REMOTE SENSING FOR SITE-SPECIFIC MANAGEMENT OF BIOTIC AND ABIOTIC STRESS IN COTTON

A Thesis

by

NYLAND RAY FALKENBERG

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2004

Major Subject: Agronomy

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May 2004

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ABSTRACT

Remote Sensing for Site-Specific Management of Biotic

and Abiotic Stress in Cotton. (May 2004)

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Co-Chairs of the Advisory Committee: Dr. Giovanni Piccinni
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This study evaluated the applicability of remote sensing instrumentation for site-specific management of abiotic and biotic stress on cotton grown under a center pivot. Three different irrigation regimes (100%, 75%, and 50% ETc) were imposed on a cotton field to 1) monitor canopy temperatures of cotton with infrared thermometers (IRTs) in order to pinpoint areas of biotic and abiotic stress, 2) compare aerial infrared photography to IRTs mounted on center pivots to correlate areas of biotic and abiotic stress, and 3) relate yield to canopy temperatures. Pivot-mounted IRTs and IR camera were able to differentiate water stress between the irrigation regimes, however, only the IR camera was effectively able to distinguish between biotic (cotton root rot) and abiotic (drought) stress with the assistance of groundtruthing. The 50% ETc regime had significantly higher canopy temperatures, which were reflected in significantly lower lint yields when compared to the 75% and 100% ETc regimes. Deficit irrigation up to 75% ETc had no impact on yield, indicating that water savings were possible without yield depletion.

DEDICATION

This thesis is dedicated to my mom, Janice, and my dad, Leland, for all of the support and opportunities that they have provided throughout my life. Without their help I would not be the person, nor in the place, that I am in today. This goal would not have been possible without their support, love, and sacrifices that they have made throughout my life.

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I would like to thank all of my family and friends who supported and encouraged me during the pursuit of my degree. Also, I thank my sister, Shollie, for her encouragement and laughter during this whole process, and wish her the best of luck with her degree.

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INTRODUCTION

Cotton (*Gossypium hirsutum* L.) belongs to the family Malvaceae. Other members of this family includes blackberry, raspberry (*Rubus spp*), and okra (*Hibiscus esculentus*) Cotton is a warm-climate crop that is cultivated for the production of clothes, cosmetics, X-ray films, animal foods, and plastics.

The history of cotton production in Texas has spanned a period of more than 17 decades. Approximately 141 of the 254 counties in Texas produce cotton (Texas Agricultural Statistics, 2002). Texas is the leading cotton producing state, with more than 30% of the total U.S. production for the crop years of 1959-60 through 1998-1999 (Texas Agricultural Statistics, 2002). Cotton has been a major agricultural crop and source of cash income in Texas for many years. Production in 2003 decreased to 4.2 million bales valued at almost $1.5 billion, compared to the 2002 cotton crop of 5.04 million bales of valued at $1.1 billion. Cotton accounted for 8 and 9% percent of total agricultural income in 2002 and 2003, respectively (Texas Agricultural Statistics, 2002). In South Texas the total cotton production for 2002 was 1 million bales with an economic impact of $2.9 million. In the Winter Garden area upland cotton is produced in both irrigated and non-irrigated conditions, due to climatic differences across the state. Average yield has increased from 314 pounds/acre in 1970 to 524 pounds/acre in 2003 for the total amount of cotton produced between irrigated and non-irrigated methods. This increase in yield can be attributed to several factors, the most important being improved irrigation tactics (Bordovsky et al. 1992) and enhanced cotton varieties.

This thesis follows the style and format of Agronomy Journal.

Irrigation is required for profitable yields in the cotton and other agricultural industries, therefore the conservation of the Edwards aquifers resources is of high priority in the Winter Garden area.

The Edwards aquifer in South Texas is one of the most permeable and productive carbonate aquifers in the United States. The recharge zone of this aquifer encompasses approximately 1500 square miles, and since this semi-arid region is noted for climatic extremes, long droughts, and intense rainfall events, water is a highly managed resource (Maclay and Land, 1988). The depletion of the Edwards aquifer and the competition for water with urban development has limited water available for irrigation (Barrett, 1999). Declining groundwater levels in parts of the Edwards aquifer region have led to the reduced irrigation in the surrounding areas of the aquifer. In 1996, the Texas Legislature placed water restrictions on the farming industry by limiting growers to a maximum use of 2 acre-foot of water per year in the Edwards aquifer region based upon historical use (Barrett, 1999). The irrigation cap placed on growers has made water an extremely valuable commodity in the Winter Garden area of Texas. The regulation of water has limited growers on the type of crops and amount of acres that can be planted yearly, since the growing season in the Winter Garden area is spread across the entire year. Due to the high temperatures and limited rainfall, irrigation scheduling of crops must be properly managed to ensure sufficient availability water for irrigation. Growers in the region generally tend to exceed the recommended crop water requirements due to inaccurate water use information. Therefore, improved irrigation efficiency and management practices can help maintain aquifer levels and enhance water savings for growers (Epstein, 2000).

Irrigation is crucial for profitable yields of cotton in the semi-arid Winter Garden area, but is also a major production cost. Traditionally irrigation has been applied through furrow irrigation, but now pivots are becoming more prevalent. Center pivot irrigation provides better control over water applications than furrow irrigation (Lyle and Bordovsky, 1981).

The need for improved irrigation efficiency has resulted in the development of many new types of irrigation systems. Center pivot irrigation are expanding across the Edwards aquifer region and replacing furrow irrigation. Center pivots have increased water efficiency up to 90% compared to furrow irrigation which is only 50% (Lyle and Bordovsky, 1981) and also require less labor (New, 1986). LEPA (Low Energy Precision Application) methods are widely used in the Edwards aquifer region to reduce water application losses and to reduce the energy requirements for pumping. The LEPA systems distribute water directly into the furrow at low pressure (5 to 6 psi) through drop tubes or orifice-controlled emitters (Lyle and Bordovsky, 1983). Generally the LEPA heads are 203 to 457 mm (8 to 18 inches) above the furrow, which minimizes the drift loss and evapotranspiration from the soil and crop canopy (Texas ET Network, 2003). LEPA irrigation is approximately 95% efficient in terms of partitioning the applied water into crop water use and allows for more precise water applications (Texas ET Network, 2003). LEPA system efficiency can be further increased to 95 to 98% when used in combination with micro-basin tillage and circular bedding (Lyle and Bordovsky, 1983). Micro-basin tillage, which is a commonly referred to as furrow diking, is a management strategy to reduce water runoff and to increase water efficiency during irrigation (New and Fipps, 1990). Therefore, the implementation of all these techniques can allow for increased irrigation efficiency.

In the past, cotton in Texas was grown under full irrigation (where water is not limiting) in order to maximize crop yields (Bordovsky et al. 1992). Limited water availability has affected irrigation methods. For example, deficit irrigation is a common practice where water application is decreased below crop water requirements. Under deficit irrigation, the crop must be drought tolerant in order to produce an acceptable yield. Bordovsky et al. (1992) found that deficit irrigation of short-season cotton using a Low Energy Precision Application (LEPA) system can enhance lint yield and conserve groundwater on the Southern High Plains of Texas.

According to Texas ET Network (2003) the total inches of consumptive water use for cotton is 23 inches per growing season in the Edwards aquifer region. The consumptive water use is the total amount of water used by the plant, and does not reflect the total amount of water applied through irrigation or rainfall. Because the competition for water has increased, growers are now forced to maintain yields while regulating the total amount of water applied.

The maximization of agricultural production efficiency has become a high priority for producers and researchers in the Winter Garden area of Texas. Recent investigations have shown Site-Specific Management (SSM) as a means to address the water management issues (Schepers and Francis, 1998). 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). Remote sensing also allows for addressing problems concerning spatial variability within fields (Plant et al., 2001). As new and improved remote sensing equipment is developed and used in agriculture, site-specific management practices will become even more efficient (Schepers and Francis, 1998).

Crop canopy temperature has been found to be an effective indicator of plant water stress (Moran et al., 1997). Remote sensing technology, can detect crop canopy temperature, which can monitor the crops response to stress. One method of remotely sensing biological stresses in plants is through the use of precision infrared thermometers (IRT) (Michels et al., 1999). IRTs are used to detect differences in surface temperatures of plants rather than reflectance or energy units (Hatfield and Pinter, 1993). IRTs are calibrated to operate in bands of 8 to 14 or 10.5 to 12.5 μm to elimate problems with reflected solar radiation. In the past, IRTs have been used to determine the optimal time of planting fruit crops (Stewart et al., 1978), the water potentials of wheat (Erhler et al., 1978), thermal stress on cotton when canopy temperatures were not within the thermal kinetic window (Burke et al., 1990), and leaf temperature (Bugbee et al., 1999). Color-infrared imagery is commonly used for a variety of applications, such as ground data, crop yields, yield components, and soil properties (Pozdnyakova et al., 2002). IRTs have been used to control irrigation scheduling by the regulation of optimal canopy temperatures for simplifying and automating irrigation management (Wanjura et al., 1992).

Two assumptions are made in using canopy temperatures for irrigation management: 1) canopy temperatures above the optimal temperature range (23 to 31^{o}C) indicate inadequate plant water status and 2) plant growth or productivity are positively correlated with the amount of time that the plant's temperature is within its optimal thermal range (Wanjura and Mahan, 1994). Hatfield (1990) used infrared thermometers to measure plant stress by recording plant canopy temperatures, which showed temperature differences between normally-watered infested and non-infested plants. Disease stress can be detected by IRTs in crops by recording the temperature changes in the canopy temperature. Remote sensing and image analysis technology have been used successfully to detect crop diseases according to canopy temperatures (Nilsson, 1995).

Michels et al. (1999) stated that remote sensing could be useful in monitoring plant stress by using IRTs mounted on center-pivot irrigation systems. Aerial "fly-overs" with IRT-equipment, or possibly tethered balloons fitted with IRTs, can be used to detect water stress by recording changes in leaf temperature caused by the alteration of water flowing through the soil-plant atmosphere continuum (Hatfield and Pinter, 1993; Michels et al., 1999). Plant temperature is influenced by water status (Idso et al., 1982; Grimes et al., 1987), which can be altered by irrigation, rainfall, environmental conditions, temperature, and plant pests. Multispectral remote sensing was used to detect water stress in crops and illustrated increased canopy temperatures in stressed areas (Maas et al., 1999), which can be correlated to yield data.

Deficit irrigation occurs when the amount of water applied to a crop is reduced below the level required for maximum yield. Water stress in cotton affects the total fruiting points (Mauney and Stewart, 1986), and boll positioning (Hearn, 1979), which in turn directly affects yield. When plant water deficit is imposed during peak flowering periods, yield is reduced more than compared to deficit irrigation occurring either earlier or later in the flowering period (Mauney and Stewart, 1986).

Introduction of new drought resistant crop varieties, has enabled growers to use limited amounts of water to produce crops. The combination of more water efficient varieties with site-specific management techniques, give growers even greater potential to improve the ways in which they manage their lands. Additional methods for enhancing water conservation includes the use of evapotranspiration (ET) values for water management (Humes et al., 1994; Kustas et al., 1994), and incorporating crop coefficients and physiological parameters (Marani et al., 1993) to regulate irrigation scheduling (Wanjura et al., 1992) and determine crop stress. These tools are vital in determining daily water use and helping minimize overall costs.

Evapotranspiration (ET), transpiration ratio (T/ET; T= transpiration), water-use efficiency (WUE), and crop coefficients (K_c) of crops are important data for water management and irrigation planning (Kato et al, 2004). The Penman-Monteith model (Monteith, 1965) is a physically based model of energy transfer between vegetation and the atmosphere, which is generally used to estimate evapotranspiration of field crops. Multi-layer models of the Penman-Monteith models have been revised for the advancement of irrigation technology (Pereira and Smith, 1989). The Penman-Monteith produces the best evapotranspiration estimates for semi-arid environments (DehghaniSanij et al, 2004). The prediction of crop water requirements is of vital importance in water resource management and planning (Abdelhadi et al. 2000). Crop coefficients have been developed to help growers determine the amount of water that a crop is using at different growing stages. Estimation of crop water use is essential in order to ensure that water supply and crop water requirements are met on a daily basis (Inman-Bamber and McGlinchey, 2003).

Soil moisture measurements are critical in determining water availability for crops under differential irrigation. Neutron probe measurements on surface irrigation studies (Janat and Somi, 2001) and tensiometers (Pettigrew, 2004) have been used to monitor and record soil moisture in soils. In addition to water management, neutron probe tubes are excellent tools to schedule differential irrigation and determine soil moisture. Soil moisture can be used to monitor or control disease development in crops, and a common cotton disease that favors wet conditions is *Phymatotrichopsis omnivora* (White et al., 1987).

Phymatotrichopsis omnivora (Duggar) and is a serious and unmanageable fungal pathogen of cotton that is indigenous to the southwestern USA and northern Mexico (Streets and Bloss, 1973; Lyda, 1978; Kenerley and Jeger, 1990). The disease has limited production in the Rio Grande Valley, South Texas, the Blacklands, and the trans-Pecos Region. Most descriptions of epidemics of *Phymatotrichopsis* root rot rely solely upon foliar symptom expression (King and Loomis, 1929; Rogers, 1942; Kenerley and Jeger, 1990). In infested fields, root rot develops in circular patterns, which gradually enlarge in subsequent years (Streets and Bloss, 1973). 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). *Phymatotrichopsis* root rot is affected by rainfall and air temperature during the growing season (Jeger and Lyda, 1986). Sclerotia are the primary source of inoculum, which leads to strands that contact and infect growing roots. In attempts to maximize production, cotton farmers tend to over irrigate, which can lead to problems with the pathogen. White et al., 1987 demonstrated that water potentials of -0.02 to –1.9 MPa supported germination and strand formation of root rot and the soil water potentials above or below these levels were either beneficial to sclerotia formation or only supported hyphal growth.

Color-infrared aerial imagery can be used to identify, quantify areas of stressed vegetation, and is a powerful tool for characterizing spatial distributions of a crop and the influencing factors to optimize the agricultural production (Everitt et al., 1999). Pozdnyakova et al., (2002) used color infrared aerial imagery to estimate spatial and spectral properties of *phytophthora* (root rot) to determine the effects on yield. As remote sensing techniques are used in combination with farming practices to enhance cotton production it is important to develop best management practices to implement this technology properly. For these reasons the ultimate goal of this research is to minimize the economic inputs of growing cotton and to maximize yields and profit. The specific objectives of this project are as follow: 1) use remote sensing instrumentation for locating areas showing biotic and abiotic stress signs in a cotton field, 2) compare aerial infrared camera to IRTs mounted on center pivots to correlate areas of biotic and abiotic stresses, 3) and evaluate canopy temperature changes between irrigation regimes in a cotton field with the use of IRTs and IR camera and relate to lint yield. We expect to find that IR remote sensing can be a useful tool in detecting areas of biotic and abiotic stresses in cotton. Also, deficit irrigation up to 75% ETc can maintain the same yields as the 100% ETc regime.

MATERIALS AND METHODS

A two-year field study was conducted at the Texas A&M Agricultural Research and Extension Center in Uvalde, Texas (99^{o}5 `W., 29$^o$1`N.). The soil type was a Knippa clay soil fine-silty, mixed, hyperthermic Aridic Calciustolls with a pH of 8.1. The land was prepared using conventional farming methods, which include chiseling, moldboard plowing, disking, bedding, and cultivating. The field was managed under a normal South Texas field rotation with no cotton being planted in the past five years. Irrigation was supplied by a center-pivot LEPA (Low Energy Precision Application) irrigation system, using a diesel well that pumped around 3785 liters (1000 gallons) per minute.

Cotton variety Stoneville 4892 Bollgard/Roundup Ready® was planted with a John Deere® MaxEmerge® vacuum planter on April 12, 2002 and April 3, 2003. The plot size was approximately 4.8 hectares (12 acres) and was bedded in a circle at 20,250 plants per hectare (50,000 plants per acre) on 1-meter (40-inch) row spacings. Furrow dikes were placed between beds to increase water capture, minimize run-off, and maximize the irrigation efficiency of the LEPA system. Lanes were cut between each irrigation regime with a rotary tiller and a border was placed between each regime to prevent water run-off. Nitrogen fertilizer was broadcast with a fertilizer spreader buggy at 112 kilogram per hectare (100 lbs per acre) for both years of the study.

The plot design consisted of two blocks and three treatments, which were replicated four times in a randomized block design. A 90-degree wedge was divided equally into twelve 7.5-degree regimes, which were maintained at 100%, 75%, and

50% ETc values (Fig. 1). The Penman-Monteith evapotranspiration (ET_o) formula in conjunction with cotton crop coefficients (Texas ET Network, 2003) was used to monitor water loss for evapotranspiration. Irrigation was scheduled and regimes were imposed according to calculations of ET_o and crop coefficients, which were maintained on a daily basis in an excel spreadsheet. Crop phenological measurements (growth stages) were taken daily so that crop coefficients could be adjusted. The pivot was programmed to automatically change the percentage of irrigation as the pivot reached the different irrigation regimes.

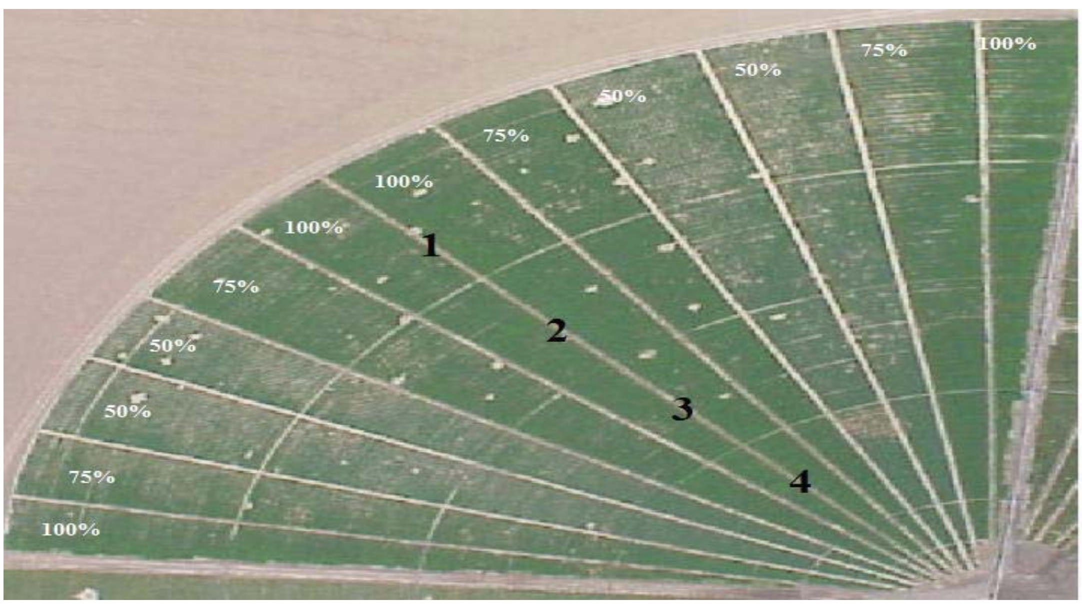

Fig. 1. Study plot design. Aerial photograph of the experimental design for the study shows three irrigation regimes of 100%, 75%, and 50% ETc with the 4 replications.

Thirty Exergen (Irt/c.01-T80F/27C) infrared thermometers were mounted at approximately 4.5 meter (15-foot) spacings along the pivot length to scan the canopy temperature as the pivot moved (Fig. 2). The IRTs measured the infrared band between 8 to14 microns. Square 25.4 millimeter (1-inch) tubing was mounted on the pivot, which had the IRTs clamped to the tubing at a 45^o angle. The IRTs had a height to view angle ratio of 1:1. Once the cotton canopy was at maximum height or full canopy the IRTs were raised to the highest level 2.7 meters (9 feet) so a wider angle of views could be covered. A Campbell Scientific 23X datalogger recorded canopy temperatures from the IRTs every 10 seconds, and averaged temperature values every 60 seconds. IRT cotton canopy temperature readings were scheduled weekly to record canopy development and temperature changes within the field overtime. Scanning was not conducted on rainy or overcast days, and all the measurements were started at solar noon.

Fig. 2. Pivot-mounted IRTs. The IRTs were used to scan cotton canopy temperatures as the pivot was moving across the field. The IRTs are positioned at 15-foot spacings with a 1:1 meter height to view angle ratio.

The pixel size for the IRTs was 3.65 x 3.65 meters (12 x 12 feet) and had approximately 25 plants within each pixel, respectively. Temperature data were stored on Campbell Scientific®, SM4M™ storage modules and downloaded to a computer for data analysis and manipulation. An IRT mapping program developed at the Texas A&M Research and Extension Center in Uvalde was used to visually depict changes in canopy temperatures between irrigation regimes. Microsoft Visual Basic™ software was used to design the mapping program. Time travel and distance from the pivot pad were calculated for the individual IRTs as the pivot scanned the field. Five different temperature classes were determined by recording the maximum and minimum canopy temperatures from each of the scans.

Canopy temperature differences were also determined among treatments using a Robinson-22 helicopter equipped with an Indigo®, TVS-700™ LWIR (Long Wave-length Infrared) camera with an infrared band of 8 to 14 microns. The Indigo® camera had a 35 mm lens, that was configured and calibrated with the camera. The temperature measurement range was from –20 to 500^{o}C and approximately 150 images with audio could be stored on 32 MB compact flash card. Imagery work was taken in a helicopter at heights of 458 to 915 meters (1500 to 3000 feet) to attempt to locate areas of biotic and abiotic stress (Fig. 3). The helicopter was positioned directly above the pivot pad so the camera was centered above the plots. Photographs were always taken perpendicular to the cotton field. The pixel size of these photographs was around 0.61 x 0.61 meters (2 x 2 feet) and had 3 to 4 plants with each pixel. The camera was used every two to three weeks to record canopy temperature readings depending on weather and irrigation scheduling. The high cost of the flights and allowing the canopy development were the contributing factors for the two-week delay between flights. Thermogram™ software, was used to perform data analysis on the IR camera canopy temperatures readings. The software was produced by the Indigo™ camera company and allows for individual plots to be analyzed. Temperature readings for the IR camera were taken around solar noon on days when there was sufficient sunlight for solar radiation to detect plants under stress. Additionally, a digital camera was always used to take aerial pictures so that there would be visual references to compare to the IR camera pictures.

Fig. 3. Aerial IR camera photographs. Use of long wave-length infrared camera to obtain aerial photographs of cotton, and to detect biotic and abiotic stress at the Texas A&M Research and Extension Center.

Glyphosate (N-(phophonomethyl) glycine) was applied for weed control at the four-leaf stage at 0.236 Lha^{-1} (8 oz per acre) during the growing season as needed using a Spra-Coupe (ground-rig chemical applicator). A cultivator and John Deere® tractor were used for weed control later in the season when crop canopy was small enough to get a tractor into the field, and chemicals could not be applied due to restrictions. Glyphosate was also applied late in the season at 0.946 liters per hectare (1 qt per acre) with a hooded sprayer mounted on a small John Deere® tractor with a 378.5 L (100–gallon) tank due to the size of the canopy and the crop starting to flower.

The Mepiquat Rate and Time (MEPRT) measuring stick was used measure internode growth, which helped monitor height and development of cotton. Mepiquat Chloride (N,N-dimthylpiperidinium) was added as needed during the course of both seasons for a total of 1.75 Lha^{-1} (24 oz per acre) in 2002 and 2.3 Lha^{-1} (32 oz per acre) in 2003 using a Spra-Coupe. Applications were made on May 27, 2002 and May 19, 2003 at the first square stage at 0.236 liters per hectare (8 oz per acre).

On September 10, 2002 and August 27, 2003 defoliant was applied to the cotton field. The chemical mix used was 0.44 liters (6 ounces) of Ginstar® (N-phenyl-N'-1,2,3-thiadiazol-5-ylurea and 3-(3,4-dichlorophenyl)-1,1-dimthylurea) combined with 90.8 grams (0.2 pounds) of Dropp® (N-phenyl-N'-1,2,3-thiadiazol-5-ylurea) per hectare, which was applied using the Spra-Coupe.

A Campbell Pacific Nuclear Corp.™ (CPN) 503 hydroprobe moisture depth gauge was used to determine soil moisture at different soil depths. A soil moisture sampler was used to install twenty-four, 38.1 mm (1.5 inch) standard Electrical Metal Tubing (EMT), which were 3.0 meters (10 feet) long. Soil moisture measurements were taken on bi-weekly schedules according to weather and irrigation scheduling.

Insect and disease control was achieved using a precision chemical applicator system (Accu-Pulse). The Accu-Pulse is a center pivot mounted spray system, that allows for chemical savings by targeting specific areas underneath the pivot rather than spraying the entire field. The Accu-Pulse has (110-gallon) a chemical tank that delivers a minimum of 300 Lha^{-1} (32 gallons/acre) spray volume, and solves the chemigation issue. Chemigation consists of applying chemicals through the main water line when irrigating crops. The Accu-Pulse has a separate water line were the chemicals are added, which is exclusive of the main water line, thereby preventing backflow of chemicals into the water source. When insect counts reached measurable levels pre- and post-treatment counts were made to determine the efficacy the Accu-Pulse and the ground applicator. The main insects that were monitored in this study were the bollworm (*Helicoverpa zea*), budworm (*Heliothis virescens*), silverleaf whitefly (*Bemisia argentifolii*), cotton fleahopper (*Pseudatomoscelis seriatus*), and cotton aphid (*Aphis gossypii*).

Dimethoate, (O-O-dimethyl S-methylcarbamoylmethyl phosphorodithioate) at 0.236 liters per hectare (8 oz per acre), was applied with the Accu-Pulse and Spra-Coupe when insect counts reached threshold levels. Insect counts were taken daily to monitor changes in insect populations. The Boll Weevil Eradication Program called for the application of four different sprays of Ultra Low Volume (ULV) Malathion (diethyl (dimethoxyphosphinothioylthio) succinate using a ground-rig sprayer when boll weevils

(*Anthomonus grandis*) were located in the field.

Severe epidemics of *Phymatotrichopsis omnivora* (root rot) 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 (water) stress. Areas of stress had to be groundtruthed and samples were analyzed to determine the type of stress (insect, disease, or water).

On October 3, 2002 and September 11, 2003 a single-row picker was used to harvest a single 24.4 meter (eighty-foot) pass from each of the plots. Sample bags were labeled for each plot, and the individual plots were weighed to record the total amount of lint cotton produced.

Temperature, yield, and soil moisture data were statistically analyzed by ANOVA and means were separated by Fisher's LSD and analyzed at $\alpha = 0.05$ level. Regression analysis was run to determine the correlation between lint yield, canopy temperature, and soil moisture data. IR camera images were analyzed by the Thermogram™ software system that was provided by Indigo®. The IRT mapping program was used to analyze digital images of IRT scans.

RESULTS

Environmental conditions for the 2002 growing season are shown in Fig. 4. The minimum and maximum temperatures were relatively normal for the area with highs around 35^oC (95^oF) and lows around 21^oC (70^oF). Maximum temperatures were higher in June and August. The irrigation regimes were only imposed during the months of May and June. In May the following amounts of irrigation were added: 50.8 mm (2 inches) were added to the 100% ETc, 38.1 mm (1.5 inches) to the 75% ETc, and 25.4 mm (1 inch) to the 50% ETc irrigation regime.

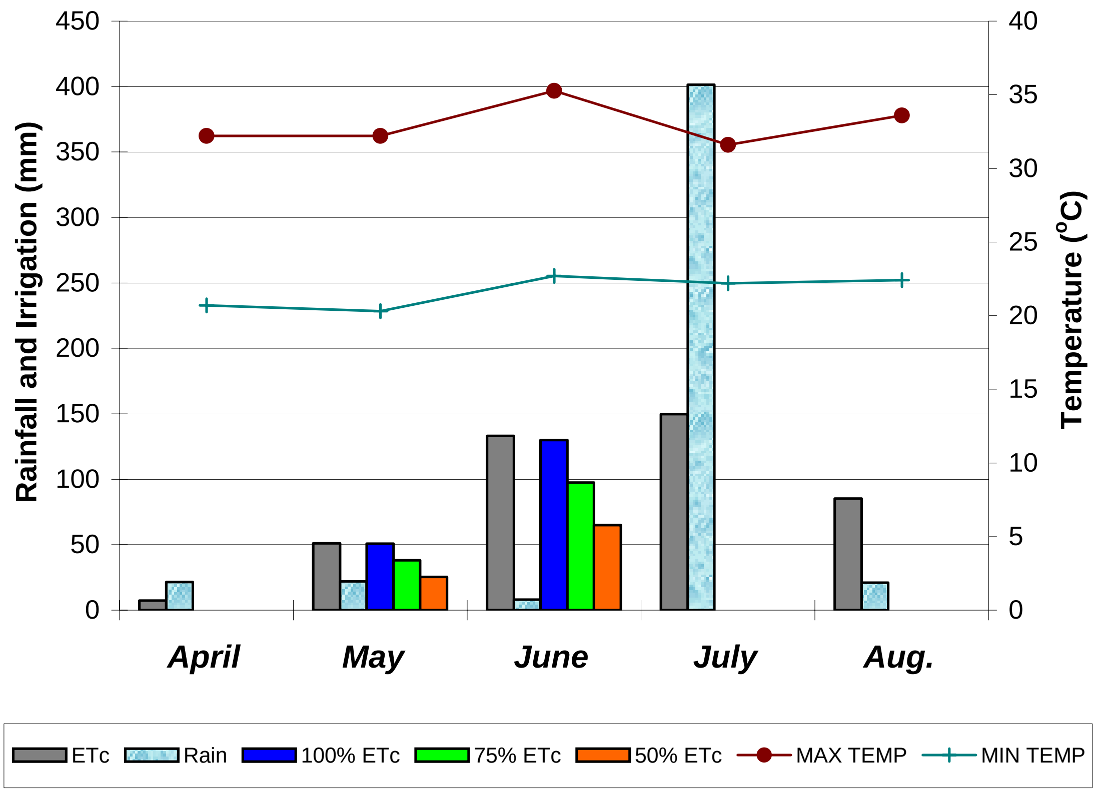

Fig. 4. 2002 Weather and irrigation. Environmental conditions and irrigation treatments for the 2002 growing season. Irrigation regimes were imposed during the months of May and June, but not in July due to excessive rainfall.

In the month of June increased daily temperatures caused increased irrigation. The following amounts of water were imposed on the treatments: 127 mm (5 inches) to the 100%, 95.25 mm (3.75 inches) to the 75% regime, and 63.5 mm (2.5 inches) the 50% irrigation regime. However, July and August received excessive rainfall of 381 mm (15 inches) and 25.4 mm (1 inch), respectively, which prevented the imposition of differential irrigation regimes throughout the rest of the growing season. Despite the excessive rainfall, the early imposition of irrigation regimes affected canopy temperatures and lint yield results.

Environmental conditions were relatively normal for the 2003 cotton season (Fig. 5). Temperature highs were around 33.3^{o}C (92^{o}F) and the lows around 18.3^{o}C (65^{o}F). Differential irrigation regimes were imposed in May, and rainfall amounts totaled around 25.4 mm. The 100% ETc regime received 50.8 mm (2 inches) of irrigation, the 75% ETc 38.1 mm (1.5 inches), and the 50% ETc 25.4 mm (1 inch). June received approximately 101.6 mm (4 inches) of rainfall. Subsequently, the following amounts of irrigation were imposed: 82 mm (3.25 inches) in the 100% ETc regime, 64 mm (2.5 inches) in the 75% ETc regime, and 41.9 mm (1.65 inches) in the 50% ETc regime. In the month of July rainfall totaled 190 mm (7 inches); however, all three irrigation regimes were imposed for the remainder of the growing season. The 100% ETc regime received 74.6 mm (3 inches), the 75% ETc regime 55.8 mm (2.25 inches), and the 50% ETc regime received 37.3 mm (1.5 inches) of irrigation. In August the 100% regime received 40.6 mm (1.60 inches), the 75% regime received 30.7 mm (1.21 inches), and the 50% regime 20.3 mm (0.80 inches) of irrigation. The weather and irrigation results for the 2003 growing season are depicted in Fig. 5.

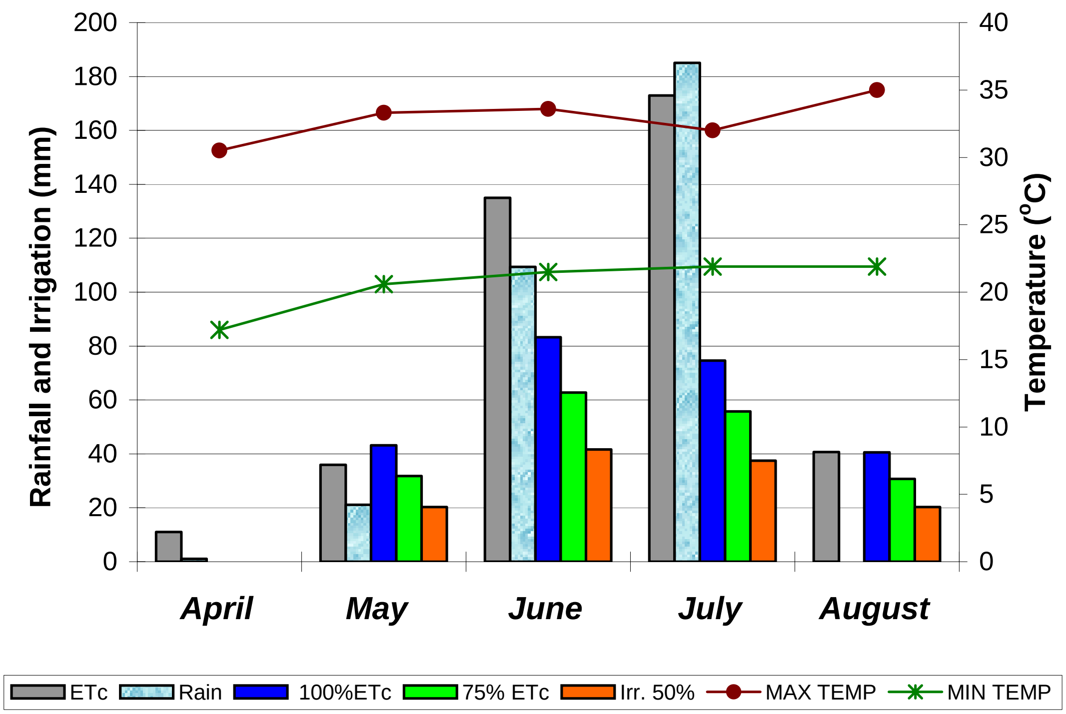

Fig. 5. 2003 Weather and irrigation. Environmental conditions and irrigation treatments for the 2003 growing season show relatively normal temperatures. Irrigation regimes were imposed in May through July despite rainfall amounts that occurred in July.

The 2002 season only allowed IRT scans to be conducted in June due to excessive rainfall and unfavorable weather conditions that occurred in the month of July. The IRT scans show changes in canopy temperature as the cotton canopy developed (Fig. 6). On June 11, no significant canopy temperature differences were detected between the 50% and 75% ETc regimes, while 100% ETc had significantly lower temperature than the other two regimes. The canopy temperatures for June 11 showed the 100%, 75% and 50% ETc irrigation regimes were 34.8, 38.1, and 40.3°C, respectively. The June 14 scan showed no significant differences in temperature between the 75% and 100% ETc regime with the canopy temperatures being 30.2 and 29.2°C, respectively. However, the 50% ETc with a mean canopy temperature of 33°C

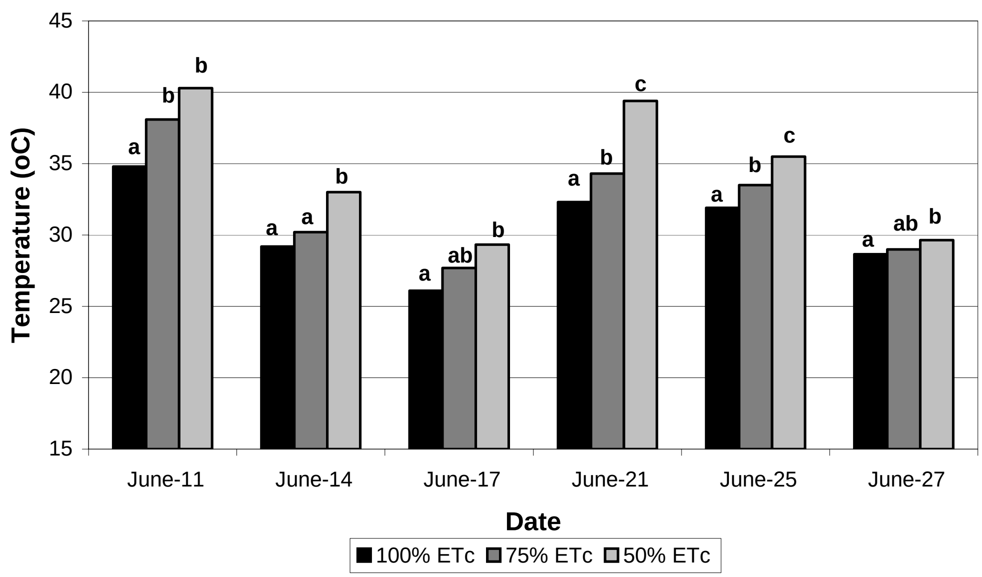

Figure 6. 2002 IRT canopy temperature readings. The 2002 IRT scans were only conducted during the month of June due to excessive rainfall amounts that occurred in July.

was significantly warmer than the other two irrigation regimes. Plants irrigated at this ETc regime had a hotter canopy due to differential irrigation affecting canopy coverage. The overall decreased canopy temperatures on June 14 and 17 were due to small rainfall amounts and irrigation that cooled the canopy.

No significant differences were detected between the 75% and 100% ETc regimes, and no significant differences were found between the 50% and 75% ETc regimes. The canopy temperature readings for the 100% ETc, 75% ETc, and 50% ETc were 26.1, 27.7 and 29.3^{o}C, which shows dramatic decreases from early in canopy development. These decreased temperatures were due to irrigation being imposed prior to the June 17 scan. On June 21, significant differences existed between all three irrigation regimes with the 100% ETc regime being 32.3^{o}C, 75% ETc being 34.3^{o}C, and the 50% ETc being 39.4^{o}C. Extremely high air temperatures caused canopy temperatures to be relatively high. Similar results are shown on June 25 when significant differences were noted between all three irrigation regimes. Before excessive rainfall amounts started to occur the scan on June 27 showed no significant differences between the 75% (29.0^{o}C) and 100% ETc (28.6^{o}C) irrigation regimes, respectively. Also, no significant differences were detected between the 50% and 75% ETc irrigation regimes with the canopy temperature being around 29.6^{o}C. The trend from the canopy temperatures obtained with the IRTs showed that the 50% ETc irrigation regime was always numerically higher than that of the 75% and 100% ETc regimes. Pivot-mounted IRTs were effective in detecting crop canopy temperature differences between the three irrigation regimes. The IRT mapping program was able to illustrate visual color images of the IRT scans. This increase in canopy temperature for the 50% ETc regime may have resulted from a decrease in plant water availability caused by the differential irrigation regimes. The canopy temperature readings showed a high correlation to the lint yield results (r^2=-0.98), with decreased temperatures having increased lint yields.

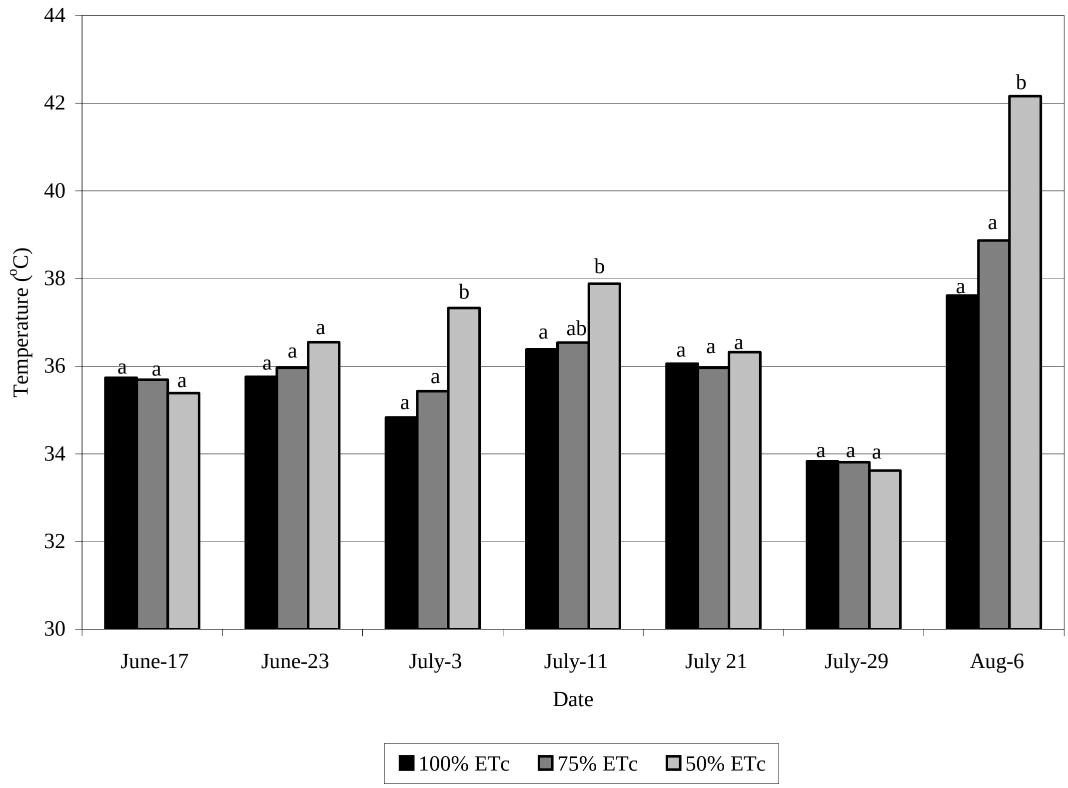

Fig. 7. 2003 IRT canopy temperature readings. Weekly IRT canopy temperature readings were taken for the three different ETc regimes in a cotton field.

IRT canopy temperatures for the 2003 growing season are depicted in Fig. 7. During the first two scans, June 17 and 23, no significant differences in IRT canopy temperatures were found among the irrigation regimes. The canopy temperatures for June 17 were 35.9°C for the 100% ETc, 35.9°C for the 75%, and 36.3°C for the 50% ETc regime, respectively. This lack of differences in canopy temperatures were likely due to rainfall in the early stages of canopy development or too much soil background. On July 3, the canopy temperatures for the 100% ETc, 75% ETc, and 50% ETc were 34.5, 34.8, and 37.2°C, respectively. During early July canopy temperature for the 50%

ETc regime started to show marked increases due to the differential irrigation. On July 11, the IRT scan showed significant differences between the 100% (36.0^{o}C) and 50% (37.2^{o}C) ETc regimes. The IRT scan on July 21 and 29 failed to show differences between the three irrigation regimes. This lack of temperature difference was due to rainfall amounts that occurred which caused the canopy temperatures to decrease. Similar results were obtained on July 29; however, at the end of the growing season on August 6 differences were detected between the 100% and 75% ETc regimes with the canopy temperatures being 37.3 and 38.3^{o}C, while the temperature of the 50% ETc regime was significantly higher (42.1^{o}C) than the other two regimes.

Biotic stress (*Phymatotrichopsis omnivora*) was present within the field and the disease caused increased canopy temperatures. The pivot mounted IRTs were not able to detect differences between biotic (root rot) and abiotic (water) stress in 2002 and 2003. As mentioned in the materials and methods, the inability to discern differences between the two types of stresses can be attributed to the large pixel size of the IRTs, which averages canopy temperature of twenty-five plants to determine the overall pixel temperature value. Root rot was present in all three irrigation regimes, but the IRTs were not able to successfully distinguish root rot stress early or late in the season from water stress. The IRTs detected increased canopy temperatures at the end of the season when root rot plants started to desiccate and die, but no pattern was detected with areas where root rot was present.

During the 2002 growing season, the IR camera was able to detect biotic and abiotic stress with the assistance of groundtruthing (Figs. 8 and 9). The IR

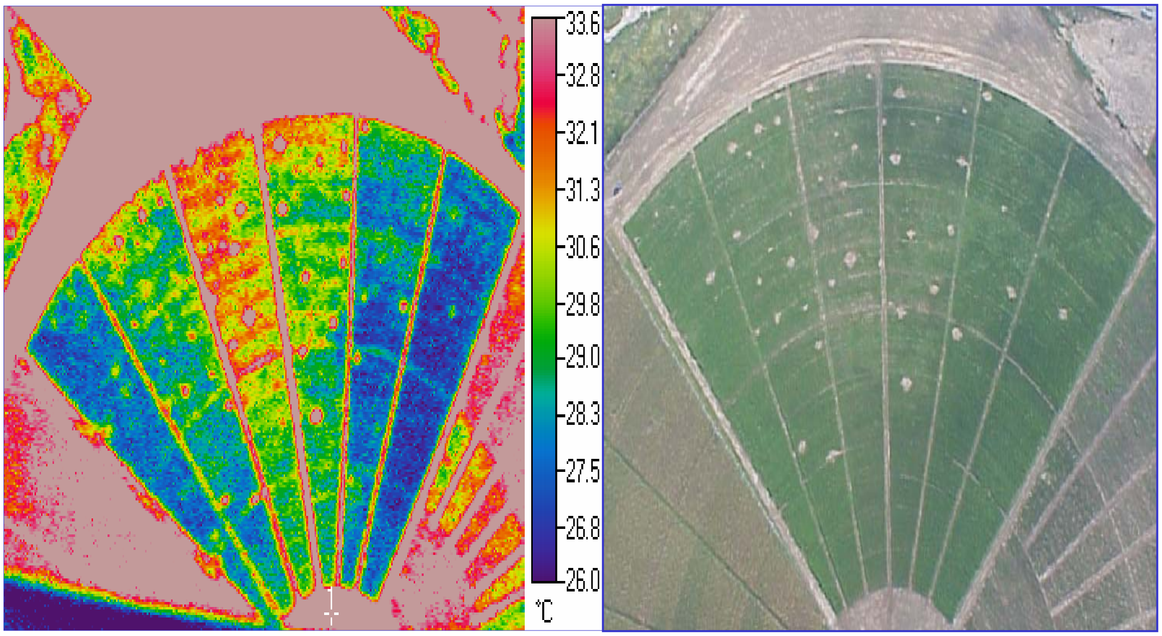

Fig. 8. 2002 IR camera and digital aerial photograph for July 29. IR images illustrate temperature differences between the irrigation regimes, and the detection of root rot stress before symptoms can be visually detected.

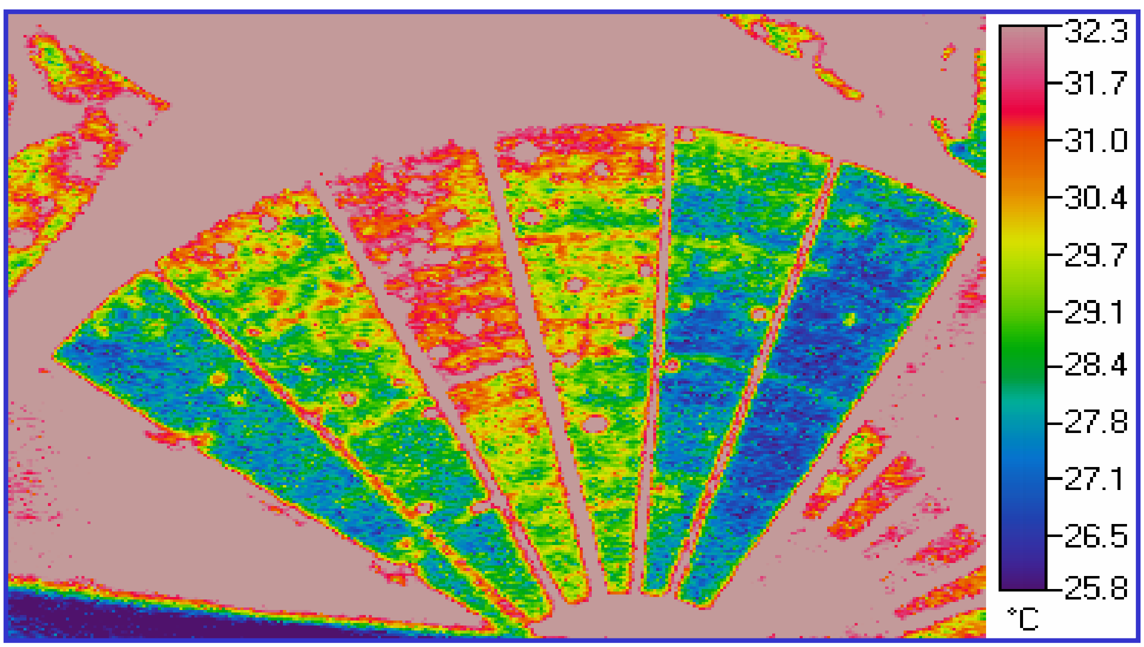

Fig. 9. 2002 IR camera canopy temperature images for August 16. Late season images show increased temperatures for root rot areas and the canopy temperatures for the irrigation regimes.

camera was able to distinguish canopy temperature differences between the irrigation regimes. Only two flights were conducted for IR detection during the 2002 growing season due to excessive rainfall early in development and camera availability. The first IR flight was conducted on July 29. There were no significant differences in canopy temperatures between the 100% (31.8°C) and 75% (32.1°C) ETc irrigation regime, but the canopy temperature for 50% (33.1°C) ETc regime was significantly higher (Fig. 10).

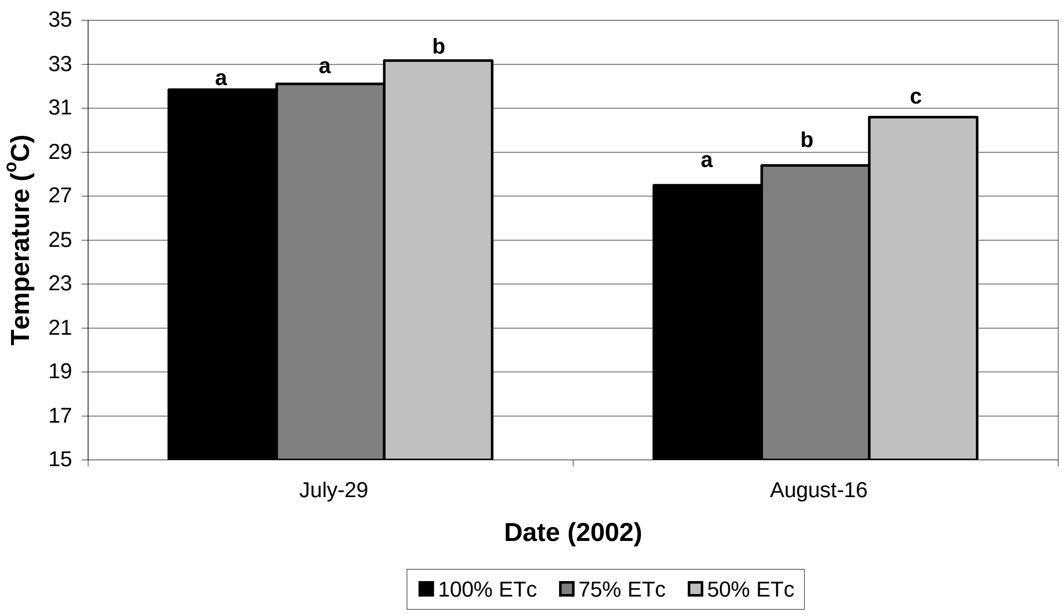

Fig. 10. 2002 IR camera canopy temperature readings. The IR camera detected canopy temperatures on only two flights due to scheduling and weather conditions.

Canopy temperatures on August 16 were 27.5°C for the 100% ETc, 28.4°C for the 75% ETc, and 30.6°C for the 50% ETc irrigation regimes, respectively (Fig. 10). Although, there were significant differences in canopy temperatures between all three of the irrigation regimes, the differences between 100% and 75% ETc was smaller compared to the 50% ETc regime.

In addition, the IR camera was able to detect temperature differences due to root rot before signs could be detected visually. By using the Thermogram™ software the canopy temperature on July 29 for root rot areas was 33.5^{o}C for the 75% and 100% regimes, while the average temperature for these regimes was 31.5^{o}C. On August 16, the root rot canopy temperature areas were 32 to 35^{o}C (Fig. 9). The average canopy temperature for the irrigation regimes at that time was around 30^{o}C. Additionally, no relationship was found between the percent of root rot development and the amount of water applied through the irrigation regimes. However, the IR camera was able to detect temperature changes throughout the field.

The IR camera was also able to detect canopy temperature differences between all three of the irrigation regimes for the 2003 season (Fig. 11). The IR camera canopy readings showed significant differences between all three irrigation regimes for the May 15 and June 3. For May 15, the canopy temperatures were 38.0, 39.0, and 40.4^{o}C for the 100% ETc, 75% ETc and 50% ETc irrigation regimes, respectively. These temperatures were higher than normal due to bare soil. However, on June 13 no differences in canopy temperature were detected between any of the three irrigation regimes with the canopy temperatures being 18.1, 18.6 and 18.9^{o}C (100% ETc, 75% ETc, and 50% ETc, respectively) for the three irrigation regimes as canopy closure occurred. The canopy temperatures were relatively low due to June rainfall amounts (Fig. 5) that decreased the canopy temperature of the cotton. The increased air temperature affected the readings obtained on the July 3 flight as indicated by increasing canopy temperatures, which showed significant differences between all three of the irrigation regimes. The 100% ETc regime had a canopy temperature of 28.1°C, the 75% ETc regime was 28.2°C, and the 50% ETc regime was 31.7°C. The next flight on July 22 failed to show differences in canopy temperatures between the 75% and 100% ETc irrigation regimes (Fig. 11). However, the canopy temperature of the 50% ETc irrigation regime was significantly higher than the other two regimes.

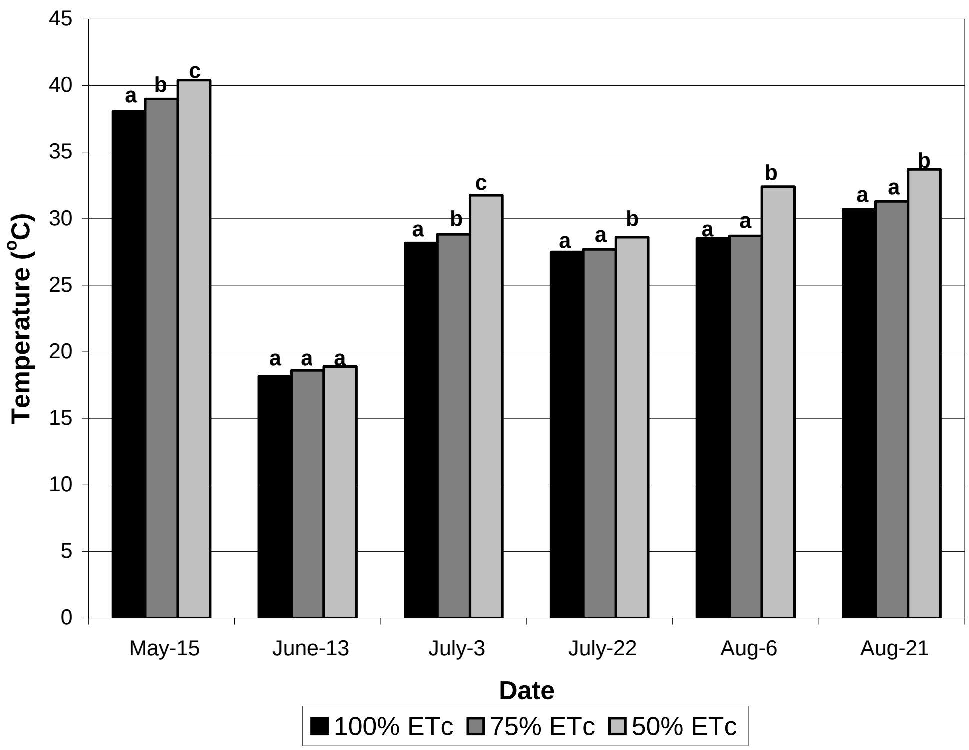

Fig. 11. 2003 IR camera canopy temperature readings. Cotton canopy temperature readings were taken throughout the season with IR camera.

The August 6 flight showed canopy temperatures of the 100% (28.5°C) and 75%

ETc (28.7^{o}C) regime with no significant differences, while the 50% ETc (32.4^{o}C) regime had a significantly warmer canopy temperature. This trend was visible in the August 21 flight as well as canopy temperatures were 30.7, 31.3, and 33.7^{o}C in the respective irrigation regimes. End of the season canopy temperatures were higher due to the plants starting to desiccate and die. IR camera canopy temperatures show that decreased canopy temperatures can be reflected in higher lint yields in cotton. This was illustrated with the 75% and 100% having decreased canopy and higher lint yields when compared to the 50% regime.

The IR camera was able to detect biotic (root rot) from abiotic (water) stress with the assistance of groundtruthing (Fig. 12). The root rot was detected on June 13, which was very early in development and before visual signs could be detected (Fig. 12). At that time field canopy temperatures were 18 to 19^{o}C, but distinct patches were found in the field that had temperatures that ranged from 28^{o}C to 32^{o}C. Early in canopy development there was a 10 to 12^{o}C temperature differential from the normal canopy temperature of the imposed irrigation regimes, which were also reduced due to rainfall amounts. However, later in the season the average temperature differences between the root rot areas and the canopy temperature of the irrigation regimes ranged from 3 to 4^{o}C as canopy temperatures increased in the areas where root rot developed. The IR camera was actually detecting root rot in these areas before it could be seen visually with the digital aerial photograph.

Midseason results (July 22) illustrate that the canopy temperatures for the root rot areas were starting to increase (Fig. 13). When IR images were compared to the digital aerial photograph pictures two small areas could be visually detected. 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 was from 27 to 29^{o}C, while the canopy temperature for the root rot stressed areas ranged from +5^{o}C to +6^{o}C, which indicated these plants would likely desiccate due to disease development. The white areas in Fig. 13 show the areas of root rot in the field. The wide temperature range can be attributed to plants different stages of disease severity.

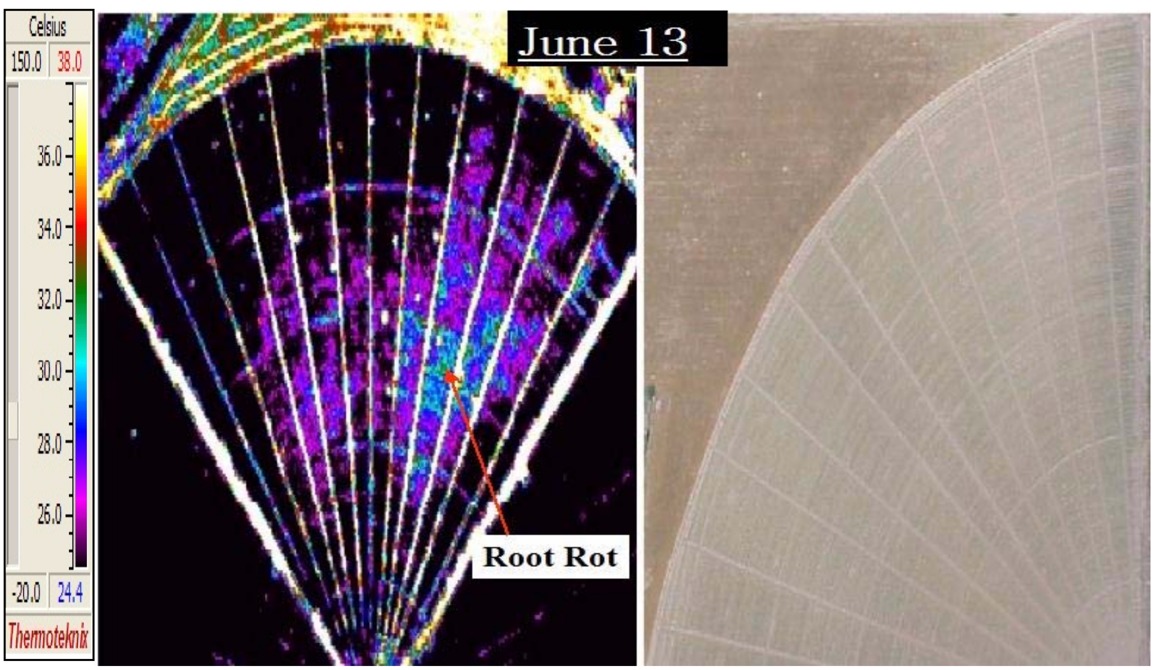

Fig. 12. Early season IR camera and digital aerial photograph. Early season results show there were increased canopy temperatures in the field due to the IR camera (left) detecting root rot before seen visually (right).

Fig. 13. Mid-season IR camera and digital aerial photograph. Mid-season results show that root rot areas continued to spread throughout the field and canopy temperatures continued to increase due to plant desiccation.

Late season results (August 21) reveal differences between root rot and water stress. The digital aerial photograph showed the progressive spread of root rot through the cotton field and its impact on cotton development (Fig. 14). The canopy temperature for the root rot areas ranged from 35 up to 40^{o}C, with the higher temperatures reflecting eventual plant death.

The 2003 soil moisture readings taken throughout the growing season are depicted in Fig. 15. On June 18 no differences were detected between any of the three irrigation regimes. Soil moisture percentages were 20.2 for the 100% ETc, 19.96 for the 75% ETc, and 20.03 for the 50% ETc regimes. The June 20 readings also failed to show differences between the 75% and 50% ETc regimes, but the 100% ETc regime had a

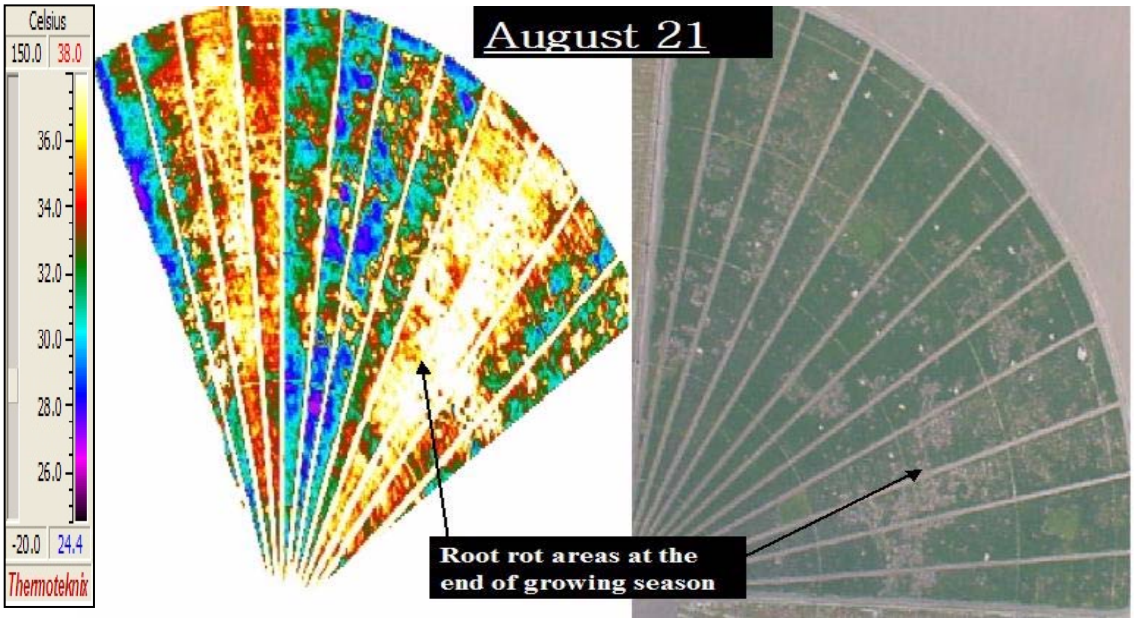

Fig. 14. Late season IR camera and digital aerial photograph. Late season results show the spread of root rot and illustrate that the IR camera was able to detect biotic and abiotic stress. Root rot development can be predicted when comparing the digital image (right) to the early season IR camera image (left).

significantly higher percentage of moisture in the soil (20.97). Samplings on June 25 and 27 showed the same trend as June 20 with significant differences only being detected in the 100% ETc regime, and no significant differences being detected in the 75% and 50% ETc regimes. Samplings on July 1 and 3 showed a decrease in soil moisture for the 50% ETc regime and differences were detected between all three irrigation regimes. On July 9, no differences in soil moisture were recorded in the 75% and 50% ETc regimes, and this trend continued on into July 30. No differences in soil moisture were detected between the previous irrigation regimes, due to rainfall that occurred during this time period. Significant differences were detected for all three irrigation regimes on August 14. The 100% ETc was 20.78, the 75% was 20.56, and the 50% was 20.21. Significant differences in percent soil moisture were achieved for the rest of the growing season in all three irrigation regimes. The 100% ETc regime had significantly higher percent soil moisture for the entire growing season (Fig. 15), and there were significant differences detected between the 50% and 75% ETc regimes except when rainfall events occurred.

Soil moisture differences during 2003 for the three irrigation regimes are illustrated on a bi-weekly basis in APPENDIX B. The deeper depths from 120 cm to 220 cm show that the percent soil moisture remained constant between the three irrigation regimes up to July 3. However, the shallower depths of 20 cm to 100 cm, illustrates that the percent soil moisture varied greatly between the irrigation regimes and between dates. Early in the season the differences were minimal between the three ETc regimes, but as the season progressed the differences became more evident, with the 100% ETc regime having the highest percent soil moisture. Generally, the 75% ETc regime had higher percent soil moisture content of the three ETc regimes, but some results (Fig. 15) show the 50% ETc regime has increased soil moisture at various depths (Figs B. 1 thru 16). This increase in soil moisture in the 50% regime was due to rainfall amounts that occurred in early July. The end season results show differences being evident between the irrigation regimes with the 100% ETc regime having the highest percent soil moisture followed by the 75% ETc regime, and the 50% ETc regime having the lowest percent soil moisture. There was a positive correlation between percent soil moisture and lint yield (r^2=0.98).

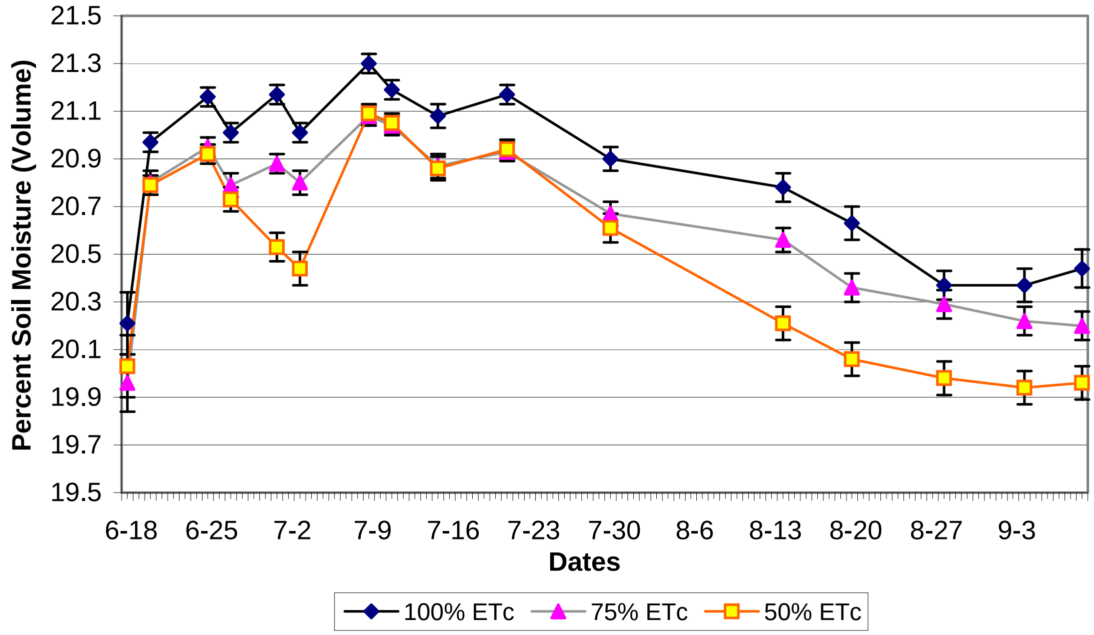

Fig. 15. Percent soil moisture for cotton growing season. The 2003 percent soil moisture was determined by using a hydroprobe moisture depth gauge throughout growing season. Significant differences were recorded between the three irrigation regimes, standard errors are represented by vertical bars.

For the 2002 growing season no significant differences in lint yield were found between the 75% and 100% ETc regimes, while the 50% regime yielded significantly less. This 30% yield reduction in the 50% regime when compared to the 100% regime was also associated with increased canopy temperatures from the IR camera and IRTs readings of this regime. Yields were 1832 kg/ha (1636 lb/acre), 2375 kg/ha (2121 lb/acre), and 2611 kg/ha (2332 lb/acre) for the 50%, 75%, and 100% ETc treatments, respectively (Fig. 16). Despite excessive rainfall, differential irrigation early in development affected cotton boll development, which is shown by yield differences between the irrigation regimes. There was a significant negative correlation between lint yield and average canopy temperature with the IRTs (r^2= -0.98) and IR camera (r^2=-0.99).

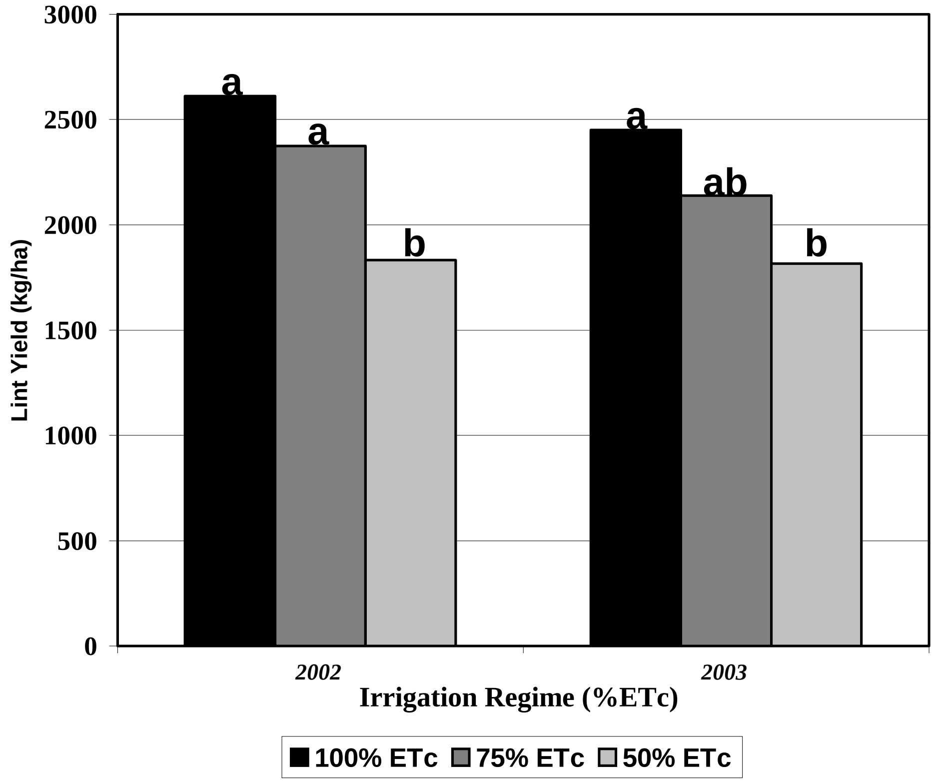

Fig. 16. Lint yield results. Lint yield comparison for the different irrigation regimes: There were no significant differences between the 75% and 100% ETc irrigation regimes for either years of the study.

For the 2003 growing season no significant differences in lint yield were found between the 75% and 100% ETc regimes (Fig. 16). Yield from the 50% and 75% ETc regimes also were not significantly different for this season. However, yield was significantly reduced at 50% ETc compared to the 100% ETc regimes. The 26% yield reduction in the 50% ETc was associated with increased canopy temperatures, deficit irrigation, and decreased soil moisture of this regime. Yields were 1816 kg/ha (1622 lb/acre), 2139 kg/ha (1910 lb/acre), and 2450 kg/ha (2188 lb/acre) for the 50%, 75%, and 100% ETc treatments, respectively. Yield results from both years indicate that deficit irrigation had no impact on yield and water savings are possible up to 75% ETc. Also, decreased canopy temperatures and increased lint yields were directly correlated. A negative correlation was detected between the IR camera temperature readings and lint yield for 2003 (r^2=-0.88). IRTs also detected a similar negative correlation between canopy temperature and lint yield (r^2=-0.88).

DISCUSSION

Environmental conditions for the 2002 growing season were relatively normal through the month of June. All irrigation regimes were imposed until excessive rainfall occurred in the month of July. However, since deficit irrigation was imposed early in the growing season, the lint yields were decreased significantly in the 50% ETc regime. The 2003 season showed optimal environmental temperatures (18 to 35^{o}C) for growing conditions. Despite heavy rainfall amounts that fell in July the irrigation regimes were imposed for the remainder of the growing season. Since, the soil profile only holds a certain amount of water depending on the soil type, after irrigation and rainfall events the field capacity of the soil was reached, crop water use was zeroed to begin recording water loss from the crop. The excessive rainfall amounts that occurred caused run-off and the crop never received excessive water due to the saturation of the soil. The deficit irrigation in the 50% ETc regime for this experiment had a direct impact of canopy temperature, lint yield, and soil moisture.

This experiment showed that IRTs were successful in detecting increased canopy temperatures differences among irrigation regimes. The results from both years of the study show that the infrared thermometry (IRT) is excellent 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, 1982). The results from this study support findings by Moran et al., (1997) that the IRTs are very effective in detecting water stress in plants.

The IRT mapping program that was developed illustrated color digital images of each IRT scan. On June 11, 2002 the IRT scans showed decreased canopy temperature differences in the 100% ETc regime as compared to the 75% and 50% ETc regime (Fig. 6). Over-irrigation occurred due to Penman-Monteith equation over estimating ET_o and K_c not developed for the geographic region of this study. The 100% regime always had significantly higher percent soil moisture than the other two moisture regimes. Increased canopy temperatures early in development can be associated with the IRTs detecting bare soil and decreased soil moisture availability. Measurements of soil surface temperatures were conducted with IRTs to detect radiation of heat from different soil types, which illustrated that different soils radiated higher amounts of heat (Ham and Senock, 1992). Results shown by Ham and Senock (1992) illustrated that IRTs were not able to correct for the emissivity of the different soil types. These results can explain how the high soil temperatures affected canopy temperature readings in this experiment early in the season. McGuire et al. (1989), after reviewing studies concerning infrared temperature measurements, stated that sensor angle, canopy structure, and percentage ground cover can affect the thermal output of a thermal sensor. Nielsen and Anderson (1989) avoided the influence of viewed-soil temperature by calculating the crop water stress index for single leaf temperatures. Their technique allowed for rapidly assessing plant water status with incomplete canopies. In our experiment increased canopy temperatures occurred when bare soil was detected early in canopy development. Also, no significant differences were detected between the 100% and 75% ETc 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 as were present in the 100% ETc regime. However, the scans on July 21 and 25 (2002) showed significant differences between canopy temperatures for all three irrigation regimes, and canopy temperatures were extremely high compared to previous readings. The extreme canopy temperature increases can be associated with the elevated air temperature, which was 38^{o}C (100^{o}F) for a four-day period. The combination of extreme air temperatures and timing of irrigation caused increased canopy temperatures for these days. Results for the 2002 season illustrate that canopy temperatures for 50% ETc regime were always numerically or significantly higher than the 75% and 100% ETc regimes for every scan conducted. The IRTs temperature trend indicates that the 50% ETc regime canopy temperatures were affected by the differential imposed irrigation. Plants within this 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 canopy temperatures to increase and cellular damage to occur. The excessive rainfall that occurred in July inhibited imposition of irrigation treatments and IRT scans were not conducted for the remainder of the year due to the crop remaining unstressed. However, deficit-irrigation imposed early in the growing season in the 50% regime had a significant yield reduction.

For the 2003 season weekly IRT canopy temperature readings showed similar trends when compared to the 2002 season. However, readings were taken throughout the season despite rainfall amounts that occurred in July (Fig. 5). The lack of significant differences among the differential treatments on June 17 and 23 was probably due to early season rainfall amounts that cooled canopy temperatures. Past research has shown that canopy temperatures decrease during irrigation (Wanjura and Mahan, 1994) and rainfall events. Burke and Upchurch (1989) stated that cotton canopy temperatures tracked air temperature up to 27.5^{o}C until decreased transpiration (water stress) caused canopy temperatures to increase. This was illustrated in this experiment when air temperatures increased above 32^{o}C in the month of July 2003. These increased air temperatures affected the irrigation regimes and consequently crop canopy temperatures were directly affected. Higher soil moisture levels at 75% and 100% regimes were associated with decreased canopy temperatures, while the 50% regime had decreased soil moisture, which caused increased canopy temperatures.

IRT can be a useful tool in determining canopy temperatures for individual plants or small random areas due to the 1:1 height to view angle ratio. A grower or consultant can use this technology to determine temperatures in random areas of the field and to schedule irrigation events. This recommendation was previously illustrated by Wanjura et al. (1992) who determined irrigation scheduling according to canopy temperatures not falling within the optimal (23 to 31^{o}C) temperature range for cotton. Michels et al. (1999) were able to use IRTs to detect but not distinguish between greenbug infestations and water stress in winter wheat. Similarly, results from this experiment show that the IRTs were not able to distinguish between irrigation stress and root rot stress. Twenty-five plants were averaged to determine the mean temperature value of the pixel and since there are 4.5-meter (15-feet) gaps between IRTs, the resolution decreases and the entire field canopy temperature cannot be recorded. All of these factors combined affected the readings of the IRTs. We expect that improvements in the IRTs pixel size configuration could enhance IRT's ability to distinguish between biotic and abiotic stress.

This experiment showed that the IR camera detected abiotic stress in cotton. This finding is in agreement with Mass et al. (1999), who demonstrated that aerial remote sensing imagery could detect stressed vegetation when irrigation was reduced in specified plots, while Nilsson (1995) showed that biotic stress could be detected through remote sensing techniques in barley(*Aegilops L*.).

In 2003 the IR camera was used on six different flights at three-week intervals throughout the growing season. Wanjura and Mahan (1994) documented that water status increased the canopy temperature as water status was decreased between different irrigation regimes. However, results from this experiment show that no differences in canopy temperature were detected between 75% and 100% ETc regimes, and usually had a temperature range of 25 to 31^{o}C. Wanjura and Mahan (1994) established that this was the optimal temperature range for cotton. Temperatures in areas where root rot was detected were 3 to 4^{o}C hotter than the 75% and 100% regimes early in the season, but as the season progressed the canopy temperatures for the root rot areas became 10^{o}C hotter than the irrigation regimes (APPENDIX A Figure 4, 8). The increase in canopy temperatures can be attributed to plants affected by root rot starting to desiccate and die. The canopy temperature differences detected at the end of the season were minimal between the root rot and irrigation stressed areas due to plants desiccating and dying. The majority of the flights failed to show significant differences between the 75% and

100% irrigation regimes for canopy temperature (Fig. 11). The lack of differences in temperature can be attributed to the 100% ETc model being over-irrigated due to inaccuracy of estimation by the Penman-Monteith formula. The results from the 75% irrigation regime support this statement by maintaining decreased canopy temperatures and comparable lint yields with less water. The tendency of all days at which the IR camera readings were determined was for the canopy temperature to increase as the availability of moisture decreased. Often no differences were noted between the 75% and 100% ETc regimes, but usually the canopy temperature of the 50% ETc regime was increased relative to the other regimes. The IR camera is a very effective type of remote sensing that covers large acreage in short time periods and has the ability to detect significant canopy temperature differences between irrigation regimes.

Nilsson (1995) showed that disease detection in barley was possible through image analysis and remote sensing tools. Aerial digital imagery was also able to detect oak wilt by the different color schemes that were detected when oak wilt was present (Everitt et al. 1999). Color infrared images have also been successful in detecting *Phytophthora* (root rot) in cranberry (*Vaccinium spp*.) fields, which help determine disease estimates (Pozdnyakova et al. 2002). The 2002 and 2003 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 visual signs were expressed, although the areas had to be groundtruthed to determine the type of stress. Since this was the first time in five years (2002) the field had been planted in cotton, small areas of root rot were present in the field during the 2002 season. Root rot spread was less than in 2003, which can be attributed to a buildup and subsequent spread of mycelia and sclerotia in the soil that became more pronounced in 2003. The canopy temperature increased following root rot invasion of the plant causing desiccation. This is due to sclerotia, which germinate to produce strand growth and move along contiguous root systems through the soil causing infection (Rush et al., 1984).

The mid-season IR camera images showed increased canopy temperatures and the infected areas beginning to spread. However, no visual canopy differences were detected. It was late in the season before visual differences could be noticed with the digital aerial images. Throughout the season the IR camera was always able to detect temperature differences between biotic and abiotic stress with the assistance of groundtruthing. Despite increased canopy temperatures at the end of the growing season caused by desiccation and decreased irrigation, the IR camera was still able to distinguish between biotic and abiotic stress. Early season detection of plant stress had been previously illustrated by imagery techniques, which were demonstrated to be effective indicators of plant stress (Chaerle and Straeten, 2000). Results from the present experiment support their research as the IR camera detected biotic and abiotic stresses before there were seen visually early in the growing season. A comparison of the early season IR images to those of late season digital aerial images show that the IR camera was able to detect root rot areas. If a grower or consultant could use IR data to detect areas that had canopy temperatures above the optimal temperature range (23 to 31^{o}C), these areas could be groundtruthed to determine if root rot was present. Root rot has no economically feasible cure, so irrigation could be cut or minimized in these areas to save water. Since water is such a valuable commodity, and restrictions have been placed on the amount of water that growers can pump in a year in the Edwards aquifer region, this would be a valuable tool for growers to conserve water and to determine infected areas in fields for future planning.

Decreased lint yields in the 50% regime can likely be attributed to limited photosynthetic assimilate ability for plant growth and boll development (Krieg, 1997) imposed by drought stress. Krieg and Sung (1986) determined that drought decreases the number of leaves on the sympodial branches of cotton. This factor causes increased canopy temperatures, decreased canopy size, and reduced photosynthetic rates (Daniel et al. 1999). In our experiment, the 50% regime had increased canopy temperatures, decreased lint yields, and reduced canopy compared to the other two irrigation regimes.

Percent soil moisture was only taken during the 2003 growing season. The neutron probe has been used to schedule irrigations in cotton according to soil moisture readings for surface and drip irrigation (Janat and Somi, 2001). In this experiment, greater depths (120 to 220 cm) showed minimal differences between the three irrigation regimes, which agrees with previous research conducted by Abassi et al. (2003). The lack of differences between irrigation regimes can be attributed to the soil profile holding water at deeper depths. The shallower (20 to 100 cm) depths showed a wide fluctuation in percent soil moisture as determined by the neutron probe. At the more shallow depths the soil dried out faster and plants could utilize the water that has a closer proximity to the root system. Burnett and Fisher (1954) reported that soil moisture is needed in the top 30 cm of soil for crop establishment, but cotton yields are more directly correlated with moisture stored between 30 and 90 cm below the soil surface. This observation helps explain the fluctuations in percent soil moisture content at shallower depths in this experiment. The imposition of irrigation regimes and rainfall amounts that occurred throughout the growing season had a direct effect on the percent soil moisture present at shallower depths (Figs B. 1 thru 16). The timing of soil moisture is critical at planting time and during flowering for increasing lint yields and maintaining a cool canopy temperature (Mauney and Stewart, 1986). Similar results are shown in this experiment with decreased lint yields and higher canopy temperatures in the 50% ETc regime where soil moisture was lacking compared to the other two irrigation regimes. The Penman-Monteith requires crop coefficients to determine ETc. The crop coefficients (K_c) used in this experiment are based upon data from Bushland, Texas, and the results obtained from this experiment indicate over estimated irrigation in this area. The 50% and 75% regimes showed no differences in soil moisture content when rainfall events occurred, but the 100% regime always had significantly higher soil moisture content. Also, the 75% regime had less percent soil moisture content than the 100% regime, but canopy temperatures and yields were not decreased in this regime. The results indicate that the Penman-Monteith formula overestimated ETc requirements, and the water that was applied to the 100% regime was not all used by the crop.

Since water is such a valuable commodity in the Edwards aquifer region, the water saved in the 75% regime compared to 100% ETc can save growers water for other crops or to sell. The 2002 and 2003 lint yield results showed no significant differences between the 100% and 75% ETc regimes. This indicates that water savings are possible in the 75% ETc without yield depletion. The decreased lint yields and increased canopy temperature results from the 50% ETc regime in this experiment support this observation. Deficit irrigation imposed early in the development of the crop, and maintained throughout much of the fruiting period may result in early cutout that occurs when plants water deficit falls below the level needed to support positive cellular turgor necessary for growth (Mauney and Stewart, 1986).

CONCLUSIONS

The Penman-Monteith formula and K_c overestimated irrigation in the 100% ETc regime. This statement is supported by the presence of increased percent soil moisture in the 100% regime, while the canopy temperatures and lint yields showed no significant differences between the 75% and 100% regime. Modifications to K_c and the Penman-Monteith 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 can prevent growers from over irrigating. Water savings were possible without yield depletion in the 75% regime. Thus growers can reduce irrigation costs or apply water to other crops later in the season. Both types of remote sensing tools were able to detect water stress within the irrigation regimes, which provides growers or consultants tools to more effectively manage water stress within fields. However, the cost of these two tools varies greatly and expenses have to be justified. The IR camera can also detect biotic stress before it can be seen visually. Irrigation can be subsequently cut in diseased areas to save growers money. The IRTs can detect water stress as shown in this study, but lack the capability of detecting biotic stress due to their poor resolution. Improvements to the IRTs could enhance their ability to detect stress and provide growers and scientists with a low cost instrument that can be used as a very effective remote sensing tool. Using remote sensing tools in conjunction with other crop data can enhance the knowledge of spatial variability in fields and yields. Although site-specific management practices are becoming effective management tools, the high costs limit grower use. However if cost can be minimized, these practices will become part of everyday farming practices.

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APPENDIX A

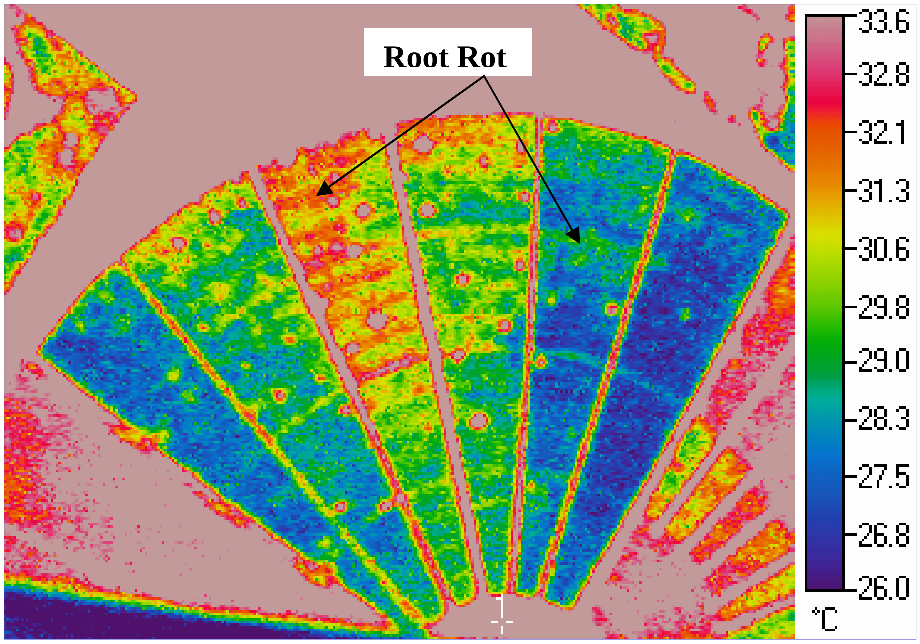

Fig A. 1. IR camera image for July 29, 2002.

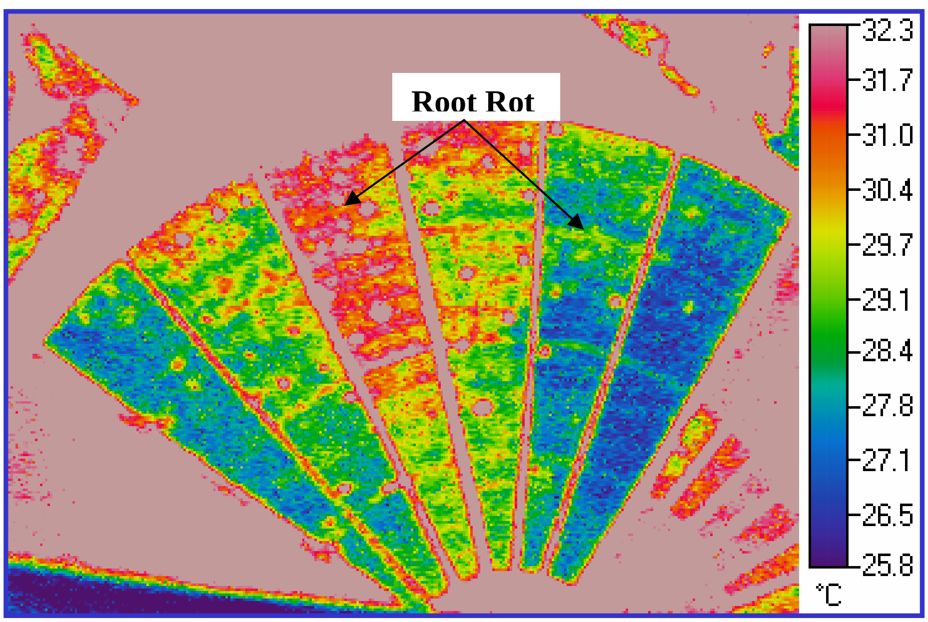

Fig A. 2. IR camera image for August 16, 2002.

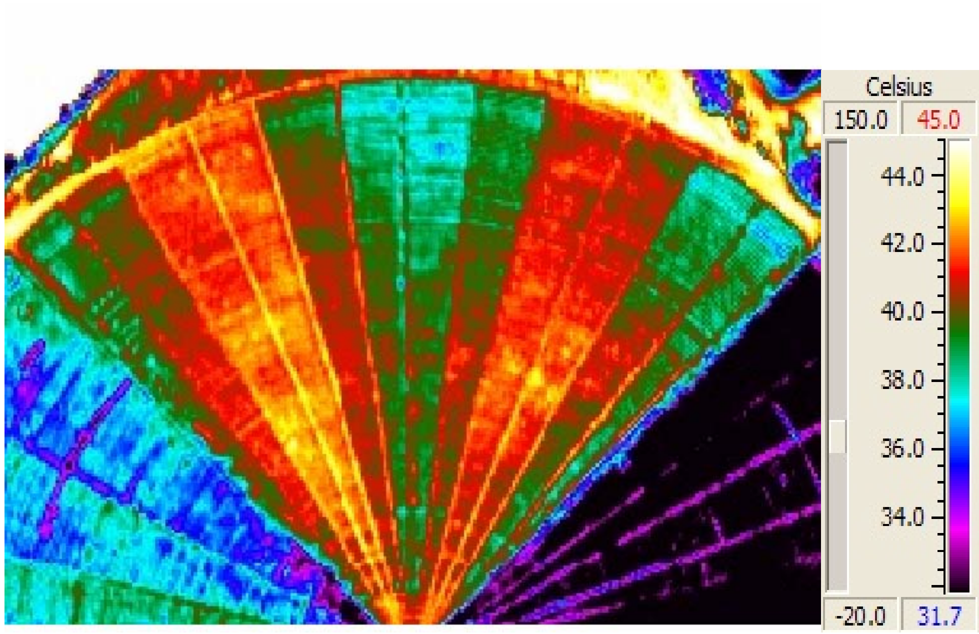

Fig A. 3. IR camera image for May 15, 2003.

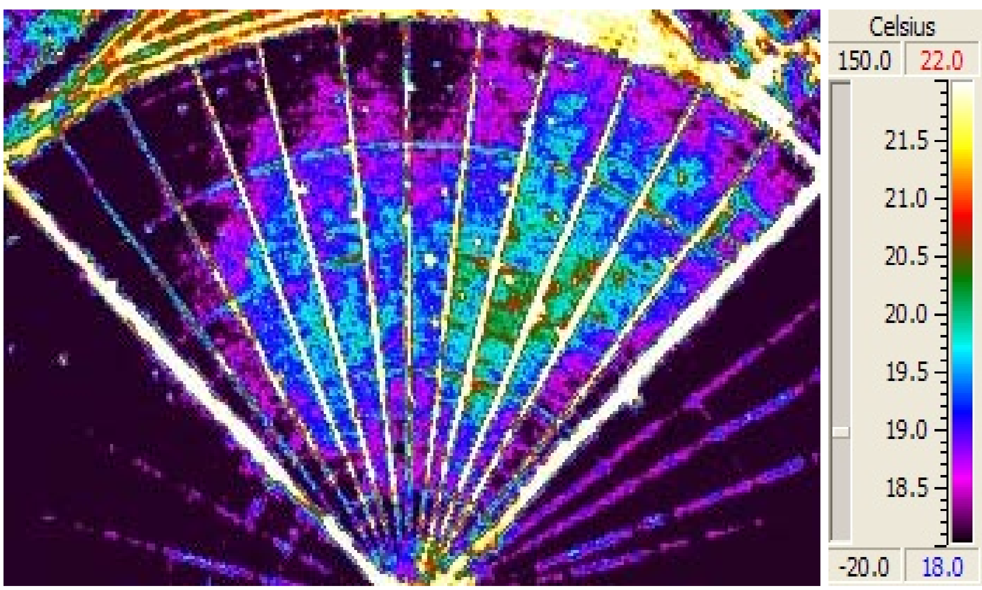

Fig A. 4. IR camera image for June 13, 2003.

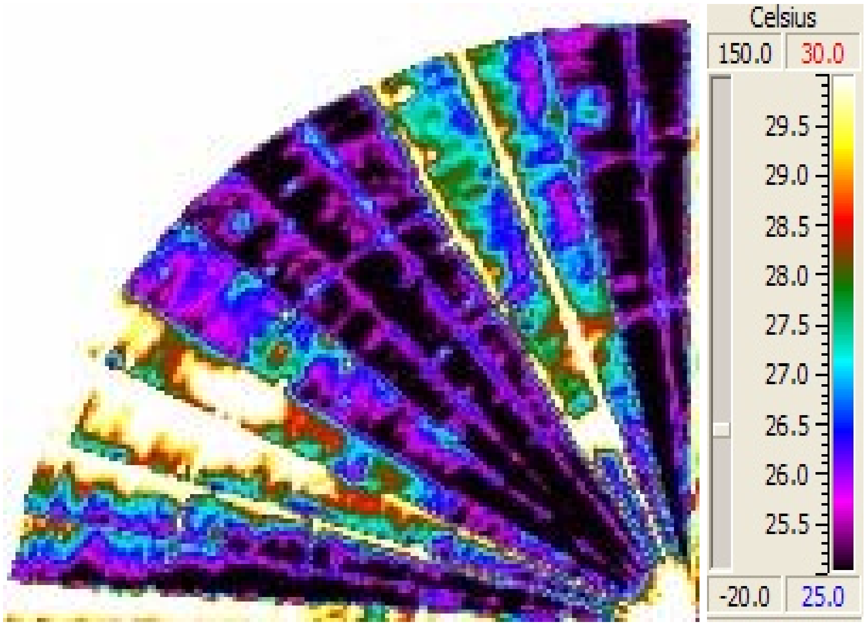

Fig A. 5. IR camera image for June 13, 2003.

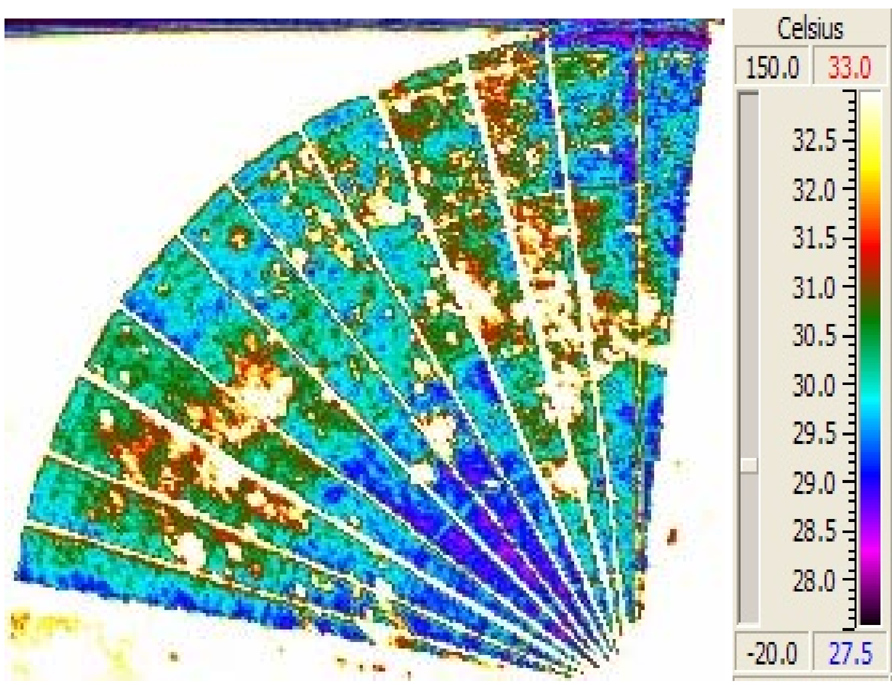

Fig A. 6. IR camera image for July 22, 2003.

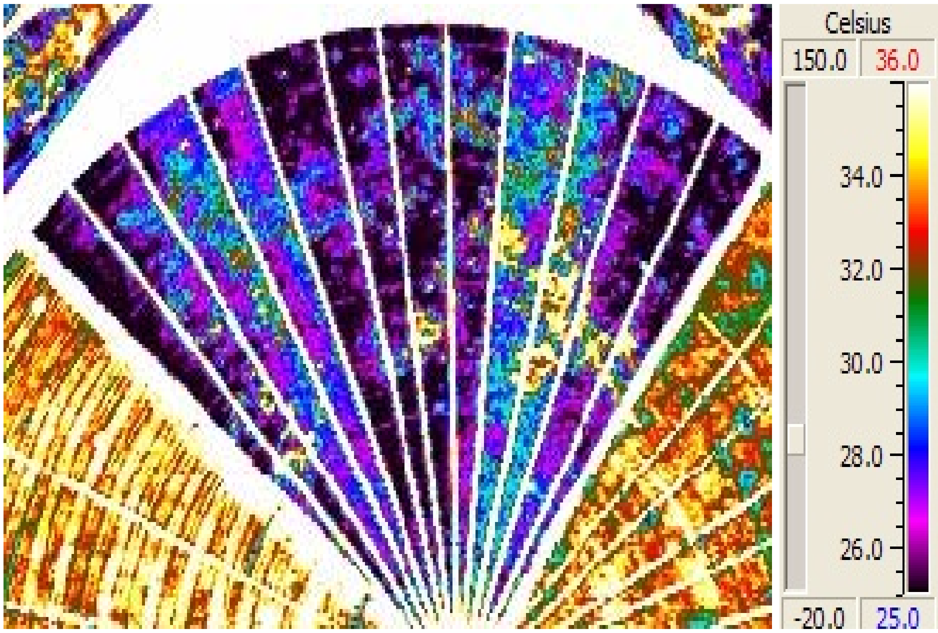

Fig A. 7. IR camera image for August 6, 2003.

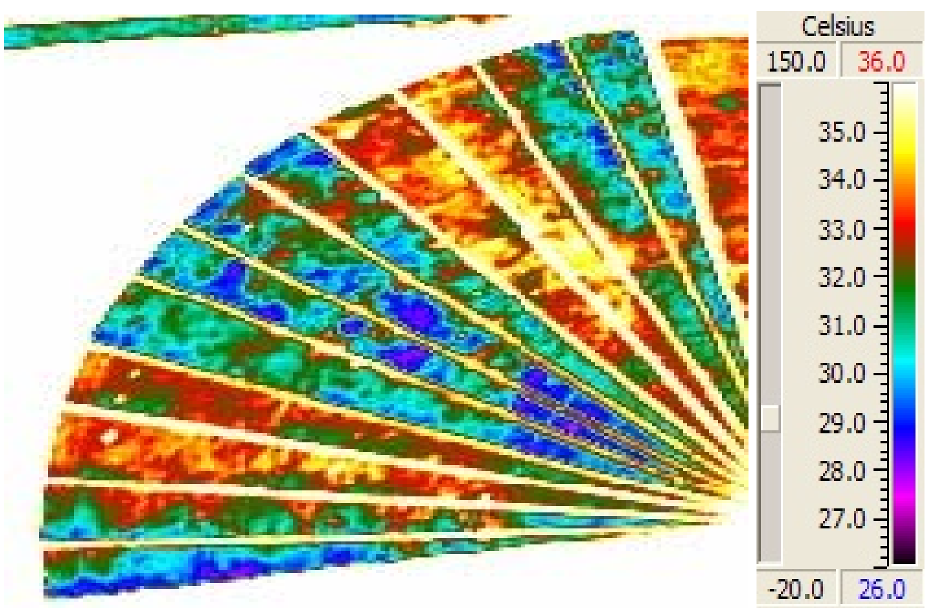

Fig A. 8. IR camera image for August 21, 2003.

APPENDIX B

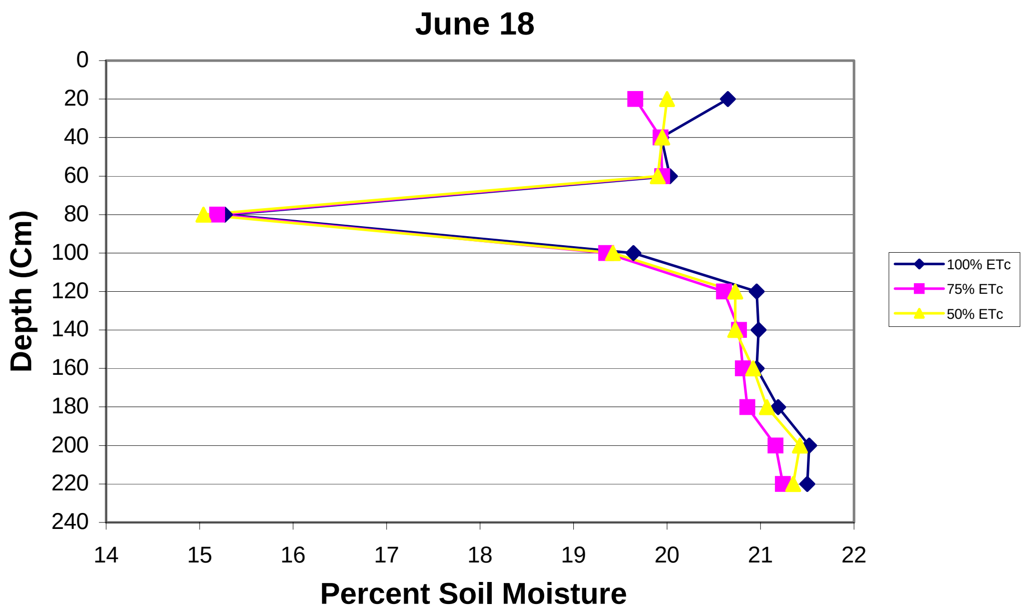

Fig B. 1. Soil moisture data for June 18.

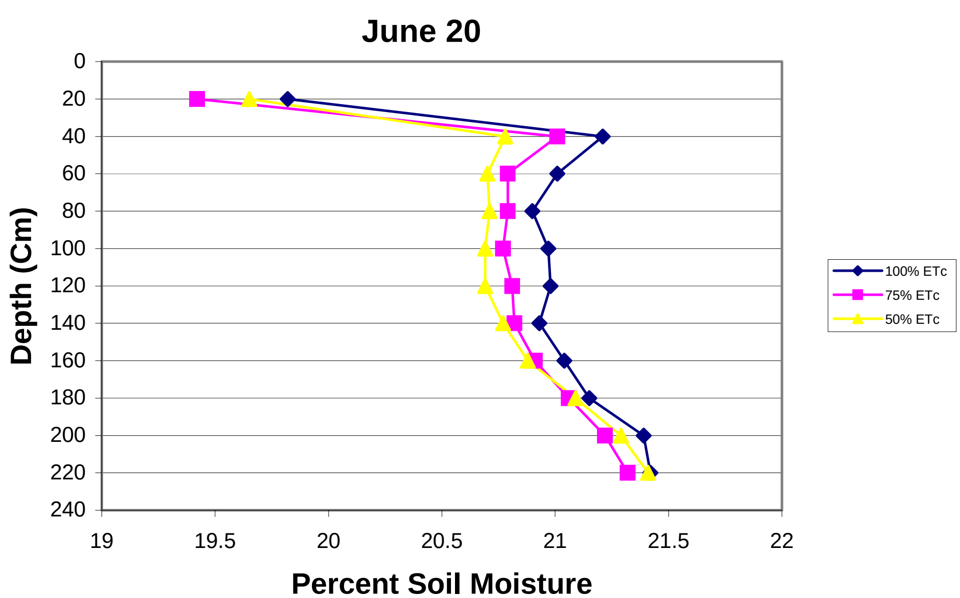

Fig B. 2. Soil moisture data for June 20.

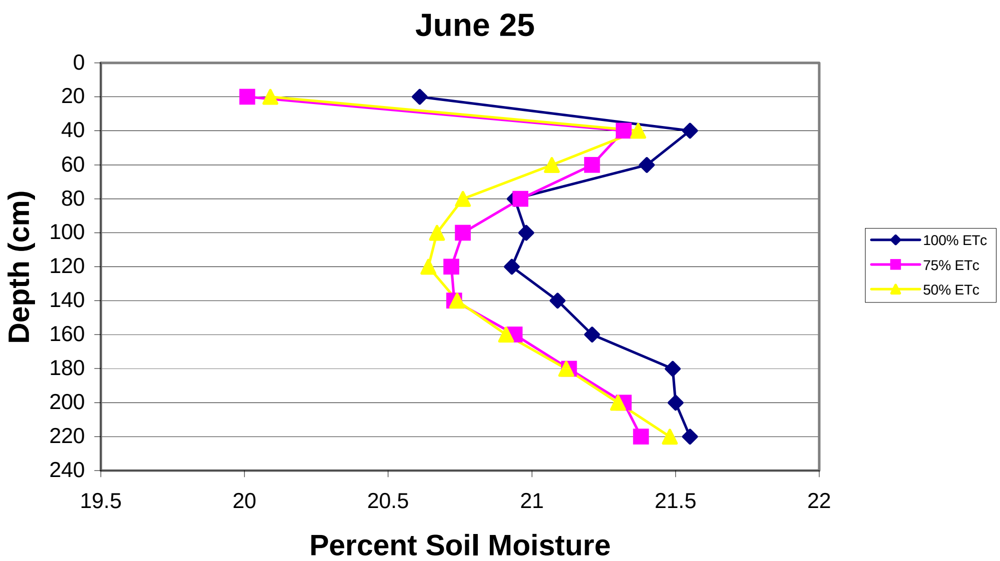

Fig B. 3. Soil moisture data for Jun.

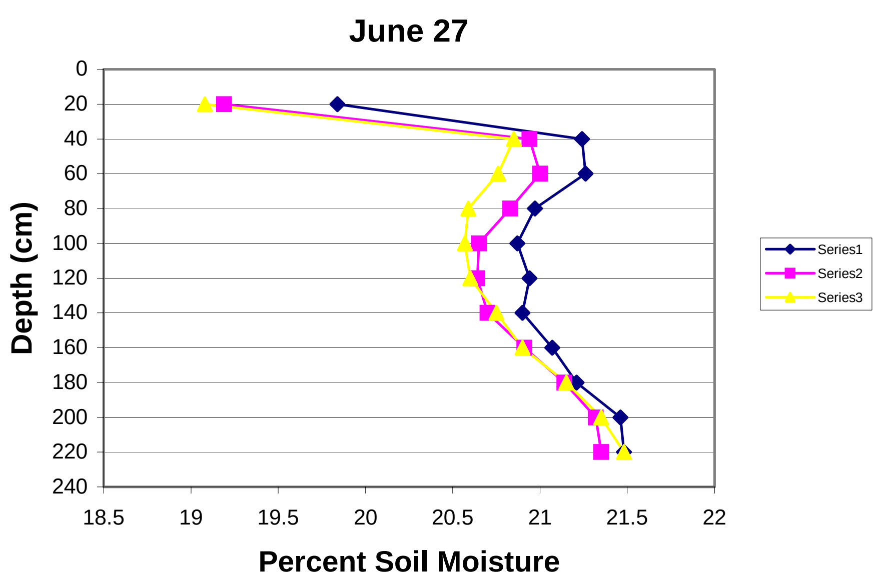

Fig B. 4. Soil moisture data for June 27.

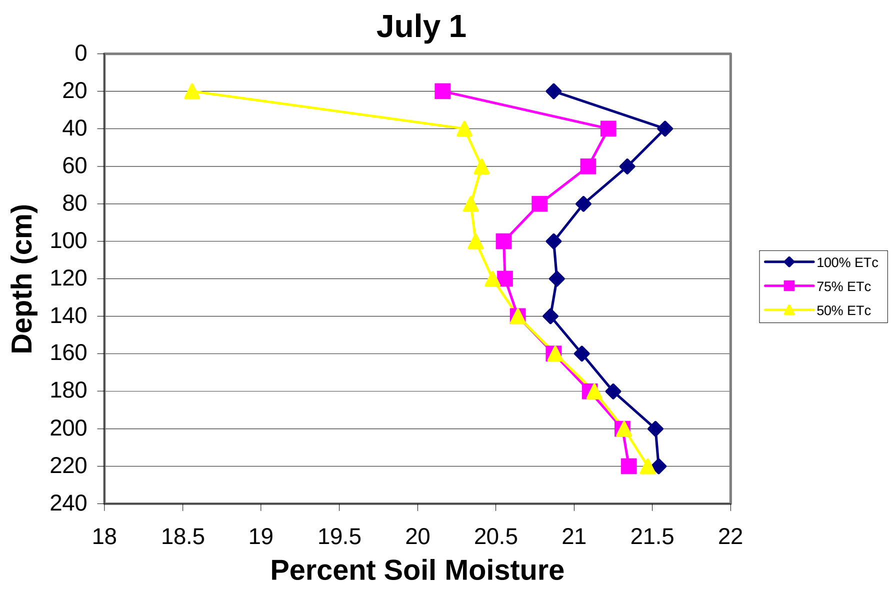

Fig B. 5. Soil moisture data for July 1.

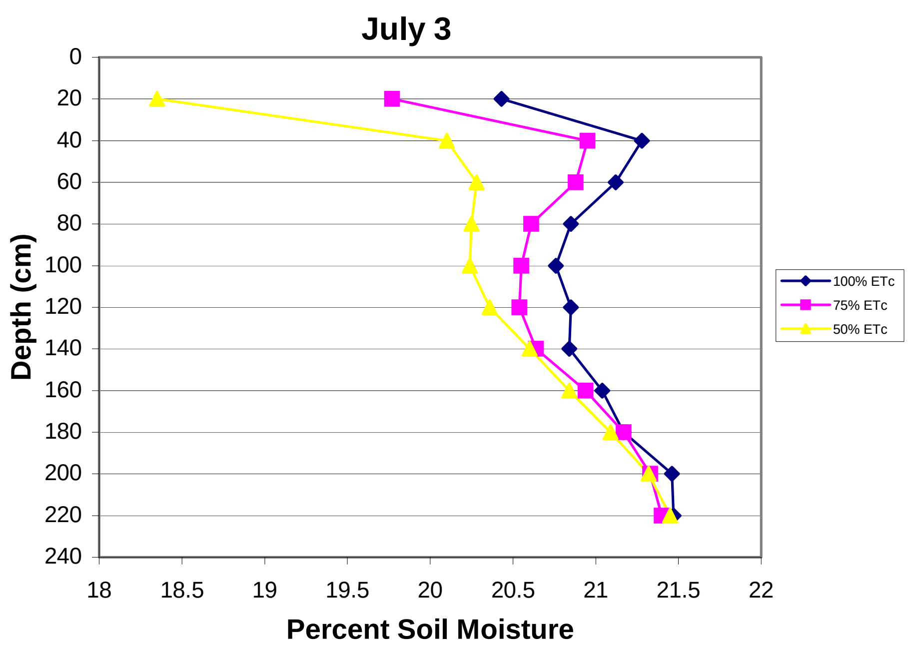

Fig B. 6. Soil moisture data for July 3.

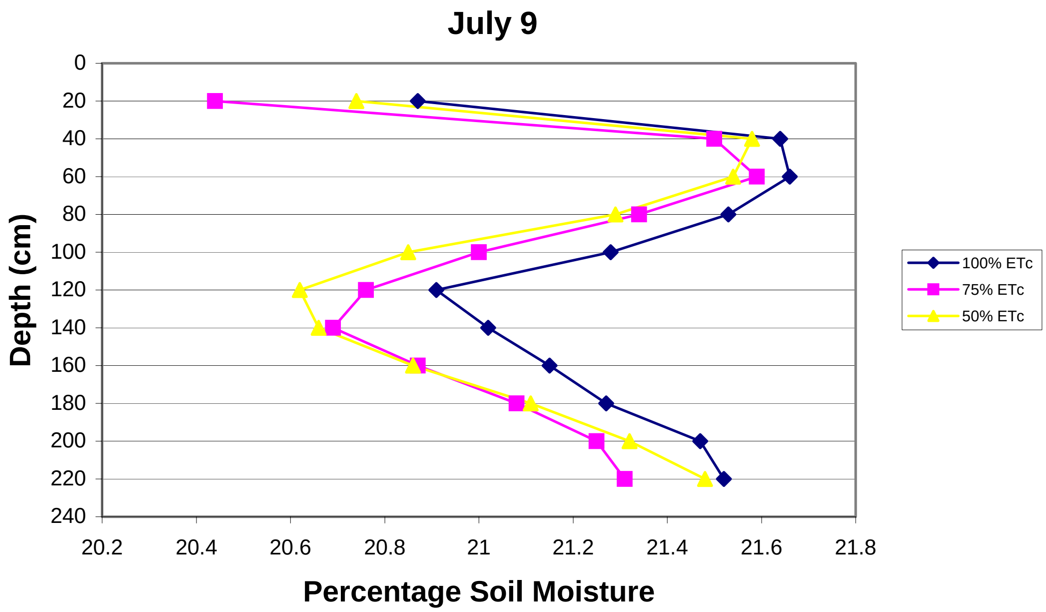

Fig B. 7. Soil moisture data for July 9.

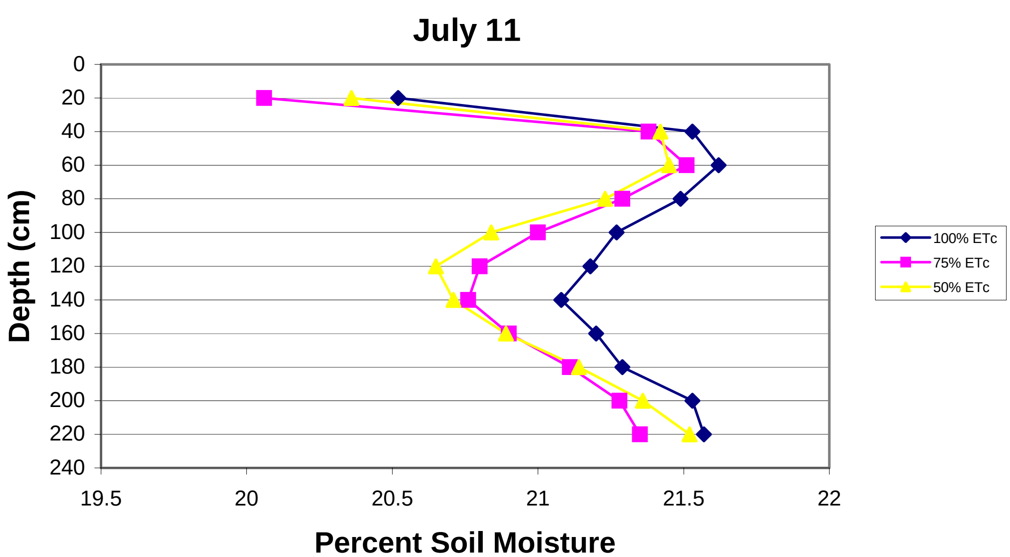

Fig B. 8. Soil moisture data for July 11.

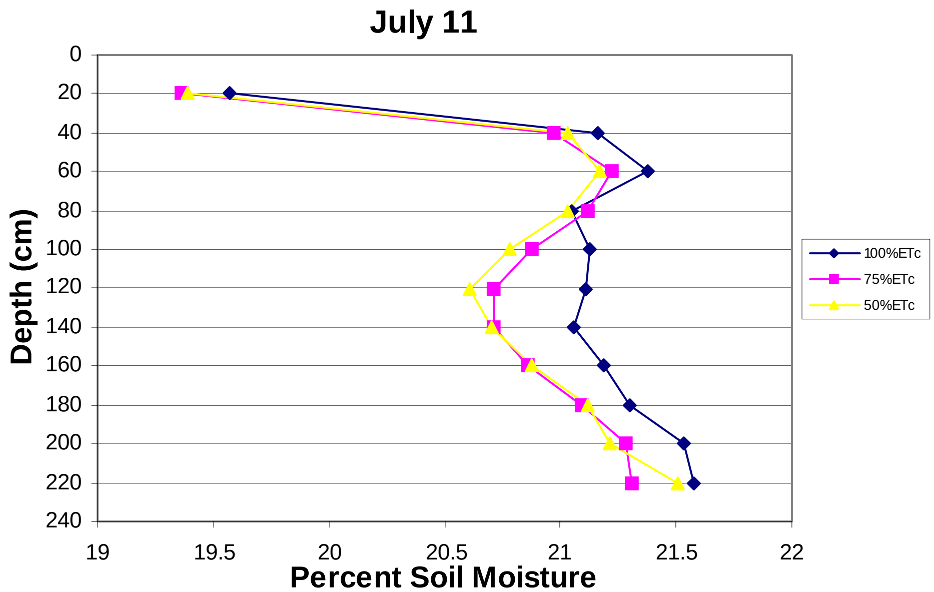

Fig B. 9. Soil moisture data for July 11.

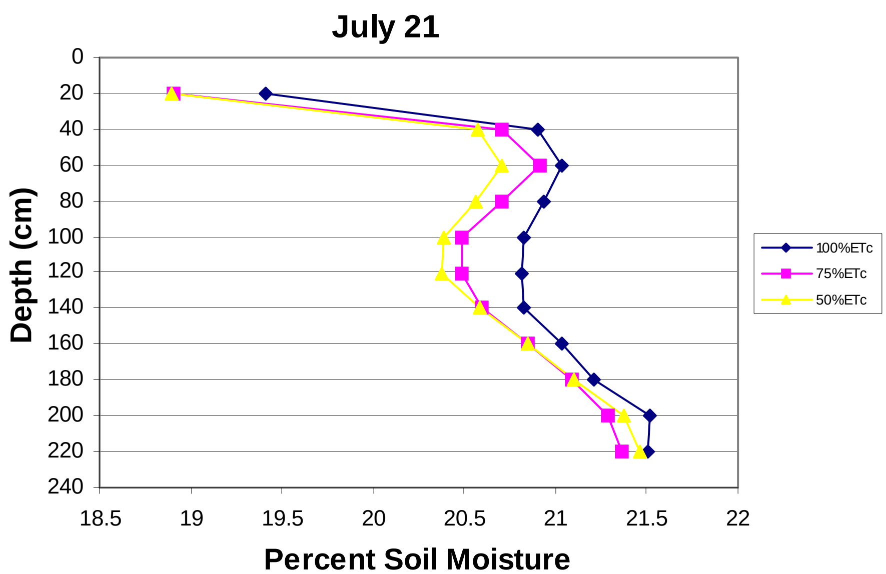

Fig B. 10. Soil moisture data for July 21.

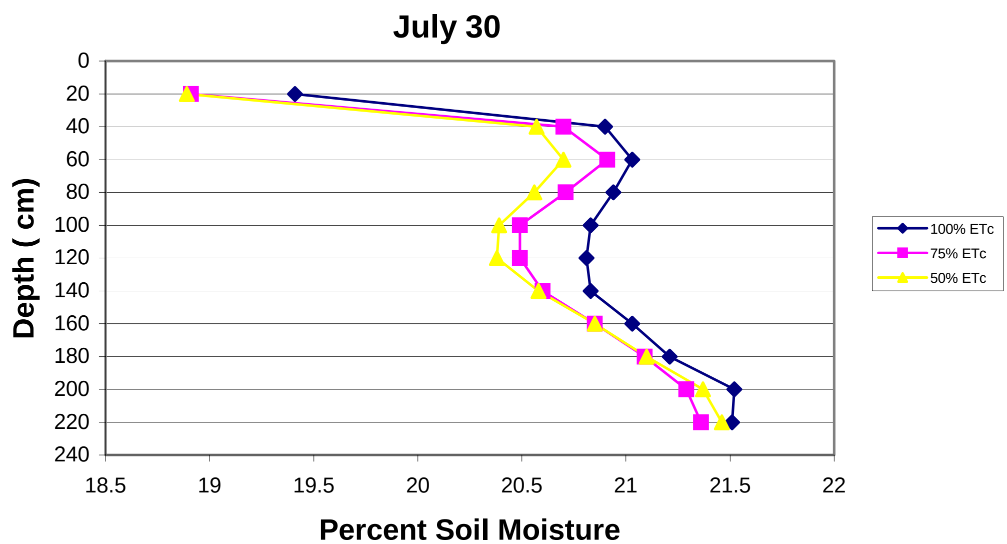

Fig B. 11. Soil moisture data for July 30.

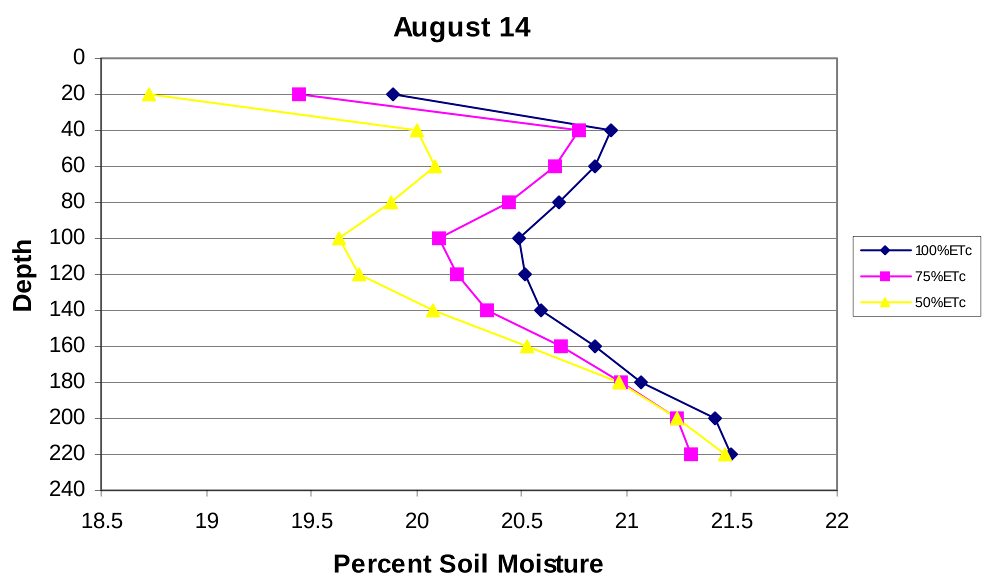

Fig B. 12. Soil moisture data for August 14.

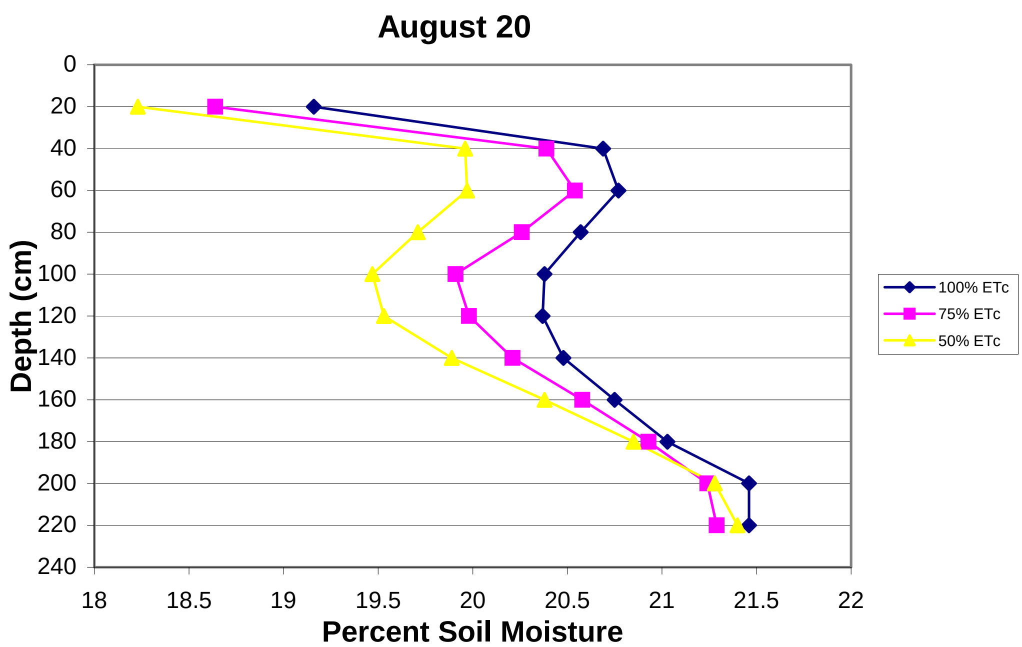

Fig B. 13. Soil moisture data for August 20.

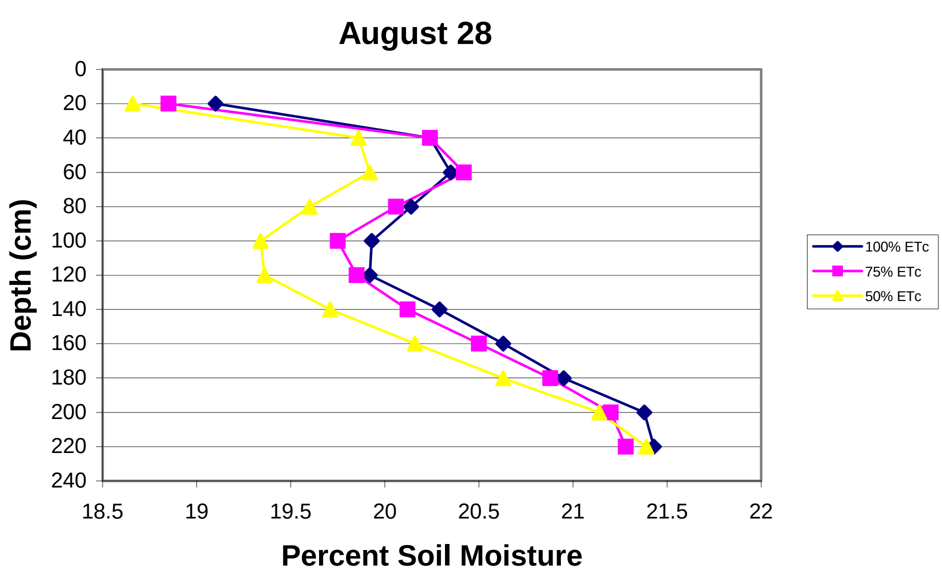

Fig B. 14. Soil moisture data for August 28.

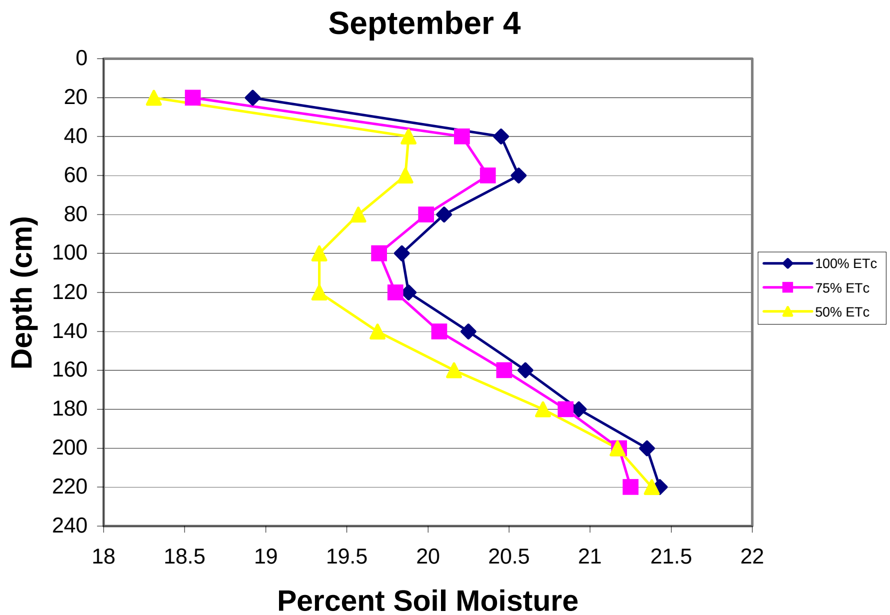

Fig B. 15. Soil moisture data for September 4.

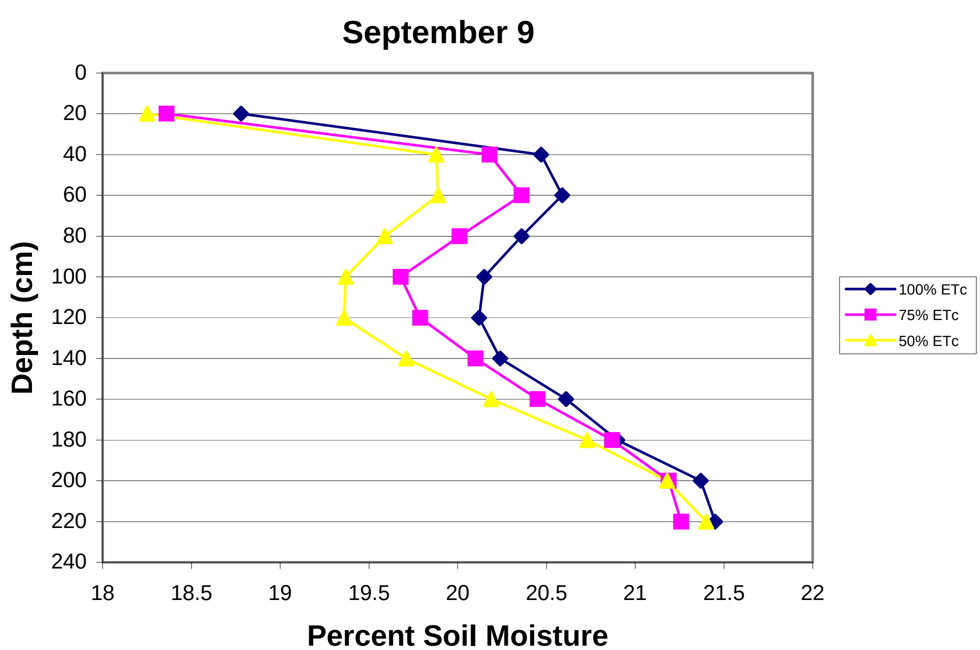

Fig B. 16. Soil moisture data for September 9.

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Education

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Cumme Laude

Professional Experience

I worked as a research associate for two years at the Texas A&M Research and Extension Center in the plant stress physiology department. My focus was remote sensing for site-specific management of biotic and abiotic stress on all crops. Infrared thermometers, cameras, and GPS were used to determine canopy temperature differences between the irrigation trials and detect biotic and abiotic stress in fields. Also, I have professional experience in range and wildlife management from the Thompson Ranch in Uvalde county and La Paloma in Kleberg county.