herwitz et al. (2002) utilized the Pathfinder Plus multispectral UAV to assess field ripeness at the Kauai Coffee Plantation using reflectance spectra. Reflectance patterns from the coffee tree canopy were positively related to yield ($r^2 = 0.81$, $\alpha = 0.01$). Data were also used to identify areas of invasive weed infestations as well as depict variability in irrigation and fertilizer management. While some investigators have used reflectance spectra, recent remotely sensed field-scale assessments of TIR emittance have been limited by timeliness of data acquisition, data delivery, and spatial resolution constraints. Thus, few studies have evaluated the potential of a UAV as a platform to collect remotely sensed thermal data that can be used for in-season crop management.

TIR emittance shows promise as a tool to assess crop response to stress, yield, and soil water content. Similarly, UAVs provide a potentially universal platform that may be used to obtain repeatable and nearly instantaneous assessments of crop conditions. Conventional applications of TIR imagery in agricultural production systems have been limited by feasibility, spatial resolution, and rapid response requirements. UAVs may be used as remote sensing platforms capable of overcoming these limitations. However, few studies have investigated the application of UAV systems equipped with TIR capabilities in an agricultural setting. This study provides a unique assessment of the use and limitations of such a system as well as a foundation for future UAV acquisitions in agriculture.

The objective of this study was to evaluate the utility of a low-altitude UAV equipped with a TIR sensor as a tool for detecting *in situ* cotton (*Gossypium hirsutum* L.) response to irrigation and crop residue management. This study serves as an evaluation of the UAV system and was therefore designed to test the strengths and weaknesses of this platform. As a consequence, results presented here are not intended for use as an assessment of an agricultural management system.

Methods

Site Description

The experiment was conducted over a 6.1 ha cotton field located at the Tennessee Valley Research and Extension Center (TVREC) in Belle Mina, Alabama. The field consists of Decatur silt loam (Rhodic Paleudults) and Decatur silty clay soils with slopes ranging from 1% to 6%. The site is managed as a no-tillage, continuous cotton system and is being used as a long-term subsurface drip irrigation (SDI) study. Cotton was planted on 18 April 2006 using 1 m row spacing. Soil fertility management was conducted according to Alabama Cooperative Extension System guidelines.

The experimental design is a randomized block design having two irrigation treatments by two cover crop treatments with four replications. The plots (3 × 381 m) traverse the field and encompass the landscape variability. Irrigation treatments are comprised of dryland versus pressure-compensated SDI. Because crop residue management has been shown to affect soil quality, infiltration, plant available water, and surface radiance, the two cover crop treatments consist of (1) no cover and (2) winter wheat (*Triticum aestivum* L.) cover crop. The winter wheat cover crop was planted 28 October 2005 and killed prior to spring planting on 29 March 2006. The residue management regime at this study site has been in place for two years, beginning the fall of 2004.

Irrigation

The Tennessee Valley region of Alabama receives on average 145 cm of yearly rainfall. However, most of this rainfall does not occur during the growing season. The mean temperature in July for this region is 27°C, with a daily maximum around 32°C and an average relative humidity of just over 70%. Therefore, irrigation is used to supplement dry periods during the growing season.

Pressure-compensated SDI tape was installed on a 2 m spacing, using a real-time kinematic (RTK) global positioning system (GPS)-based autoguidance system to ensure parallel placement of tape. SDI tape was installed at a nominal depth of 32 cm. Since cotton was planted on 1 m row spacing, a single run of SDI tape supplies water simultaneously to two rows of cotton. Sand media and disc filters were installed to remove suspended particles from irrigation water in order to reduce drip emitter clogs. Routine flushing and chemical treatment was implemented to alleviate any evidence of clogging as a result of back siphonage.

Irrigation was scheduled based on 60% pan evaporation and adjusted for canopy closure. The pan evaporation is based on the accumulated pan evaporation from the previous day. This level was selected based on six years of prior SDI research on cotton at the same research facility (Fulton et al., 2005). Water flow volumes during an irrigation event were monitored using water meters. Irrigation was initiated on 26 May 2006 for this site. Figure 1 presents daily precipitation, irrigation, and pan evaporation a week prior to data acquisition.

Ground Truth

Ground truth data were collected coincident with remotely sensed TIR data acquisition to quantify differences in plant, soil, and residue attributes contributing to measured

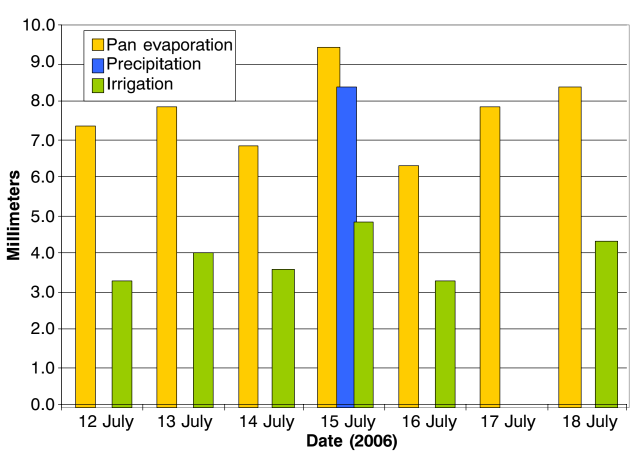

Figure 1. Accumulated daily irrigation, precipitation, and pan evaporation a week prior to data collection.

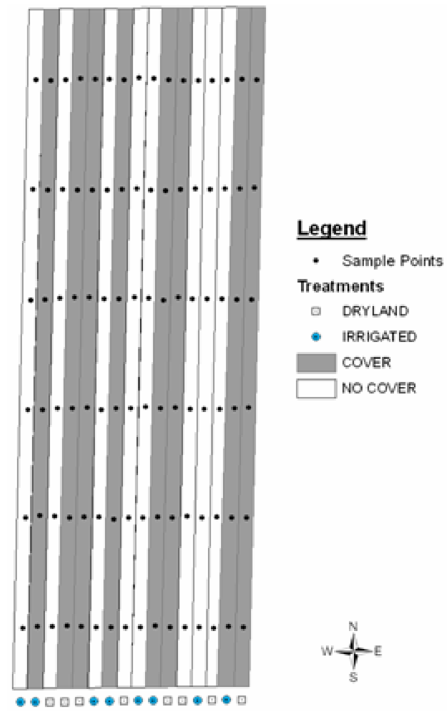

Figure 2. Treatment diagram and sample locations for soil water content (θ_g) and stomatal conductance (mmol m^{-2} s^{-1}).

emittance and to directly verify the relationship between canopy response and emittance. Six sample locations along the length of each plot (n = 96) were identified and marked using an RTK survey-grade GPS unit (fig. 2). Ground truth consisted of soil water content (n = 45), stomatal conductance (n = 47), and digital photographs (n = 96). Due to the size of the study area, and time sensitivity of the data set, only a representative number of sample locations were utilized in this study (fig 2).

Gravimetric soil water content (0-25 cm) was collected as a composite of five subsamples within a 1 m radius of the sampling point at 45 locations. Stomatal conductance (mmol m^{-2} s^{-1}) was measured using a leaf porometer (Decagon Devices, Pullman, Wash.). Due to sensitivity in crop response to changing environmental conditions, these data were acquired within 30 min of TIR data acquisition using a randomized sampling scheme to minimize bias between treatments associated with time. Four measurements were collected from the uppermost, fully developed, exposed leaves within a 1 m radius of each sample location.

A single digital image was taken at nadir from each of the sample locations to quantify vegetative canopy cover and crop residue cover. Digital images were acquired without a flash, using a 5 megapixel Olympus C-505 Zoom (London, U.K.). Images were acquired from approximately 1.5 m above the ground, centered directly over the row, and represent an area of 1.4 m^2 on the ground. To accomplish this, the zoom feature was turned off. Images were classified into three classes (crop residue, vegetation, or other) using ERDAS Imagine 8.7 (Leica Geosystems, Heerbrugg, Switzerland). Images were classified using an unsupervised classification that assigns pixels to a specified number of classes based on an iterative self-organizing data analysis technique (ISODATA) (Tou and Gonzalez, 1974). The ISODATA procedure groups pixels based on a minimum Euclidean distance between a pixel value and the class mean on each iteration of the procedure until a specified convergence factor or maximum number of iterations has been reached (Fridgen et al., 2004). In our study, the ISODATA algorithm specified 30 classes, a maximum of 90 iterations, and a convergence of 0.98. Upon completion, each of the 30 classes was assigned a class name (crop residue, vegetation, soil, or other).

Percent cover was calculated by dividing pixels classified as vegetation or crop residue by the total pixel count in each image (5 million). Based on previous studies, this method of classification provides an average accuracy of ~80% (Sullivan et al., 2004).

Unmanned TIR Aerial System

Thermal infrared data were collected using a UAV equipped with a TIR sensor (L3 Communications Infrared Products, Dallas, Tex.). The UAV consisted of a commercially available hobby-type radio control airplane kit that has been modified for electric propulsion and support of the imaging payload (NASA Goddard Spaceflight Center, Wallops Island, Va.). The UAV has a 2.4 m wingspan, a single propeller (38 cm diameter), and a gross weight of 3.6 kg. The UAV was electrically driven via a 300 W electric motor powered by two 6.0 Ah lithium polymer batteries. The payload control consisted of a 72 MHz PCM radio control. The UAV has a minimum speed of 24 km h^{-1} in flight with a maximum speed of 64 km h^{-1}. The maximum climb rate observed was 180 m min^{-1} with a descent rate of 90 m min^{-1}. Maximum time in flight was not to exceed 60 min.

The TIR system consisted of a lightweight (145 g) camera with a thermal sensitivity of $\leq$100 mK. The focal plane array (160 × 120 pixels) for the camera consisted of an uncooled, amorphous silicon microbolometer. The system records emittance (7 to 14 μm) as a digital value ranging from 0 to 255, with increasing emittance represented by increasing digital value. The TIR camera was equipped with an 8.5 mm lens having a 50° × 35° field of view and fixed focus. A 2.4 GHz radio link was used to transmit video from the camera to a ground control station for viewing and recording. The real-time video allows for greater control over image acquisition and estimation of altitude.

TIR data were acquired on 18 July 2006, at 10:13 a.m. central standard time, under clear conditions. At this time, the cotton crop was between first and peak flower with a percent canopy ranging from 15% to 72%. Data acquisition was completed within 17 min at an average altitude of 90 m. Images used in this study were acquired within 5 min of launch. Based on the field of view of the sensor, at a 90 m altitude the TIR system had a vertical swath of 58 m and a horizontal swath of 85 m. The UAV was hand-launched in the direction of the southern edge of the research site and flown in a circular pattern until a majority of the research area was captured. The average ground resolution per pixel was 0.5 m.

To estimate or adjust the altitude in real-time, ground targets were placed every 30 m in the vertical direction and every 35 m in the horizontal direction and marked with an RTK survey-grade GPS unit. Thus, the altitude of acquisition for any image showing two targets in the vertical and horizontal direction was estimated at 90 m. Images having a greater number of targets were considered out of range (>90 m), while images having fewer targets were acquired at altitudes <90 m and did not contain the minimum number of georeferenced targets to georegister the image for further analysis.

Post-acquisition video was downloaded using the Sonic MyDVD V 5.2 software package (Adaptec, Novato, Cal.). Once saved, the video was replayed frame by frame. Only nadir-looking frames capturing a minimum of three ground targets were retrieved for further analysis. Data were saved in lossless TIFF file format along with time in flight, and imported into ERDAS Image 8.7 for clipping, georegistration, and data extraction. Due to the wide-angle lens used in this study, pixels along the edge of the flight line were distorted. To avoid sampling these areas, each image was clipped to the area of interest, eliminating all pixels along the flight line edges. Georegistered data falling within a 1 m buffered area of each sample location were extracted for statistical analyses (n = 16).

Because the research site encompassed a large area, several passes with the UAV were required, thereby providing duplicate passes over some sample locations. To assess the impact of changing atmospheric conditions and UAV stability during the flight, each file was time-stamped and the average digital value for each sample location was calculated for each pass. The coefficient of variation (CV) between samples across passes was used to determine the reliability of the dataset. Duplicates represented 40% (n = 13) of the total number of sites sampled, having a CV range from 1% to 88%. When comparing sample locations across flight lines, nine of the thirteen duplicates had CVs <40%, twelve had CVs <50%, and a single outlier had a CV of 88%. Compared to field measurements of stomatal conductance with CVs ranging from 2% to 75%, variability in digital values was within the observed tolerance of ground truth measurements of stomatal conductance. Moreover, a majority of the data was unaffected by time in flight, and all sample locations with CVs >40% were eliminated.

Statistical Analyses

Using the Statistical Analysis System (SAS Institute, Inc., Cary, N.C.), an analysis of variance was conducted using the General Linear Model to (1) ensure that differences in ground truth were detectable and significant, and (2) to determine if TIR data could be used to differentiate between varying levels of crop stress. To account for the effect of soil background on emittance, an analysis of covariance was used to determine the impact of variable vegetative cover fraction on the observed emittance spectra. Pearson correlation coefficients were also calculated to evaluate the relationship between TIR emittance, stomatal conductance, soil water content or plant available water, crop residue management, and vegetative fraction (canopy closure). Because stomatal conductance and canopy closure departed from normality, these data were log transformed prior to statistical analysis.

Results and Discussion

Descriptive Site Data

Because the integrated effect of surface characteristics (canopy closure, % actively transpiring vegetation, crop residue cover, and bare soil) drives observed emittance (digital values), variability in surface characteristics at the time of TIR acquisition were evaluated (table 1). It was necessary to log transform stomatal conductance and canopy cover to normalize the dataset prior to analysis of variance (ANOVA). No differences in soil water content were observed between

Table 1. Soil water content, canopy closure, crop residue cover, and stomatal conductance reported for significant treatment effects. Interactions between treatments are denoted by "×". It was necessary to log transform canopy closure and stomatal conductance measurements prior to analysis of variance.[a]

Treatment: Irrigation		Treatment: Cover	Stomatal Conductance[b] (mmol m^{-2} s^{-1})			Soil Water Content (cm^3 cm^{-3})	Thermal Infrared Digital Value		Canopy Closure[b] (%)			Crop Residue Cover[c] (%)	
Irrigated			6.09	(514.6)	A	NS	94.6	B	3.65	(40)	A		
Dryland			5.36	(233.8)	B	NS	157.2	A	3.24	(26)	B		
			LSD = 0.30				24.1		0.11				
		Cover	NS			NS	114.7	B	3.53	(36)	A		
		No Cover	NS			NS	143.9	A	3.36	(30)	B		
							LSD = 23.9		LSD = 0.1				
Irrigated	×	Cover	NS			NS	NS		NS			24.4	A
Irrigated	×	No Cover	NS			NS	NS		NS			27.7	A
												LSD = 3.8	
Dryland	×	Cover	NS			NS	NS		NS			32.7	A
Dryland	×	No Cover	NS			NS	NS		NS			27.5	B
												LSD = 3.9	

[a] Means followed by the same letter are not statistically different at $\alpha = 0.05$. NS indicates no significant response.
[b] Data in parentheses represent the non-transformed values for stomatal conductance and canopy closure.
[c] A significant interaction was observed between irrigation and cover treatments for estimates of residue cover only.

treatments. This observation is likely because the depth of soil moisture measurements was 7 cm above the subsurface drip tape.

Significant differences in canopy closure were noted across irrigation as well as cover treatments (table 1). No significant interaction between treatments was observed. The impact of irrigation management on canopy closure was most significant, having 40% canopy closure on irrigated treatments and 26% canopy closure on non-irrigated treatments. Differences in canopy closure between cover and no-cover treatments were less significant, but showed greater canopy closure on cover treatments compared to no-cover treatments. Variability in canopy closure between treatments is an important consideration, because differing amounts of bare soil or crop residue will be present in any given pixel. As a result, background emittance contributions are variable between treatments. The impact of background emittance will be evaluated in the discussion of the TIR system sensitivity.

Crop residue cover was measured across all treatments at a nadir viewing angle by classifying a digital image into its component parts (vegetation, residue, and soil). This was done as a measure of the impact that increasing canopy closure and exposed bare soil may have on emittance. A significant interaction in the amount of exposed crop residue cover was observed between irrigated and dryland treatments (table 1). In irrigated areas where canopy closure approached 40%, no differences in crop residue cover were noted between cover and no-cover treatments. The relatively high fraction of canopy likely obscured any real differences in crop residue cover at the nadir viewing angle. However, under dryland conditions where the canopy was only 26% closed, differences in the amount of exposed crop residue was significant for cover and no-cover treatments.

Variability in stomatal conductance between treatments provided a base for evaluating the sensitivity of the TIR system and the relationship between emittance and canopy response. The integrated effects of canopy temperature and stomatal conductance were first demonstrated by Monteith and Szeicz (1963) using a simple infrared thermometer. Specifically, their study showed that as water stress increases: (1) stomatal conductance decreases, (2) more energy is partitioned to sensible heat (Turner, 1973; Cline and Campbell, 1976; Campbell, 1977), and (3) canopy temperatures rise. Early research by Cline and Campbell (1976) also demonstrated the relationship between stomatal conductance and available soil water, suggesting that stomatal conductance decreases when the soil water deficit exceeds a certain threshold. As water stress increases and stomatal conductance decreases, canopy temperatures rise to dissipate excess heat (Campbell, 1977). In this study, significant differences in stomatal conductance were observed solely between irrigated and dryland treatments (table 1). As expected, irrigated treatments exhibited more than twice the stomatal conductance rate (average conductance = 515 mmol m^{-2} s^{-1}) of dryland treatments (average conductance = 234 mmol m^{-2} s^{-1}). Because healthy vegetation with available water can maintain cooler canopies via transpiration, data confirmed that canopy stress may be detected via an increase in emitted radiation.

Correlation Between Ground Truth and TIR

The relationships between observed TIR emittance and ground truth parameters were evaluated using Pearson linear correlation coefficients. Of particular importance to the evaluation of the TIR system, a negative correlation between stomatal conductance and TIR emittance ($r = -0.48$, $\alpha = 0.05$) provides evidence that the TIR system was related to plant transpiration. In a ground-based study by Dr. Diane Rowland in Dawson, Georgia, sapflow measurements from peanut were related to canopy temperatures acquired using infrared thermometers ($r^2 = 0.64$) (Thomson et al., 2005). Sapflow measurements indicated increased water use during peak canopy temperatures. Lack of a stronger correlation in the present study was likely associated with variable atmospheric conditions during stomatal conductance measurements, as well as atmospheric attenuation of emittance spectra. Still, the observed correlation is sufficient to allow for testing of relative differences in canopy response within a given field or acquisition. As transpiration rates increased, TIR emittance decreased. Additionally, a negative linear relationship was observed between TIR emittance and canopy closure (r = –0.44, α = 0.05), indicating cooler surface conditions as canopy closure increased.

Although soil water content was correlated with stomatal conductance (r = 0.58, α = 0.05), no significant correlation was observed between TIR emittance and soil water content. Similar observations have been made by Barnes et al. (2000) and Thomson et al. (2005), who indicated poor correlations (r = 0.22 to 0.30) between canopy temperature measurements and soil water content. Our observations may be related to the fact that soil measurements (0-25 cm) were taken 7 cm above the irrigation level (32 cm). However, given the correlation observed between stomatal conductance and soil water content, lack of a significant correlation between soil water and canopy temperature measurements is likely a function of the cumulative effects of canopy architecture, rooting depth, bare soil exposure, and crop residue exposure. Thus, under the conditions studied here, canopy emittance may not be a reliable surrogate for direct measures of soil water content within the 0-25 cm depth.

Sensitivity of TIR to Variability in Canopy Characteristics

At the field scale, observed emittance was recorded as a digital value ranging from 21 to 222, having a CV of 37%. A closer look at the range in digital values re-emphasizes the correlation between stomatal conductance and emittance, showing a negative relationship between observed emittance and stomatal conductance (r = –0.48, α = 0.05). A frequency distribution curve (fig. 3) was used to evaluate the range in observed emittance.

Five data points exhibited relatively high emittance (digital value >182), indicating a decrease in stomatal conductance and higher levels of canopy stress. Four of the observed treatments corresponded to dryland treatments without cover, having stomatal conductance values ranging from 183 to 291 mmol m^{-2} s^{-1}. The fifth data point occurred within an irrigated without cover treatment and can be attributed to a crimped SDI tape (fig. 4). Therefore, part of this treatment had not received water, causing the high emittance value observed at this sampling point.

Eleven additional data points exhibited digital values <100, indicating a full and actively transpiring cotton canopy. Stomatal conductance in this case ranged from 377 to 721 mmol m^{-2} s^{-1}, nearly two times the transpiration rate observed for the aforementioned dryland sample locations. The corresponding treatments consisted of an equal distribution of irrigated treatments with or without crop residue cover. In all cases, canopy closure exceeded 34%, peaking at 40%.

The remainder of the data points (n = 17) exhibited digital values from 120 to 180 with canopy closure ranging from 24% to 29%. Corresponding treatments within this digital value range were predominantly dryland, with variable crop residue cover. More specifically, treatments having a digital value between 120 and 160 were predominantly cover treatments, while treatments with digital values from 160 to 180 were predominantly no-cover treatments.

The TIR system showed significant differences (α = 0.05) in observed emittance between irrigated versus non-irrigated and cover versus no-cover treatments (table 1). No interaction was observed between treatments. Irrigation management was the principal contributing factor to canopy stress, separating irrigated from dryland treatments by a margin of 62 digital values. For cover treatments, differences were not as great, with significantly higher emittance (digital value = 144) from the no-cover treatments compared to cover treatments (digital value = 115).

Compared to ground truth assessments using stomatal conductance as a measure of crop response, TIR emittance was more sensitive to treatment (irrigation and cover) effects. This sensitivity was likely a function of the timeliness of data collection and variability in canopy closure. Sadler et al. (2002) noted similar constraints associated with time lag when using a linear move pivot to assess canopy temperature. To compensate for the time lag, canopy temperatures were adjusted for increasing air temperatures during the 3 h acquisition period using a difference approach. In our study, stomatal conductance data were collected within 30 min of data acquisition to minimize the effects of changes in environmental conditions. Comparatively, TIR data were collected within 5 min of launch and were much less affected by variable environmental conditions. Thus, the UAV provided a near-instantaneous assessment of all sample locations, allowing for greater separation among small differences in canopy response.

Due to variability in canopy closure across treatments, an analysis of covariance was conducted using canopy cover as a covariate to determine the impact of variable bare soil/crop residue cover contributions on TIR emittance (table 2). The observed emittance values were therefore adjusted according to variability in canopy closure. The effect of bare soil was observed in the adjusted means, showing higher adjusted emittance for irrigated or cover treatments and a corresponding decrease in adjusted emittance for dryland or no-cover treatments. Data demonstrated that sample locations with a greater proportion of exposed bare soil resulted in relatively higher observed emittance, which could lead to inaccurate assessments of crop water stress. However, comparing observed and adjusted emittance values, variability in bare soil/crop residue cover contributions resulted in only slight increase/decreases in observed emittance, ranging from 2 to 4 digital values. The impact of an error of 2 to 4 digital values is equivalent to a 1.5% error in observed emittance. Considering that differences in emittance between treatments were 11% when averaging over crop residue cover treatments and 24% when averaging over irrigation treatments, a 1.5% error in observed emittance is well within the limits of treatment

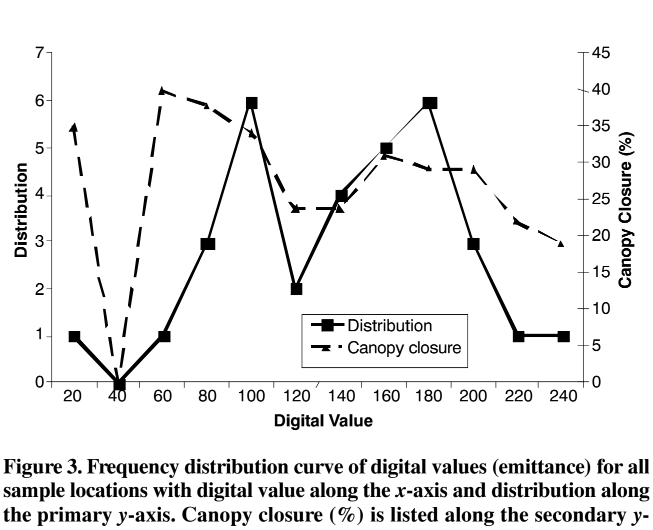

Figure 3. Frequency distribution curve of digital values (emittance) for all sample locations with digital value along the *x*-axis and distribution along the primary *y*-axis. Canopy closure (%) is listed along the secondary *y*-axis.

Table 2. Results of the analysis of covariance, adjusting observed digital values for variability in canopy closure across treatments.

Treatment		Thermal Infrared Digital Value			
Irrigation	Cover	Initial	Adjusted	Diff.	P Value
Irrigated		94.6	98.9	-4.3	<0.01
Dryland		157.2	154.2	3.0	<0.01
	Cover	114.7	116.7	-2.0	<0.01
	No Cover	143.9	142.3	1.6	<0.01

separability. Thus, our data suggest that the UAV-mounted TIR system may be used to assess variability in crop response with a minimum canopy closure of 26%. Additional research is necessary to determine the sensitivity of this system to a greater range in crop water stress at various crop growth stages.

Using TIR Imagery as a Diagnostic Tool

At this study location, pressure-compensated SDI tape is being evaluated as a means of equally distributing water over rolling terrain in the Tennessee Valley physiographic region of Alabama. In the past, SDI products were designed and recommended for fields that are flat or have a minimum, uniform slope, but a new product (pressure-compensated SDI) is now available. Pressure-compensated SDI offers a method to apply subsurface water uniformly on rolling terrain by maintaining uniform emitter flow over a range of pressure differences. This technology negates the effect of gravity, which causes more water to be distributed downslope, compared to traditional SDI products. System design and management is a major factor in determining application uniformity. Due to the nature of the system, clogs and crimped lines are not visible and often manifest themselves as yield losses at harvest. Thus, this site provided an ideal location to demonstrate the utility of a UAV as a tool for SDI system evaluation and improved water management.

TIR imagery captured during the evaluation phase of the UAV was used to demonstrate the utility of this type of imagery for within-season management of the SDI system. During the image pre-processing phase, several images were selected having a minimum of three ground targets within the field of view. A single image acquired over the northeastern quadrant of the field was selected for demonstration purposes, visually inspected for stress, and compared to end-of-season yields (fig. 4).

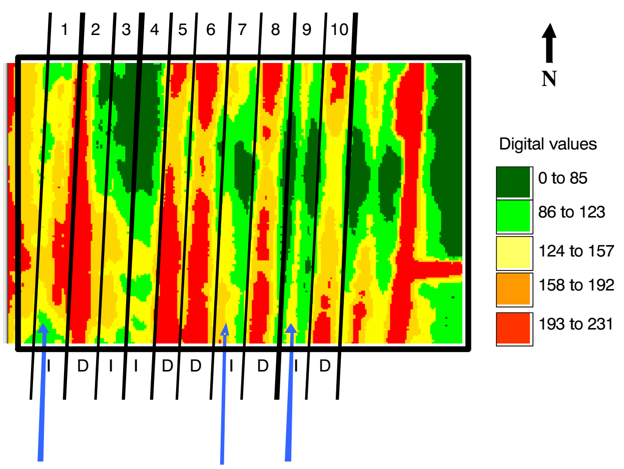

Figure 4. Thermal infrared image (TIR) illustrating the identification of crimped SDI tape and poor water distribution. Letters along the south edge indicate the irrigation treatment (D = dryland, I = irrigation), and numbers along the north edge serve as plot identifiers. Arrows designate crimped lines and areas of unequal water distribution.

Visual inspection of the TIR image exemplifies the utility of this system as a means for rapidly depicting crop response to environmental conditions. Dryland treatments are easily identified and classified into groups that have emittance values ranging from 158 to 231. The image also shows that the response to dryland management is not uniform along the length of the field, suggesting that other soil and landscape features are likely impacting plant available water. Similar distribution patterns can be observed in irrigated treatments as well, with well-watered portions of the field exhibiting very low digital values, ranging from 0 to 123, indicative of an actively transpiring canopy. Perhaps most notably, the data were useful in identifying crimped SDI lines and areas of unequal water distribution. The crimped lines are evident in three of the irrigated treatments, spanning the length of plots 1, 7, and 9. Digital values along the crimped lines ranged primarily from 124 to 192, compared to well-watered areas on either side with digital values ranging from 0 to 123. Additionally, a second feature was identified, showing variability in water distribution throughout plots 3 and 4. The distribution issues are represented by zones with relatively high digital values (canopy stress) that are bounded on the northern portions of plots 3 and 4 by zones with low digital values (actively transpiring canopy). Variability in canopy response along these lines is attributable to water distribution issues and pressurization of the SDI line.

In terms of yield, the crimped lines resulted in yield losses of up to 35% compared to adjacent rows of well-watered cotton. Left unidentified, crimped lines manifested themselves as a yield loss. However, the data presented here suggest that SDI problems can be rapidly and easily identified using the UAV and TIR imagery, allowing such issues to be corrected in a timely fashion during the growing season to minimize yield loss.

Conclusion

The utility of a UAV equipped with a TIR sensor to detect variability in cotton response to irrigation and crop residue cover management was evaluated. Analysis of sample locations present in multiple, consecutive flight lines demonstrates that system stability and comparability of data between flight lines was high. Approximately 70% of sample locations present in multiple flight lines exhibited a CV <40%. Emittance spectra were also correlated with stomatal conductance ($r = -0.48$, $\alpha = 0.05$), providing evidence that observed emittance was related to variability in canopy response to irrigation and cover treatments. More importantly, the UAV observations more accurately differentiated between relative differences in canopy response to irrigation and crop residue cover management compared to ground measurements of stomatal conductance, which were time and labor intensive.

One of the limitations of using emittance spectra for detection of canopy stress is the impact of bare soil background contributions during periods of low canopy cover. However, data collected during this study (spatial resolution = 0.5 m) indicated that emittance spectra may be used to evaluate relative differences in crop response when the vegetative canopy fraction is as low as 26%. Variability between observed emittance and emittance adjusted for soil background contributions was as low as 1.5%.

As a practical demonstration of the utility of the UAV system, selected imagery was used as a tool to evaluate the efficacy of a newly available subsurface drip irrigation system installed for testing at the same site. Visual inspection of relative differences in emittance spectra across the site identified two crimped lines and an area of unequal water distribution. Untreated, cotton rows along either side of the crimped line resulted in as much as 35% reduction in yield compared to adjacent and well-watered rows.

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