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IRRIGATION SYSTEM MANAGEMENT ASSISTED BY THERMAL IMAGERY AND SPATIAL STATISTICS

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ABSTRACT Thermal imaging has the potential to assist with many aspects of irrigation management including scheduling water application, detecting leaky irrigation canals, and gauging the overall effectiveness of water distribution networks used in furrow irrigation. Many challenges exist for the use of thermal imagery to accurately determine the timing of irrigation based on crop water status. These challenges include proper accounting for variations in solar radiation and wind on a spatiotemporal basis, delineating canopy-air temperature difference (CATD) under periods of low vapour-pressure deficit, and accounting for altitude effects on canopy temperature represented at the camera. At the Crop Production Systems Research Unit of the USDA-ARS in Stoneville, MS (USA), information from thermal imagery obtained with agricultural aircraft are being used along with ground-based readings of soil moisture status and canopy temperature in an attempt to develop consistent criteria for scheduling irrigation. A review of some issues with thermal imaging is presented, along with a proposed approach using spatial statistics that can enhance the value of thermal imagery for detecting water-stressed field areas. Thermal imagery has been used to identify plant canopy temperature differences related to crop water/heat stress. In addition, we have applied spatial statistics to help to delineate areas of the field with high potential for crop water stress. Thirdly, we illustrate the utility of thermal imagery for detecting leakage from irrigation canals and poly-pipe furrow irrigation systems. Lastly, operational characteristics of a new variable-rate center pivot irrigation system that can utilize spatial irrigation scheduling criteria are described.

Keywords: remote sensing, thermal imaging, CWSI, canopy temperature, irrigation, spatial statistics

INTRODUCTION Canopy temperature has proven its utility for detection of crop water stress over large field scales, but has yet to find widespread acceptance as a tool for water management based on canopy temperature status. Temperature of a crop canopy is related to general physiological status of the crop, which includes photosynthesis, respiration, and stomatal conductance (Inoue, 1990). As crop water status is a major component influencing canopy temperature, remote measurement of this variable over pertinent phenological stages could optimize water application amounts.

The use of canopy temperature for water management in humid subtropical climates is considered problematic with current technologies. As the crop begins to show signs of stress, small increases in canopy temperature can be difficult to detect with adequate resolution (Thomson and Sullivan, 2006). The prevailing low vapour-pressure deficit (VPD) characteristic of a humid subtropical climate reduces the magnitude of natural crop cooling by evaporation. Compounding the problem is frequent and periodic cloud cover (characteristic of this climate regime), which rapidly alters the representation of canopy temperature (Pennington and Heatherly, 1989). New technological approaches are needed to overcome these complications to better tailor irrigation inputs to crop- and soil-specific needs. In this paper, we examine some of the canopy temperature-based schemes for irrigation management and discuss positive aspects as well as challenges for using these techniques with aircraft-based thermal remote sensing. We also describe a method that uses a fusion of visible, NIR, and thermal imagery, coupled with spatial statistics to help identify problem field areas; this type of processing can assist with prioritizing areas to irrigate. Thermal imagery has been beneficial to support irrigation system diagnostics, and examples are presented for detection of water leakage from irrigation canals and polypipe systems.

THERMAL IMAGING FOR DETECTION OF CROP WATER STRESS

Crop Water Stress Index (CWSI) Canopy-to-air temperature difference (CATD) can provide information on crop energy status. As the leaf transpires, it cools relative to the surrounding air; however as water becomes limiting, transpiration is reduced and the leaf temperature increases. Under certain environmental conditions, this measurement alone may be sufficient to determine water stress for specific crops (Taylor, 1980; Gardner et al., 1992a, 1992b). Most of the successful work in this area has been accomplished in arid, semiarid, or Mediterranean climates, as large CATD permit adequate sensitivity for water management. Mathematical relationships using canopy temperature have been developed with an eye on practical irrigation scheduling (Pinter and Reginato, 1981; Stockle and Dugas, 1992; Colaizzi et al., 2003; Cohen et al., 2005).

Most studies have used the crop-water stress index (CWSI) for full canopies; however, complications arise when attempting to apply this index in fields with partial canopy cover. Regardless of the climate characteristics (humid or arid), early season CWSI values are particularly difficult to obtain with partial canopies. In the early growing season when plants are small or populations are sparse, a portion of the soil surface is usually viewable by infrared thermometer when canopy temperature measurements are made (Irmak et al., 2000). Although ground-based infrared sensing systems and hand-held devices could be physically manipulated to provide temperature of the canopy only by viewing at oblique angles or close-up, a more realistic approach would be to consider the effect of soil cover and develop methods to determine the relative influence of canopy and soil on remotely sensed temperature. Moran et al. (1994) developed a method to combine spectral vegetation indices with composite surface temperature measurement to allow application of CWSI theory to partially vegetated fields. The authors developed a vegetation index/temperature (VIT) bounded trapezoid to plot surface-air temperature difference against fractional vegetation cover. More recently, Emekli et al. (2007) evaluated the CWSI for irrigation scheduling of bermudagrass using infrared thermometry. The authors examined four irrigation treatments corresponding to levels of evaporation as measured by Class A evaporation pan; a non-irrigated treatment was also implemented. Both soil water content and potential were monitored using a neutron probe and tensiometers, and CWSI values were empirically determined. In this study, the visual quality of bermudagrass was monitored seasonally using a Munsell color scale. Average seasonal CWSI values were determined as 0.086, 0.102, 0.165, and 0.394 for irrigation treatments representing 100%, 75%, 50%, and 25% of evaporation measured in the Class A pan respectively, and 0.899 for the non-irrigated plot. The authors concluded that the CWSI could be used as a criterion for irrigation timing of bermudagrass, and an acceptable color quality could be sustained seasonally if the CWSI value stayed below about 0.10. Kar and Kumar (2007) used a lower and upper limit for calculation of the CWSI in groundnut under irrigated ecosystem. The lower baseline was developed with linear regression analysis for measurements in the cold season after the crops had received full irrigation on humid and dry days, whereas the upper limit was determined by monitoring plants and recording when the transpiration rate closely approached zero.

Idso (1982) reiterated the importance of accurately specifying the non-stressed baseline for CWSI calculation. Baseline from an artificial wet reference surface (Meron et al., 2003) was used to specify the wet CWSI baseline, T_{cm} for a study by Cohen et al. (2005), who used the CWSI to estimate leaf water potential. Use of this reference surface greatly simplified use of the CWSI, as it was simple to maintain as compared with well-watered crop sections. The authors used a Thermacam model PM545 thermal imaging camera mounted 5-m above the ground, pointing downward to image the canopy. Camera resolution was adequate to distinguish leaves from soil so only leaves could be analyzed. The authors found very good correlation between CWSI and leaf water potential measured using an ARIMAD 1 pressure chamber. Alchanatis et al. (2006) indicated the difficulties still present in adopting the crop water stress index (CWSI) for practical irrigation management. Temperatures of the relevant crop canopy, of the general leaf population, and of the soil background are mixed, altering the represented value of canopy temperature. Normalization of the CWSI can also be complicated under changing atmospheric conditions.

Time-temperature thresholds Researchers have used the canopy temperature measured by Infrared Thermometer (IRT) with time thresholds to assist with practical irrigation scheduling (Wanjura et al., 1995; Mahan et al., 2005). The idea is to signal irrigation based on the amount of time a crop-specific canopy temperature threshold is exceeded by modeling the CWSI as a function of environmental factors. The amount of time that the calculated canopy temperature is above the threshold temperature can be used to schedule irrigation. Peters and Evett (2008) developed a completely automated center pivot irrigation system based on this concept. Canopy temperature data were logged from sixteen calibrated IRTs on the pivot lateral. Minutes that the canopy temperature as read by IRTs exceeded the threshold temperature were accumulated during the day. If the daily total exceeded the time threshold at the end of the day, irrigation of a fixed depth was initiated. Yield of soybeans was compared between irrigation scheduled using the time-temperature threshold method and weekly scheduled irrigation using a neutron probe to determine the amount of water required to replenish the profile to field capacity.

No significant differences were found between water use efficiency or yield between the two scheduling methods.

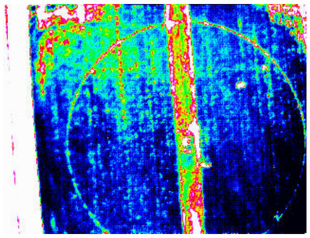
Plant response to variations in solar radiation No matter which scheme is developed to utilize canopy-air temperature difference for determination of crop water stress, plant response to varying solar radiation and cloud cover effects need to be considered. This is especially critical to adequately resolve CATD during periods of low vapour-pressure deficit. To help quantify these effects, Pennington and Heatherly (1989) plotted solar radiation (SR) against canopy-air temperature difference for cotton, obtaining a linear fit with a fair amount of scatter (R^2 = 0.84). The canopy typically took about 100 s to stabilize to a new temperature after a cloud passed over the field. Time lags were accounted for to obtain the much better fit of the canopy-air temperature difference/solar radiation data (R^2 = 0.98).

Aerial imagery for determination of canopy temperature Imaging sensors have been used on aerial platforms to determine canopy and soil temperature. These systems have the potential for rapidly determining the onset of water stress in the whole field or sections of a field. Thermal sensing from easily scheduled aerial platforms might hold the key to practical adoption of canopy temperature-based technologies for irrigation scheduling if proper application and analysis techniques are employed.

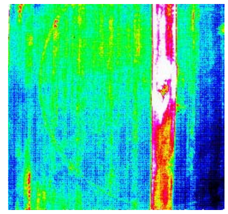
Early work by Bartholic et al. (1972) used an airplane-mounted Texas Instruments (TI) RS-14 scanner to measure thermal radiance in the 8 to14 µm wavelength interval. A radiance difference of 6 C was observed between the most and least water-stressed plots. Heilman et al. (1976) used an aerial thermal scanner at aircraft altitudes of 610 and 1220 m to measure canopy temperatures for estimation of evapotranspiration (ET). Atmospheric attenuation produced errors of 1 to 6 C in scanner measurements, so a correction procedure relating temperature error to atmospheric perceptible water was applied. Relative errors ranged from +62.5 to -43.6% between lysimetric and model-based estimates of ET. The effect of temperature error on ET was partially influenced by thermal diffusion resistance, which was derived from wind and air temperature profiles. Smith et al. (1989) studied how radiative surface temperature of a water-stressed crop could be used to indicate sources of variability in soil characteristics. Instrumentation included a Daedalus thermal scanner (DEI-100) with a 120-degree field-of-view, mounted in an aircraft flown at 1000-m altitude. The authors also measured ground-based surface temperatures with an Everest Interscience Series 100 handheld IR thermometer. Analysis of data indicated patterns in radiative surface temperature obtained using the aerial system could be related to spatial differences in soil type and water availability under complete crop cover.

As part of a multifaceted remote sensing program, Goodrich et al. (1998), Qi et al. (1998), and Moran et al. (1998) used an Agrometrics single-band thermal video system to measure surface temperatures for ET determination over a riparian zone. The aerial system gave 0.5 m ground resolution and covered spectral wavelengths of 8 to 12µm. Preliminary results from Qi et al. (1998) showed that spatial ET could be mapped using thermal images obtained from the single-channel Agrometrics sensor. Thomson et al. (2005) used a Raytheon Palm-IR thermal imaging camera, which indicated visible differences in canopy temperature before and after irrigation. However, varying cloud cover appeared to alter image contrast and relative temperature representations within a field for other image pairs. Temperature effects due to shading have been determined or modeled (Zhang et al., 2001; Leinonen and Jones, 2004), and their 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 of a Sharkey series clay soil planted in soybeans. Over a full canopy, canopy temperature represented by the camera was 4 to 6 C cooler than temperatures measured of single leaves using Apogee precision IRTs. This difference was smaller when the IRTs measured several leaves of a single plant later in the season, taking care not to include soil background. Subsequent analysis indicated a linear influence of altitude (sunny conditions only) on canopy temperature (Pearson's r = 0.58). Altitude effects could account for some of the differences in canopy temperature, but canopy shading appeared to be a more significant effect as a single pixel from the camera represented the composite of shaded and sunlit leaves. The degree of this effect was noticed to vary with time of day and sun angle.

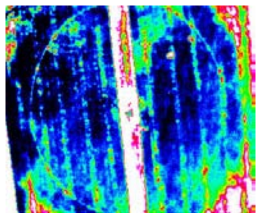
Figure 1 illustrates images of a soybean canopy obtained with the Electrophysics camera at 460-m altitude (Thomson and Sullivan, 2006). Blue areas indicate cooler temperatures; green and yellow indicate warmer temperatures. A constant range of temperatures between 28 and 33^{o}C (83 and 93^{o}F) corresponding to pixel values was set for consistency between images. This is a relatively narrow range within which the full range of color differences could be seen in a field. Typical canopy temperatures as measured by the camera ranged from 28 to 31^{o}C (83 and 88^{o}F). Rainfall on days 195, 199, and 202 kept the soil environment adequately replenished with water, as indicated by readings from granular matrix soil moisture sensors. The image obtained on day 207 (Fig. 1) can serve as a baseline for comparison with subsequent days. Rainfall totalled 1.9 cm over days 208 and 209 but soil water sensor (SWS) readings indicated slightly drier soil conditions on day 214. The image for day 214 appears to show a warmer canopy overall, but the degree of increase was not consistent with the crop's apparent stress level as indicated indirectly by SWS. Altitude of flight was lower for this run, and this could account for some of the increase in temperature represented at the camera. Spatial differences in canopy temperature were well defined for days 221 and 229. This pair of images indicates how a temporal comparison should look if conditions were consistent between days. The angle and location of image capture, solar radiation, and flight altitude were all closely comparable. No significant rainfall occurred between those days, and temporal analysis of Watermark readings indicated higher water uptake at the 46 cm depth at three out of four stations on day 229.



07-26-05 (DOY 207)



08-02-05 (DOY 214)



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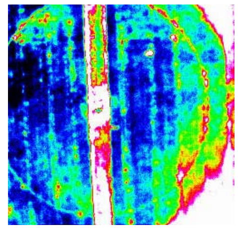


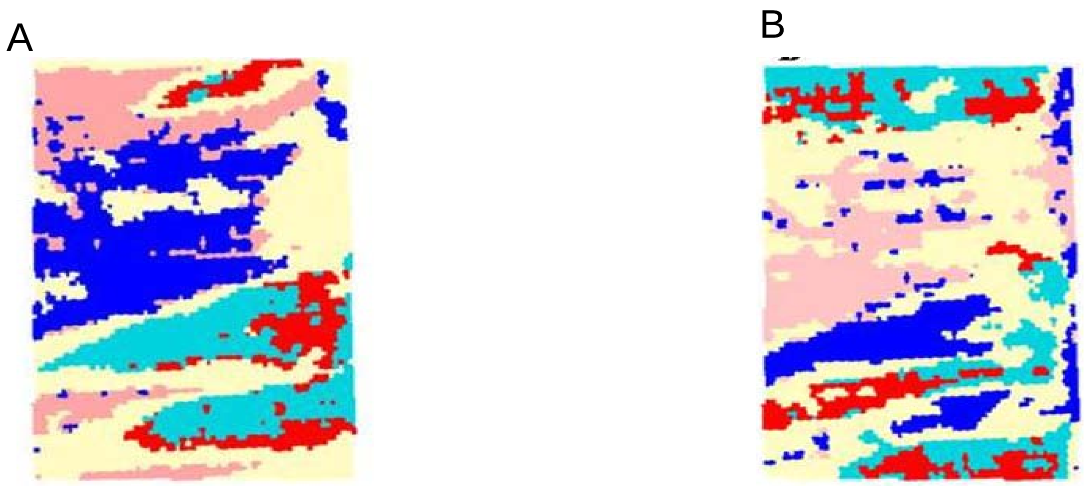
08-17-05 (DOY 229)

Figure 1. Thermal imagery illustrating temporal canopy temperature responses. A drying cycle without measurable precipitation occurred during the period between DOY 221 to DOY 229

SPATIAL RELATIONSHIPS INVOLVING CANOPY TEMPERATURE Cotton management involves many factors that must work together properly to ensure a high yielding and quality crop. Depending on soil texture, nutrient levels, and other field characteristics, some field areas have lower yield potential and have differing needs with regard to timing of water application and insecticide management.

Thermal images acquired over a five-week interval from July through August 2006 (using an Electrophysics PV-320T camera mounted in an agricultural aircraft flown at an altitude of 460m) were composited (Fig. 2) to produce a cumulative thermal map of a cotton canopy (Thomson et al., 2007, 2008). This 2.3-ha field was managed uniformly with regard to nutrient levels and was non-irrigated. In addition to the thermal images, two CIR images (12-bit, 0.15 m resolution) were obtained using the Emerge Digital Sensor System (DSS) (Emerge Sensor Group, Andover, Mass, USA); this camera was flown at an altitude of 600m on 10 July and 24 August 2006. Images were processed using an intensity normalization method followed by calculation of Normalized Difference Vegetation Index (NDVI). These two normalized CIR images were also processed using Isodata unsupervised classification (Jensen, 1996) to establish 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.

English et al. (2008) reported on the highly significant patterns of yield linked to the thermal zonation evident in this irrigated field (using a bivariate Local Indicator of Spatial Association or LISA map) with close to 65% of the field extent at $p \leq 0.01$ and 15% of the field area at $0.01 < p \leq 0.05$. Another bivariate LISA map, using GeoDa (Spatial Analysis Laboratory, University of Illinois, Urbana-Champaign, IL) charts significant autocorrelations ($p \leq 0.05$) between cotton canopy cover change and the cumulative thermal maps (Fig. 2A).



Legend:
Red = high Δ canopy cover, high canopy temperature
Cyan = low Δ canopy cover, high canopy temperature
Pink = high Δ canopy cover, low canopy temperature
Blue = low Δ canopy cover, low canopy temperature
Beige = not significantly autocorrelated

Legend:
Red = high yield, high Δ canopy cover
Cyan = low yield, high Δ canopy cover
Pink = high yield, low Δ canopy cover
Blue = low yield, low Δ canopy cover
Beige = not significantly autocorrelated

Figure 2. Geospatial relationships between change in canopy cover, canopy temperature as determined by thermal imaging, and yield

Low canopy cover change was coupled with the lowest cumulative canopy temperatures (depicted in dark blue). Similarly, the adjacent areas of the field (portrayed in pink) displayed relatively high canopy cover change paired with low canopy temperature change. The second bivariate LISA map (comparing patterns of yield with in-season canopy cover change - Fig. 2B), resolves four field-scale production zones including: (1) high yielding areas with low canopy cover change; (2) a more scattered grouping of high yielding areas paired with relatively high canopy cover change; (3) "stressed" portions of the field with low yield and low canopy cover change; and (4) low yielding areas coupled with relatively high canopy cover change. Ground-truthing demonstrated that from mid to late August, cotton plants subjected to consistently high temperatures had 50-90% open boll. These results indicate that 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. Management of water (termination of irrigation) is tied to phenological stage in cotton, and maps such as these can also foster the development of site-specific insecticide applications to protect high-yielding areas and promote cost-effective application of defoliants/harvest aids. Assuming an irrigation system is capable of varying water application rates or can be scheduled by zones, spatial differences as indicated in thermal imagery can be useful for irrigation timing decisions on select portions of the field.

IRRIGATION SYSTEM DIAGNOSTICS Detection of water leaks in irrigation systems has been successfully accomplished using thermal imagery. Huang et al. (2009) used a multispectral imaging system that included an Indigo Systems Merlin Thermal IR

12-bit camera and dual digital Dalsa 1M30 cameras fitted with interference filters for the red (0.66 micron) and near-IR (0.8 micron) wavelengths. Results showed that the thermal image performed well in detecting leaks from concrete canal segments, and ancillary data from the higher resolution Red, NIR, and NDVI images were valuable in indicating the presence of trees or shadows that might normally be seen as water leakage if thermal imagery alone were used. NDVI images were also able to detect areas of higher grass density, which inferred higher seepage in those areas.

An example illustrates the how useful information on water leakage and other irrigation-related characteristics can be obtained. Figure 3 illustrates an image taken over a corn/soybean rotation study in the Spring of 2005 at the USDA ARS Stoneville research fields. Moving from left to right in the image, soybean soil environment was drying from the previous irrigation causing higher canopy temperature as indicated by yellow-green areas. To the right of that field, corn was being irrigated or was just recently irrigated. The polypipe at the top of the corn field is a dark blue indicating that water was still flowing. Red-yellow “hot spots” can be seen in the field, which indicate restricted water flow to these areas most likely due to trash or high spots. If these are determined to be high spots, careful field levelling might be in order. The area to the right of the corn field shows system leakage down several furrows of a soybean field (indicated by the dark blue color). To the right of that leakage is evidence of a previous irrigation that was stopped a few days before, as this field was irrigated inadvertently.

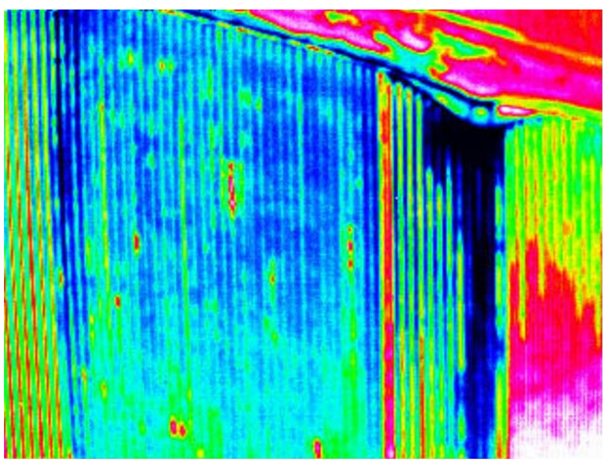


Figure 3. Thermal image of a furrow irrigated field showing system leaks, misapplication three days prior and other anomalies

VARIABLE-RATE IRRIGATION SYSTEM Variable-rate irrigation (VRI) is a technology that enables a moveable irrigation system to vary the amount of water applied at any given point across the field (McCann and Stark, 1993). The ability to vary the application rate allows the irrigation system to deliver the appropriate amount of water in response to a number of variables, including soil type and infiltration rate, multiple crops, topography, and non-cropped areas. Research dealing with variable-rate application of water has been reported using center-pivot irrigation systems (Camp et al., 1998; Perry et al., 2002; Sadler et al., 2005) and lateral-move systems (Han et al., 2009). VRI technology allows a producer to easily apply varying rates of irrigation water based on management zones created in response to soil, crop, and other variables. Providing the proper amount of water to all areas of the field can improve crop growth and yield and reduce water use.

VRI equipment (FarmScan, Bentley WA 6102, Australia) was installed on an existing center-pivot irrigation system at the Stoneville research fields. The system was retrofit by installing a global-positioning satellite (GPS) receiver on the single-span's end tower. Pneumatic valves were installed on each sprinkler, and connected to a compressed-air source. An additional computer-control unit was integrated into the existing control system to receive the GPS information and activate the pneumatic valves. To use the VRI system, a map of the field was created using the system's software on a desktop computer. The desired water application rates were assigned to each of the management zones, and the prescription map was stored on a flash-memory card. The card was then taken to the field, and the map was uploaded to the VRI control unit. The well pump and irrigation system engine were then turned on. In operation, as the center-pivot system traveled around the field, the GPS receiver monitored its position. The VRI control unit adjusted the speed of the irrigation system and opened and closed the pneumatic valves to vary the amount of water discharged by each sprinkler. The VRI control unit continuously made adjustments to maintain a near-constant flow rate through the irrigation system to minimize impacts on the well pump.

SUMMARY AND CONCLUSIONS Thermal imagery can be used to provide geospatial information for scheduling and to support timely application of field inputs. Challenges still exist for improving thermal imagery products to accurately track spatiotemporal changes in canopy-air temperature difference (CATD); factors to consider include variable solar radiation, wind, RH, and height of image acquisition. Investigations are continuing to determine whether these factors could be included in a model whose output could be used as compensation to permit accurate temporal comparison of images. Spatial statistics have shown utility in tracking variability in the field, and the example presented herein was for cotton, a crop that requires intensive management and finer-scale application of insecticide, harvesting aids, and water near the end of the season. Using spatial information and ground truthing, a VRI system like the one described herein can be used to apply water by zones paying particular attention to those areas prone to stress using prior information. Although on-the-go application using thermal imagery might be feasible using time-temperature thresholds or similar methods that rely on CATD, better methods for delineation of CATD that account for weather variables and height of image acquisition need to be developed if canopy temperatures are to be acquired from aerial platforms.

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