Review

Remote sensing of biotic and abiotic stress for irrigation management of cotton

Nyland R. Falkenberg a,*, Giovanni Piccinnib, J. Tom Cothren c, Daniel I. Leskovarb, Charlie M. Rush d

a Texas A&M University 2474 TAMU, College Station, TX 77843-2474, United States
b Texas A&M Research and Extension Center, 1619 Garner Field Rd., Uvalde, TX 78801, United States
c Texas A&M University, Soil and Crop Sciences Department, 370 Olsen Blvd., College Station, TX 77843-2474, United States
d Texas Agricultural Experiment Station, PO Drawer 10, Bushland, TX 79012, United States

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The applicability of commercially available remote sensing instrumentation was evaluated for site-specific management of abiotic and biotic stress on cotton (Gossypium hirsutum L.) grown under a center pivot low energy precision application (LEPA) irrigation system. This study was conducted in a field where three irrigation regimes (100%, 75%, and 50% ETc) were imposed on areas of Phymatotrichum (root rot) with the specific objectives to (1) examine commercial remote sensing instrumentation for locating areas showing biotic and abiotic stress symptomology in a cotton field, (2) compare data obtained from commercial aerial infrared photography to that collected by infrared transducers (IRTs) mounted on a center pivot, (3) evaluate canopy temperature changes between irrigation regimes and their relationship to lint yield with IRTs and/or IR photography, and (4) explore the use of deficit irrigation and the use of crop coefficients for irrigation scheduling. Pivot-mounted IRTs and an IR camera were able to differentiate water stress among irrigation regimes. The IR camera distinguished between biotic (root rot) and abiotic (drought) stress with the assistance of groundtruthing. The 50% ETc regime had significantly higher canopy temperatures than the other two regimes, which was reflected in significantly lower lint yields when compared to the 75% and 100% ETc regimes. Deficit irrigation down to 75% ETc had no impact on lint yield, indicating that water savings were possible without reducing yield.

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* Corresponding author. Tel.: +1 830 278 9151; fax: +1 979 845 8696.
E-mail address: n-falkenberg@tamu.edu (N.R. Falkenberg).
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1. Introduction

The history of cotton production in Texas has spanned a period of more than 17 decades, and approximately 141 of the 254 counties in Texas produce cotton (Texas Agricultural Statistics, 1959–2002). Texas is the leading cotton producing state, with more than 30% of the total U.S. production for the crop years of 1959–1960 through 1998–1999 (Texas Agricultural Statistics, 1959–2002). Cotton accounted for 8% and 9% of the state’s total agricultural income in 2002 and 2003, respectively (Texas Agricultural Statistics, 1959–2002).

In the Winter Garden area of Texas, upland cotton is primarily produced as an irrigated crop. Although irrigation is required for profitable yields in cotton and other agricultural crops, it is also a major production cost because irrigation water must be pumped from the Edwards aquifer. Therefore, the conservation of the Edwards aquifer resource is of high priority in the Winter Garden area.

In 1996, the Texas Legislature placed water restrictions on the farming industry by limiting growers to a maximum use of 2467 m$^3$ of water per year in the Edwards aquifer region (Barrett, 1999). This “irrigation cap” made water an extremely valuable commodity in the Winter Garden area of Texas. Since 60% of water drawn from the aquifer is for agronomic use, improved irrigation efficiency and management practices could help maintain aquifer levels and enhance water savings for growers (Epstein, 2000).

In the past, irrigated cotton in Texas was grown under full irrigation (where water was not limiting) in order to maximize crop yields (Bordovsky et al., 1992). However, limited water availability and restrictions have affected irrigation strategies. Now, deficit irrigation is becoming a common practice where water application is decreased below crop water requirements. Bordovsky et al. (1992) found that deficit irrigation using a LEPA system on short-season cotton enhanced lint yield and conserved groundwater on the Southern High Plains of Texas. It was suggested that this method would be applicable for multiple crops and regions where center pivot irrigation is practiced and when used in combination with crop coefficients could enhance a management system.

Although irrigation and crop water use efficiency are important, irrigation timing is also critical, especially with deficit irrigation, to prevent plants from becoming too stressed. When plant water deficit is imposed during peak flowering periods, yield is reduced more than when deficit irrigation is imposed either earlier or later in the flowering period (Mauney and Stewart, 1986). Recent investigations have shown site-specific management (SSM) as an additional means to address water management issues (Schepers and Francis, 1998). Because efforts to maximize agricultural production efficiency have become a high priority for producers and researchers in the Winter Garden area of Texas, SSM has become a major topic of interest for the area. SSM can involve satellite-based remote sensing technology and mapping systems to detect specific areas suffering from stress within a field (i.e. water, insect, and disease).

Crop canopy temperature, an effective indicator of plant water stress (Moran et al., 1997), could also be useful in developing an efficient irrigation management system. The use of remote sensing to determine canopy temperature has been useful in monitoring plant stress by using IRTs mounted on center-pivot irrigation systems (Michels et al., 1999). Aerial “fly-overs” with infrared equipment, and tethered balloons fitted with IRTs, have also been used to detect crop water stress by recording changes in leaf temperature (Hatfield and Pinter, 1993; Michels et al., 1999). IRTs have been used previously to determine leaf temperatures (Bugbee et al., 1999) and thermal stress of cotton (Burke et al., 1990).

The different types of IR spectrums that have been used as remote sensing tools are near and thermal IR. Near IR measures the light reflectance in the form of wavelengths and has been used to determine plant water and disease stress (Nixon et al., 1975; Tolier et al., 1981). Past research introduced thermal IR as a way to measure canopy temperature, which can help schedule irrigation applications on cotton (Wanjura et al., 1992; Wanjura and Mahan, 1994). Color-infrared imagery is now commonly used to determine ground data, crop yields, yield components, soil properties, and the detection of crop diseases (Tolier et al., 1981; Jackson, 1986; Pozdnjakova et al., 2002). Several companies are now selling products based on IR imagery (Crop Quest Agronomic Services Inc., John Deere Inc., and Tetracam Inc.).

Phymatotrichopsis omnivora (Duggar), an economically important and unmanageable fungal pathogen of cotton, is indigenous to the southwestern USA and northern Mexico (Streets and Bloss, 1973; Lyda, 1978; Kenerley and Jeger, 1990). This fungus is an example of an important disease that might be monitored with remote sensing technology due to suddenness of plant death in infected areas (Smith et al., 1977). The disease has limited production in the Rio Grande Valley, South Texas, The Blacklands, and the trans-Pecos region of Texas. The incidence and severity of root rot is affected by soil and environmental conditions (Rush et al., 1984; Kenerley and Jeger, 1990), which include pH, mineral content, and soil temperature (Kenerley et al., 1998).

The implementation of variable rate irrigation and nutrient management (Camp and Sadler, 1994), spatially-variable fertilizer applicators (Schueller, 1989), spot sprayers (Felton and McCloy, 1992) for disease and insect control, and herbicide control using GIS weed maps (Brown et al., 1990) are all technologies that can be used in combination with remote sensing data to improve on-farm SSM practices. Therefore, we initiated a study to address the following objectives: (1) evaluation of the efficacy of commercial aerial thermal IR camera for locating areas of biotic and abiotic stress in a cotton field, (2) comparison of commercial aerial thermal infrared photography to IRTs mounted on a center pivot irrigation system for usefulness in detecting and managing biotic and...
2. Materials and methods

A 2-year field study was conducted in a cotton field at the Texas A&M Agricultural Research and Extension Center in Uvalde, Texas (99° 5′ W, 29° 1′ N). Soil type was a Knippa clay soil fine-silty, mixed, hyperthermic Aridic Calciustolls with a pH of 8.1. Irrigation was supplied by a center-pivot LEPA irrigation system. Cotton variety Stoneville 4892 Bollgard/Roundup Ready® was planted with a vacuum planter on 12 April 2002 and 3 April 2003. The experimental site, approximately 4.8 ha, was bedded in a circle that was planted at 20,250 seed ha⁻¹ on 1-m row spacings. Furrow dikes were placed between beds and lanes were cut between irrigation regimes to increase water capture, minimize run-off, and maximize irrigation efficiency. Nitrogen was broadcast with a fertilizer spreader buggy at 112 kg ha⁻¹ for both years of the study. The plot design consisted of three treatments, which were replicated four times in a randomized block design. A 90° wedge of a field under a center pivot was divided equally into twelve 7.5° regimes, which were maintained at 100%, 75%, and 50% ETc values (Fig. 1). Irrigation was scheduled and ETc regimes were imposed according to calculations of the Penman–Monteith (P–M) (Monteith, 1965) ETc formula and crop coefficient (Kc) values obtained from the Texas ET Network (2003), which ranged from 0.07 to 1.10 for the different growth stages.

For pivot-installed-remote sensing, 30 IR/c.™ 01-T80F/27C infrared transducers available from Exergen® (Watertown, MA) were mounted at approximately 4.5-m spacings along the pivot length to record canopy temperatures. The IRTs measured the infrared band between 8 and 14 μm and had a height to view angle ratio of 1:1. Once the cotton canopy reached full closure, the IRTs were raised to the highest level (2.7-m), in order to maximize the area imaged. A CR 23X Micrologger® by Campbell Scientific Inc. (Logan, UT), recorded canopy temperatures from the IRTs every 10 s, and averaged temperature values every 60 s. IRT cotton canopy temperature readings were scheduled weekly at solar noon on sunny days to record temperature changes within the field over time. The canopy temperatures for all 30 IRTs were averaged for each irrigation regime, which in turn gave a single canopy temperature value for each regime scanned. The pixel size for the IRTs was 3.65 m x 3.65 m and had approximately 25 plants within each pixel. An IRT mapping program developed at the Texas A&M Research and Extension Center in Uvalde was used to visually distinguish differences between canopy temperatures for the irrigation regimes (copy of the program can be obtained from the corresponding author).

For aerial remote sensing, a TV5-700 Long Wave-length Infrared (LWIR) camera produced by Indigo Systems® (Dallas, TX) with an infrared band of 8–14 μm was mounted in a helicopter and evaluated for its ability to detect canopy temperature differences. The camera had a 35-mm lens with a temperature measurement range from –20 to 500 °C. Images were taken from a helicopter perpendicular to the cotton field at heights of 458–915 m. The pixel size of these images was approximately 0.61 m x 0.61 m and had three to four plants within each pixel. The camera was used every 2–3 weeks to record canopy temperature, depending on weather, irrigation scheduling, and availability from the company. Software supplied by the manufacturer was used for data analysis. The IR TherMonitor® software, by Thermodeteknix Systems Ltd. (Dallas, TX), was provided by Indigo Systems® and has the capability of calculating the average canopy temperature for all pixels in an image as well as the ability to remove specific pixels. Root rot areas, which first began to develop during crop anthesis, were not computed into the average canopy temperature value. This allowed the average canopy temperatures of root rot areas or irrigation regimes to be calculated separately. Temperature readings with the IR camera were taken around solar noon on sunny days when there was sufficient sunlight for the camera to detect plants under stress. Additionally, a digital camera was used to take aerial pictures as visual references.

Glyphosate® [N-(phosphonomethyl) glycine] was applied for weed control at the four-leaf stage at 0.236 L ha⁻¹ during the growing season as needed using a Spra-Coupe (ground-rig chemical applicator). Mepiquat® (N,N-dimethylpiperidinium) chloride was added as needed during the course of both seasons for a total of 1.75 L ha⁻¹ in 2002 and 2.3 L ha⁻¹ in 2003. Defoliant was applied to the cotton field using 0.44 L of Ginstar® (N-phenyl-N’-1,2,3-thiadiazol-5-ylurea) and 3-(3,4-dichlorophenyl)-1,1-dimethyleurea) combined with 90.8 g of Dropp® (N-phenyl-N’-1,2,3-thiadiazol-5-ylurea) per hectare. A Campbell Pacific Nuclear Corp.™ (CPN) 503 hydprobe water content depth gauge was used to determine soil water content at 20-cm increments to a depth of 2-m. Insect control was achieved by a pivot-mounted precision spray system (Accu-Pulse by Valmont Inc.), applying Dimethoate® (O-O-dimethyl-S-methylcarbamoylmethyl phosphorodithioate) at 0.236 L ha⁻¹.

Severe epidemics of Phymatotrichopsis root rot caused by Phymatotrichopsis omnivora appeared in the cotton fields during both years of the study. Although root rot was not planned for the study, these areas of biotic stress were monitored with the IRTs and IR camera to determine if canopy temperature differences could be detected and distinguished from abiotic (drought) stress. Each year the research field was groundtruthed.

Fig. 1 – Study plot design. Aerial photograph of the experimental design for the study shows three irrigation regimes of 100%, 75%, and 50% ETc with the four replications.
weekly by visual observations to determine the type of stress (insect, disease, or water) and to determine the crop growth stages.

A single-row cotton picker was used to harvest a single 24.4-m pass from each of the plots. Temperature, lint yield, and percent soil water content data were statistically analyzed by ANOVA, and means were separated by Fisher’s LSD and analyzed at $P < 0.05$ level. Regression analysis was run to determine the relationship between lint yield, canopy temperature, and percent soil water content.

3. Results

Environmental conditions and irrigation amounts for the 2002 and 2003 growing seasons are depicted in Figs. 2 and 3. Minimum and maximum temperatures were relatively normal for the region with highs around 35 °C and lows around 18 °C, which were very similar to the 50-year average of 35 and 15 °C. In 2002 the irrigation regimes were only imposed during the months of May and June due to late season rainfall events, while in 2003 all three irrigation regimes were imposed throughout the growing season despite excessive rainfall that occurred.

The IRT scans showed changes in canopy temperature as the cotton canopy developed (Figs. 4 and 5). In 2002, IRT scans were conducted only through June due to excessive rainfall amounts that occurred in July. The extreme canopy temperatures observed early during crop development in 2002 were due to soil background (Fig. 4), while 2003 showed decreased canopy temperatures, which were due to rainfall in the early stages of canopy development (Fig. 5). Scans for 14, 17 and 27 June in 2002 showed no significant differences in temperature between the 75% and 100% ET$_c$ regime with the canopy temperatures being 30.2 and 29.2 °C, respectively (Fig. 4). The trend from the canopy temperatures obtained with the IRTs showed that the 50% ET$_c$ irrigation regime was always numerically higher than that of the 75% and 100% ET$_c$ regimes.
Similar trends were shown in the 2003 growing season with no significant differences detected between the 75% and 100% irrigation regimes on 3, 11 July and 6 August (Fig. 5).

The IR camera was able to distinguish canopy temperature differences between the irrigation regimes in 2002 and 2003 (Figs. 6 and 7). Only two flights were conducted for IR detection during the 2002 growing season due to excessive rainfall early in crop development. On 29 July, the canopy temperature between the 100% (31.8 °C) and 75% (32.1 °C) ETc irrigation regimes was not significantly different, but the canopy temperature for the 50% (33.1 °C) ETc regime was significantly higher than the other two irrigation regimes (Fig. 6). Although there were significant differences in canopy temperatures between all three of the irrigation regimes for the 16 August flight, the differences between 100% and 75% ETc were smaller compared to the 50% ETc regime.

In 2003, the IR camera was also able to detect canopy temperature differences between the irrigation regimes in five of the six flights for the period of 15 May through 21 August (Fig. 7). These temperatures were higher than normal due to bare soil detection and the decreased canopy coverage early in development. However, the remaining flights on 13 June, 22 July, 6 August, and 21 August detected no significant canopy temperature differences between the 75% and 100% irrigation regimes.

The IR camera was able to differentiate biotic (root rot) from abiotic (drought) stress with the assistance of groundtruthing (Fig. 8). Biotic stress (Phymatotrichum root rot) was present within the field, and canopy temperatures increased in areas where disease was present (data not shown). Early season images showed the development of root rot before visual signs could be detected. Canopy temperatures early in the season were 18–19 °C, but distinct patches of root rot, which ranged from single plants up to areas 6 m in diameter, were found in the field that had canopy temperatures that ranged from 28 to 32 °C. Midseason results (22 July) (Fig. 9) illustrated that the canopy temperatures for the root rot areas were starting to increase although the digital aerial photograph pictures still showed no visual symptoms of root rot. Examination of the IR image showed the root rot areas were continuing to develop and were affecting plants in different areas of the field. The
average canopy temperatures for the irrigation regimes ranged from 27 to 29 °C, while the canopy temperature for the root rot stressed areas ranged from +5 to +6 °C higher. Late season evaluations on 21 August revealed differences between root rot and water stress (Fig. 10). The digital aerial photograph showed the progressive spread of root rot through the cotton field. The canopy temperature for the root rot areas ranged from 35 up to 40 °C, with the higher temperatures reflecting desiccating plants and soil surface. No relationship was found between the percent of root rot development and the amount of water applied through the irrigation regimes.

The June 20, 25, and 27% soil water content readings for 2003 failed to show differences between the 75% and 50% ETc regimes, but the 100% ETc regime had a significantly higher percentage of soil water content (Fig. 11). On 9 July, no differences in soil water content were recorded in the 75% and 50% ETc regimes due to rainfall, and this trend continued on into July 30. Thereafter, significant differences were detected for all three irrigation regimes and continued for the rest of the growing season. The 100% ETc regime had significantly higher percent soil water content than the other two regimes for the entire growing season (Fig. 11).

For the 2002 and 2003 growing seasons, lint yield was not different between the 75% (2375 and 2139 kg/ha) and 100% (2611 and 2450 kg/ha) ETc regimes, while the 50% (1832 and 1816 kg/ha) regime yielded significantly less than either of these regimes (Fig. 12). Despite excessive and timely rainfall events, differential irrigation during early development affected cotton boll maturation, which is shown by yield differences between the irrigation regimes. Percent soil water content and lint yield were positively correlated ($r^2 = 0.98$). A negative correlation was recorded between the percent soil water content and canopy temperatures with the IR camera ($r^2 = –0.80$) and IRTs ($r^2 = –0.81$) during peak bloom when water use was at its highest. A significant negative correlation existed between lint yield and average canopy temperature in
2002 with the IRTs ($r^2 = 0.98$) and the IR camera canopy temperatures for areas not infected with *Phymatotrichum* root rot ($r^2 = 0.99$). A similar negative correlation was detected between the IR camera and IRTs temperature readings and lint yield for 2003 ($r^2 = 0.88$).

4. Discussion

The results from both years of the study confirm previous findings that the infrared thermometry (IRT) is an effective tool for monitoring plant stress. Plant canopy temperature has been recognized as a sensitive indicator of plant water status, which has led to the development of stress related indices based on the difference between plant canopy and ambient air temperature (Idso et al., 1982). The results from this study support the findings by Moran et al. (1997) that the IRTs are very effective in detecting water stress in plants. Increased canopy temperatures as detected with the IRTs and IR camera early in the season can be associated with bare soil. Significant temperature differences were not detected between the 100% and 75% ET$_c$ irrigation regimes, suggesting that the amount of irrigation applied in the 75% irrigation regimes was sufficient to maintain canopy temperatures at the same non-yield limiting values present in the 100% ET$_c$ regime. According to the IRT temperature, plants within the 50% regime were unable to acquire sufficient water, which altered the soil–plant–water airflow continuum and consequently the crop was prevented from transpiring and releasing heat, which causes increased canopy temperatures and subsequent cellular impairment. Results from this experiment, however, showed no distinction between the water and root rot stressed areas. The inability of the IRTs to distinguish between biotic and abiotic stress can be attributed to the height at which the IRTs were maintained. The IRTs were raised as high as possible to maximize the area covered, but this decreased resolution and more plants were averaged into one pixel. If the IRTs could have been lowered, the resolution would have increased, and with groundtruthing the IRTs possibly could have distinguished between the two types of stress, although total area covered would have decreased. Increasing the resolution of the IRTs will enhance the pixel size and ability to distinguish between biotic and abiotic stress at different heights. Using GPS coordinates for the IRTs will allow pixels to be logged and points can be overlaid on IR and digital images using GIS software to allow water and root rot stressed areas to be pinpointed over time.

Results from this study indicate that the thermal IR camera was very effective in detecting abiotic stress in cotton by monitoring canopy temperatures. Thermal IR has been used in past research to detect biotic and abiotic stress in crops (Jackson, 1986; Maas et al., 1999). However, the thermal IR camera used in this experiment detected both biotic and abiotic stress in cotton, and the global positioning systems (GPS) and geographic information systems (GIS) capabilities associated with this camera have a tremendous potential for SSM. Within the same field, crops often require different amounts of irrigation due to soil texture, depth, and runoff. The development of variable rate irrigation (Bordovsky and Lascano, 2003; Camp and Sadler, 1994) in combination with GIS software and IR data provided by local agencies can prevent producers from over irrigating in the Winter Garden area by selecting areas that are under stress according to canopy temperatures. Wanjura and Mahan (1994) documented that increased water status decreased canopy temperatures among different irrigation regimes. However, results from this experiment failed to show differences in canopy temperature in 2003 between 75% and 100% ET$_c$ regimes, which may be attributed to excess irrigation in the 100% ET$_c$ model due to an inaccurate estimation of ET$_c$ by the P–M formula for our experiment.

Nilsson (1995) showed that disease detection in barley (*Hordeum* sp.) was possible through image analysis and remote sensing tools. Color infrared images also have been successful in detecting *Phymatotrichum* root rot in cotton fields, and helping to determine disease losses (Toler et al., 1981). Results
in the current experiment showed a similar response to previously reported studies with the IR aerial camera detecting root rot areas early in development. Biotic stress was detected with the IR camera before disease symptoms were visible, although root rot areas had to be groundtruthed to determine the type of stress. A comparison of the early season IR images to those of late season digital aerial images verified that the IR camera was able to detect root rot areas. This ability highlights the potential use of the technology for disease management under drought stress. A cotton grower or consultant could use IR data to detect areas that had canopy temperatures above the optimal temperature range (23–31 °C) for cotton, and these areas could be groundtruthed to determine if root rot was present. Since root rot has no economically feasible cure, and restrictions have been placed on the amount of water that growers can pump in a year in the Edwards aquifer region, the use of IR data would be a valuable tool for future planning for growers to conserve water and to determine infected areas in fields. However, for this technology to be useful images would have to be made in a timely manner. The mapping capability of the IR camera software to exclude specific areas within images further complements the use of this tool with other site-specific management practices by allowing variable rate irrigation to be used to conserve water and chemical injection applications to be used to control diseases in selected areas.

This technology may be conducted in vegetables and other row crops to control diseases in the Winter Garden area by combining data from the IR camera and GIS to that of past research using site-specific management tools such as spot sprayers (Felton and McCloy, 1992), variable rate sprayer systems (Rockwell and Ayers, 1993) for disease and insect control, and site-specific water and nutrient management (Bordovsky and Lascano, 2003; Camp and Sadler, 1994), which allows the stressed areas to be pinpointed and treated.

The Kc used in this experiment was based upon data from Bushland in the Texas Panhandle, and apparently overestimated ETc and the amount of irrigation needed for the Winter Garden area in South Texas. Because water is such a valuable commodity in this region, the water saved in the 75% regime compared to 100% ETc could save growers water to use for other crops or to sell to municipalities. The lack of significant lint yield differences between the 100% and 75% ETc regimes in both years, suggests that water savings are possible with 75% ETc, without yield loss. Also, the decreased lint yields and increased canopy temperatures in the 50% ETc regimes, support this observation. However, although overestimation was evident, Kc values need to be developed for the Winter Garden area before reliable recommendations can be made to growers.

5. Conclusions

It appears that the P–M formula and the Kc used for the experiment overestimated irrigation in the 100% ETc regime. This is illustrated by the presence of increased percent soil water content in the 100% regime, while the canopy temperatures and lint yields showed no significant differences between the 75% and 100% regime. Modifications of Kc and the P–M formula for different areas and environmental conditions can prevent over-irrigation. Since water is such a valuable commodity in the Edwards aquifer region, these modifications could help prevent growers from over-irrigating. In the 75% regime, water savings were possible without yield depletion, thus providing growers the potential to reduce irrigation costs or apply water to other crops later in the season.

The ability to detect water stress within the irrigation regimes with IRTs and the IR camera can provide growers or consultants more effective methods to manage water stress within fields. However, the cost of these tools varies greatly and expenses have to be justified with increases in yields and water savings. The IR camera detected biotic stress before it was seen visually. Irrigation can be subsequently cut in diseased areas for additional savings. The IRTs can detect water stress as shown in this study, but due to trade offs between area covered and resolution, they lacked the capability of detecting biotic stress due to their poor resolution. If more IRTs were mounted on the pivot, and used in combination with GPS they may have the ability to detect stress and provide growers and scientists alike with a low cost instrument that can be used as an effective remote sensing tool. Combining the use of variable rate irrigation, chemical injections with spot sprayers, and GIS field maps to the data from the IR camera will allow producers to conserve water, prevent diseases, and reduce fuel and pumping costs in various crops grown in the Winter Garden area.

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