Estimation of soil water deficit in an irrigated cotton field with infrared thermography

J. Padhi[a], R.K. Misra[a*] and J.O. Payero[b]
[a]*Faculty of Engineering and Surveying, National Centre for Engineering in Agriculture and CRC for Irrigation Futures, University of Southern Queensland, Toowoomba, Queensland 4350, Australia*
[b]*The University of Queensland, Queensland Alliance for Agriculture and Food Innovation (QAAFI), 203 Tor Street, Toowoomba, Queensland 4350, Australia*

Abstract

Plant growth and soil water deficit can vary spatially and temporally in crop fields due to variation in soil properties and/or irrigation and crop management factors. We conducted field experiments with cotton (*Gossypium hirsutum* L.) over two seasons during 2007-2009 to test if infrared thermography can distinguish systematic variation in deficit irrigation applied to various parts of the field over time. Soil water content was measured with a neutron probe and thermal images of crop plants were taken with a thermal infrared camera. Leaf water potential and stomatal conductance were also measured on selected occasions. All measurements were made at fixed locations within three replicate plots of an irrigation experiment consisting of four soil-water deficit treatments. Canopy temperature related as well with soil water within the root zone of cotton as the stomatal conductance index derived from canopy temperature, but it neglected the effect of local and seasonal variation in environmental conditions. Similarities in the pattern of spatial variation in canopy temperature and soil water over the experimental field indicates that thermography can be used with stomatal conductance index to assess soil water deficit in cotton fields for scheduling of irrigation and to apply water in areas within the field where it is most needed to reduce water deficit stress to the crop. Further confidence with application of infrared thermography can be gained by testing our measurement approach and analysis with irrigation scheduling of other crops.

Keywords: canopy temperature; irrigation; leaf water potential; soil water deficit; stomatal conductance; stomatal conductance index; thermal imagery

1. Introduction

Irrigation is essential for cotton production in eastern Australia as in-season rainfall is inadequate to meet crop water demand (Tennakoon and Hulugalle, 2006). As water is a critical resource, irrigators need to maximise return from this limited resource. As cotton fields in Australia are large, often irrigated with long furrows or mobile irrigation systems (e.g. lateral move or centre pivot), soil properties may vary spatially requiring variable rate and timing of irrigation application. Spatial variability in distribution of irrigation or rain water may be due to inherent variation in soil properties and/or nonuniform application of irrigation leading to spatial variation in crop growth and yield. Rapid, non-destructive estimation of soil water over large area is required to estimate soil water deficit for effective scheduling of irrigation.

Stress to a crop plant is often caused by water deficit within the plant due to a reduction in the availability of soil water (Wanjura and Upchurch, 2000) inadequate to meet the evapotranspiration demand. Jones (1990) suggested that greater precision in irrigation application can potentially be achieved with ‘plant stress sensing’ because crop plants can integrate the effects of water deficit in the soil and the atmosphere. Thus, it is necessary to quantify the level of water deficit in crop plants and use that information for irrigation management of crops (Wanjura et al., 2006). For decades, it has been well established that crop water stress can be detected remotely by measuring the surface temperature of crop plants (Jackson, 1982). When crop plants are experiencing water shortage, transpiration from the leaves decreases, causing a reduction in both stomatal conductance and water potential of leaves. A decrease in transpiration can also cause insufficient cooling of leaf surface leading to an increase in leaf temperature (Jackson et al., 1981). For these reasons, leaf temperature is considered as an important indicator of actual level of water stress in a plant (Petersen et

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[*] Corresponding author. Tel: +61 7 4631 2805; Fax: +61 7 4631 2526,
Email address: misrar@usq.edu.au (R.K. Misra)

al., 1992) and considered as a valuable tool for irrigation scheduling (Gates, 1964). Measurement of canopy temperature without physically contacting a plant (Ehrler et al., 1978) became possible since the availability of infrared thermometers (IRTs).

Due to the low cost of infrared thermometers, a large number of studies have used thermal signal of plant canopies and the surrounding area for the detection of water stress in plants (e.g. Mahan and Yeater, 2008). Measurement of canopy temperature in crop fields with infrared thermometers is reliable and non-invasive, but it is usually based on a few point measurements and therefore depends on the assumption of uniform soil water content and plant density over large areas. In order to map variability in crop water status over an area at an adequate resolution, several IRTs may be needed. Thermography, on the other hand, is the process of obtaining thermal image of an area controlled by the user. The potential advantage of thermal imagery (also known as infrared thermography) over point measurements with infrared thermometers is the ability of the image to cover a large number of individual leaves and plants at one time at a high spatial resolution. Infrared thermometers usually have a finite angle of view so that it is common for the acquired thermal signal to include thermal emission from leaves as well as some background noise from other objects (e.g. soil or sky) within the field of view. The thermal image also includes similar background noise, but any bias introduced by the background noise can be easily corrected during analysis and interpretation of the image (Leinonen and Jones, 2004).

Recent developments and commercial availability of portable thermal imagers and the associated image analysis software has overcome the problems associated with infrared thermometers. Thermal imaging has the potential to provide a more robust measure of the crop water status. Availability of equipment for digital thermal imaging also provides a unique opportunity to develop instantaneous spatial canopy stress indices for use in precision agriculture (Chaerle and van der Straten, 2000). Thermal and visual imagery can be combined to estimate the canopy temperature and identify plant stress in a number of crops, e.g. grape vines (Leinonen and Jones, 2004) and cotton (Cohen et al., 2005). The sensitivity of an unmanned air vehicle equipped with a thermal infrared sensor has been also tested to measure the response of cotton to irrigation and crop residue management (Sullivan et al., 2007). Plant water stress in cotton at full canopy can be detected by a number of spectral sensors including hyperspectral, multispectral and thermal infrared sensors (DeTar et al., 2006).

Rigorous testing of thermal imaging against more traditional physiological techniques under field conditions is still required to determine the correspondence between thermal emission characteristics and physiological response of plants to water deficit for various types of crops (Grant et al., 2006). Earlier studies which have used infrared methods for irrigation scheduling are able to indicate stomatal closure or evapotranspiration rate but they give no information on the amount of soil water available or that needs to be supplemented via irrigation at that time (Jones, 2004). Grant et al. (2006) suggested that experiments in which irrigation scheduling is determined by a range of methods, one of these should include thermal imaging. In this work we aim to assess the spatial and temporal variation in soil water deficit in an irrigated field experiment with cotton to test:

(a) if thermal imaging can be used to distinguish soil water deficit in cotton fields under a systematic variation in deficit irrigation treatments;
(b) if canopy temperature and internal water status of leaves relate to soil water within the root zone.

2. Materials and methods

Field experiments with cotton (*Gossypium hirsutum* L.) were conducted over two seasons (2007-2008 and 2008-2009) in an experimental field (27°30'44"S, 151°46'55"E, and 431 m elevation) at the Kingsthorpe Research Station, approx. 20 km west of Toowoomba, Queensland, Australia. The soil at the experimental site is referred to as a haplic, self-mulching, black vertosol (Isbell, 1996) consisting of medium to heavy cracking clay soil with 76% clay, 14% silt and 10% sand in the surface horizons (Foley and Harris, 2007). The soil had an organic carbon content of 1.3%, pH 7.2, EC 35 mS m^{-1} and CEC 86 $cmol_c$ kg^{-1} and a field bulk density of 1.2 Mg m^{-3}.

An automatic weather station was installed at appox. 30 m from the edge of the experimental site to measure rainfall, solar radiation, relative humidity, wind speed and air temperature (maximum and minimum) at 1 h interval. During the experimental period in 2007-2008, the range of daily maximum and minimum air temperature was 0.2-38.4 °C and relative humidity 20-100%. During 2008-2009, similar range for daily maximum and minimum air temperature was 1.1-40.1 °C and relative humidity 16-100%. Total rainfall during the cotton seasons in 2007-2008 and 2008-2009 were 272 and 471 mm, respectively.

2.1 Crop management

During both years, seeds of Bollgard II cotton variety Sicala 60 BRF were sown at a depth of 5 cm during mid-November and the crop was harvested in mid-May. The row and plant spacing was maintained at 100 and 10 cm, respectively. At planting, either a starter fertilizer (10.5% N, 19.5% P and 2.2% S) or urea was applied followed by a second application of urea at 68-70 DAP. Most of the crop emerged within 8 days after planting (DAP) with a final planting density of 11 plants m^{-1} row (2007-2008 season) or 17 plants m^{-1} row (2008-2009 season). For weed control, glyphosate (1 kg ha^{-1}) was applied once in 2007-2008 and twice during the 2008-2009 season. An insecticide Decis (Deltamethrin as the active ingredient) was applied at a rate of 200 ml ha^{-1} during 2008 to control the pest pale cotton stainer.

2.2 Irrigation treatments

Field experiments in each year consisted of four irrigation treatments with three replicates based on a randomized block design. Irrigation treatments were based on plant available water capacity (PAWC) for the experimental site. PAWC was taken as the difference between the upper soil-water storage limit and the lower water extraction limit for a growing crop over the rooting depth (Gardner 1985). Field determination of PAWC was based on two parameters: drained upper limit (DUL) as the upper soil-water storage limit and crop lower limit (CLL) as the lower extraction limit over the rooting depth. DUL was measured as the volumetric water content of the soil after thorough wetting and allowing it to drain under the influence of gravity to a steady state condition (Ratliff et al., 1983). CLL was measured as the water content by allowing the crop to extract sufficient water beyond which no further extraction was possible. Both DUL and CLL were determined in the field at 10 cm depth increment within 0-150 cm. The methods used to determine DUL and CLL were similar to those described by Ritchie (1981) and Ratliff et al. (1983).

Irrigation treatments used for the experiments were: T50 – 50% depletion of PAWC, T60 – 60% depletion of PAWC, T70 – 70% of PAWC and T85 – 85% of PAWC. These treatments were used to schedule irrigation of specific plots using the measured soil water for each replicate plot with a neutron probe (details given later). All T85 treatment plots were subdivided into solid (T85-Solid) and skip-row (T85-Skip) planting. Here, solid planting refers to the normal planting whereas skip-row planting refers to leaving one blank row (without plants) between two adjacent rows of cotton.

There were altogether 12 experimental plots consisting of 4 irrigation treatments (T50, T60, T70 and T85) and 3 replicates. Each replicate plot (20 m × 13 m) was separated from the adjacent plots with 4 m wide buffer. An additional area of 20 m × 7 m was used alongside the experiment for a refugee crop as Bollgard II cotton variety Sicala 60 BRF used for this experiment is a genetically modified variety of cotton intended to reduce pesticide use by 80% compared with the conventional varieties of cotton. A non-Bollgard cotton variety Sicala 41 RRF was used in this experiment as a refugee crop to divert the attention of insects from the Bollgard crop.

Each replicate plot was irrigated with bore water using a hand-shift solid sprinkler system. Partial-circle sprinkler heads were used to avoid irrigation of adjacent plots. Three rain gauges were installed in each plot to estimate the quantity of water applied during irrigation. Since irrigation treatments were influenced by the initial soil water content at planting and rainfall received during the experiment, the irrigation treatments could be imposed on cotton during 75-162 DAP in 2007-2008 and 67-136 DAP in 2008-2009. The replicate plots of T50, T60 and T70 treatments received 228.0, 82.8 and 82.3 mm irrigation water, respectively in 2007-2008 and T85 treatment did not require any irrigation. During 2008-2009 seasons, the replicate plots of T50, T60, T70 and T85 treatments received 214, 78, 58 and 23 mm of irrigation water, respectively.

2.3 Soil water measurements

A neutron probe access tube was installed in each of 12 plots to monitor the soil water distribution over the growing season. For T85-Solid and skip-row irrigation treatments, additional neutron probe access tubes were installed. A neutron probe (503DR Hydroprobe, Campbell Pacific Nuclear Inc., USA) was used to measure soil water content from the surface to a depth of 1.33 m at 0.1 m depth increments. Standard reference count for the neutron probe was taken in the field before measurements of neutron counts in the experimental plots. Neutron count ratio (n_z) for a specific soil depth was estimated by dividing each neutron count with the standard reference count and later converted to the volumetric soil water content (θ, $m^3\ m^{-3}$) for that depth using the calibration equation

$$\theta = 1.36\, n_z - 0.44. \qquad (R^2 = 0.86,\ n = 10,\ P \leq 0.001) \qquad (1)$$

Soil water content was measured with the neutron probe in each replicate plot to determine the timing of irrigation for the irrigation treatments described earlier. The effective root zone depth was determined at various times during the crop growth period by examining the temporal variation in volumetric soil water content (θ) with soil depth (z) (data not shown). Effective rooting depth was assumed to be the soil depth nearest to the soil surface at which temporal variation in successive water content was negligible. All measured values of θ were converted to mm of water for each soil depth and then accumulated up to the effective root-zone depth to estimate soil water within the root zone (θ_z).

2.4 Thermal imagery

A single thermal image of a few plants was taken from each plot on the same day as for soil water measurement in order to explore any correspondence between canopy temperature (°C) and soil water content within the root zone (θ_z). Thermal images of cotton plants (located near the neutron access tubes) were acquired from each plot with a thermal infrared camera (NEC TH7800 model, NEC, Japan). The camera operated within the waveband of 8-14 µm with the capability of achieving a thermal resolution of 0.1 °C and a spatial resolution of 320 (V) × 240 (H) pixels, where V and H respectively refer to vertical and horizontal directions. This camera also permitted acquisition of both thermal and visual images. All images were captured at a distance of 2 m from plants to enclose mostly leaves in the upper part of the canopy while avoiding soil and other background objects. Average canopy temperature (°C) was derived from the analysis of a selected region within each image with the Image Processor Pro II software (Version 4.0.3, NEC, Japan). Since an emissivity of 1.0 for plants have been reported to induce an error of <1 °C (Jackson, 1982) and that the emissivity for plant leaves varies in the range of 0.92-0.99 (Idso et al., 1969; Sutherland, 1986), the emissivity for all measurements was kept constant at 0.97 (also used by Wittich, 1997). A rectangular area within an image was selected to enclose several leaves for the estimation of average canopy temperature. The sensitivity of the average canopy temperature to the size and position of the area selected for image analysis was found to be low (<0.3 °C). Estimates of canopy temperature for a growing plant was based on several leaves (of around 50,000 pixels) rather than single leaves because temperature averaging over several leaves has been found to reduce the impact of variation in leaf angles on leaf temperature (Grant et al., 2006) and recommended for irrigated plants.

Canopy temperature (°C) was derived from the analysis of the thermal images with the image processing software. Data for air temperature was obtained from the nearby weather station during 2007-2008 season and later measured with a hand-held RTD (resistance temperature detector) probe on 4 occasions (76, 125, 136 and 144 DAP) at the time of thermal imaging during 2008-2009. The position of cotton plants in the experimental plot viewed with the infrared camera were recorded with a hand-held GPS (Garmin, KS, USA) at the first measurement and later replaced with a fixed marker for subsequent image acquisition during the season. The GPS recorded location of all measurements in latitude and longitude format (i.e. degree, minute and second) were converted to easting and northing by using a UTM conversion Excel spread sheet (Dutch, 2007).

Since water loss from leaves via transpiration is dependent on many factors, such as radiation, wind speed, air temperature, and humidity; all of which affect the energy balance of plant canopy (Jones, 1992), leaf temperature alone may not adequately explain transpiration rate or stomatal conductance of leaves. Jones et al. (2002) proposed the use of leaves sprayed with water as wet references and leaves for which all transpiration was prevented by covering it with petroleum jelly as dry references. Therefore, cotton leaves were sprayed with water on both sides for about 1 min to simulate the condition of a fully transpiring leaf immediately before image acquisition to estimate temperature of wet reference leaf (T_{wet}). Additional reference leaves were covered with petroleum jelly to simulate the condition of a non-transpiring leaf for estimation of dry reference leaf (T_{dry}). Images of wet and dry reference leaves were taken from each replicate plot for each irrigation treatment at the time of image acquisition of normal leaves (Fig. 1).

2.5 Estimation of stomatal conductance index

Thermal infrared images of cotton plants were taken on six occasions in each year (74, 81, 94, 135, 144 and 155 DAP during 2007-2008 and 62, 76, 88, 125, 136 and 144 DAP in 2008-2009). It took 30-40 minutes to obtain thermal images of selected plants and wet and dry reference leaves for the whole experiment. On 74, 144 and 155 DAP of 2007-2008 season, thermal images were obtained between 1000 and 1200 h, whereas at other times during 1200-1500 h. During the 2008-2009 season, thermal images were obtained between 0920 and 1300 h. Most of the thermal images were taken in clear and sunny weather conditions. However, image clarity may have been reduced as the camera was held by hand during image acquisition affecting its focus. Average canopy temperature estimated from each image (Fig. 2) was combined with the temperatures of wet and dry reference leaves to calculate the stomatal conductance index (I_{G}) as follows.

$$I_{\mathrm{G}} = \frac{T_{\mathrm{dry}} - T_{\mathrm{c}}}{T_{\mathrm{c}} - T_{\mathrm{wet}}} \quad , \qquad (2)$$

where T_{dry} (°C) was the temperature of the leaf covered with petroleum jelly on both sides, T_{c} (°C) the average canopy temperature of normal leaf and T_{wet} (°C) is the temperature of leaf sprayed with water on both sides of the leaf. All parameters of Equation (2) were obtained from the analysis of thermal images. The index I_{G} in this equation is an indicator of water stress to plants (Jones et al., 2002) as it is directly proportional to the stomatal conductance of leaves and inversely proportional to the crop water stress index (CWSI).

2.6 Leaf water potential and stomatal conductance

In order to assess the water status of leaves, leaf water potential (Ψ_{l}) was measured with a Model 1000 pressure chamber (PMS Instrument Company, OR, USA) on two occasions (74 and 94 DAP) during 2007-2008 season and four occasions (62, 76, 88, 125 and 136 DAP) during 2008-2009 season. Most measurements were made on clear and sunny days during 1200-1400 h, except on 62 and 76 DAP of 2008-2009 season when these measurements were made during 1000-1200 h. For all measurements, the third leaf from the top of the canopy was cut with a thin-blade scissor and inserted into the pressure chamber as soon as possible to avoid any change in Ψ_{l}. Compressed nitrogen gas was used to apply gas pressure to the chamber in small increments until visible flow of sap occurred. The final bleeding pressure was taken as the equilibrium water potential of the leaf.

Stomatal conductance (g_{s}) of the leaves was measured with a PMR-5 steady-state porometer (PP Systems, Norfolk, UK) under ambient light conditions on leaves of plants used for thermal imaging. Stomatal conductance measurements were made in clear and sunny weather conditions during 1100-1400 h of the 2008-2009 season on five occasions (76, 88, 125, 136 and 144 DAP).

3. Results

3.1 Soil water and canopy temperature

Soil water within the root zone (θ_{z}) of cotton was significantly influenced by the irrigation treatments on five out of the six measurement occasions during both 2007-2008 and 2008-2009 seasons (Table 1). Spatial variation in soil water over the experimental field at early growth of cotton (74 DAP in 2007-2008 and 62 DAP in 2008-2009) was small and not significantly affected by irrigation treatments. After the first irrigation (75 DAP in 2007-2008 and 67 DAP in 2008-2009), spatial variation in θ_{z} increased within the experimental field due to variable quantity of irrigation water applied. Over both seasons of cotton, θ_{z} remained significantly higher for the most frequently irrigated treatment (T50) than the least frequently irrigated treatment (T85) (Table 1). θ_{z} for the intermediate irrigation treatments (T60 and T70) were either similar to T50 or T85 treatment. The LSD values in Table 1 indicate the average difference in θ_{z} that persisted between various treatments at the experimental site. However, actual difference in θ_z was as low as 35 mm at 76 DAP in 2008-2009 and as high as 110 mm at 144 DAP in 2007-2008 (Table 1).

Seasonal variation in canopy temperature (T_c, derived from thermal infrared images) of cotton was similar to variation in θ_z in both years (Table 2). Mean canopy temperature for various irrigation treatments differed significantly on most occasions except during the early growth of cotton before irrigation application. Canopy temperature of cotton in T50 irrigation treatment remained significantly lower than T85 treatment on most occasions during both seasons of cotton. Canopy temperature for the intermediate treatments (T60 and T70) was similar on most occasions in both seasons and on a few occasions, it was not significantly different from T85. Although average difference in T_c was in the range of 0.6-2.8 °C (shown as LSD in Table 2), the maximum difference in canopy temperature was mostly observed between T50 and T85 irrigation treatments (7.1 °C in 2007-2008 season and 3.7 °C in 2008-2009 season). Data for air temperature (T_a) and temperature of wet and dry reference leaves (T_{wet} and T_{dry}, respectively) given in Table 2 indicated that canopy temperature for most irrigation treatments was mostly higher than the air temperature, but intermediate to T_{wet} and T_{dry}. Since weather condition (e.g. temperature, T_a and sunlight) within a plant canopy can vary quite considerably during the day and to even a larger extent over a cropping season, lack of consistent variation in T_c in relation to T_a suggested that there may be some similarity in the variation of soil water or air temperature with time.

3.2 Physiological responses of leaves

Table 3 shows the effect of irrigation treatments on leaf water potential (ψ_l) on selected occasions. Although ψ_l was measured on a fewer occasion than soil water or canopy temperature, less frequently irrigated plants (in T85) experienced significantly greater leaf water deficit than those irrigated more frequently (T50). However, lack of significant effects of irrigation treatments on ψ_l a number of occasions (Table 3) indicates lower sensitivity of ψ_l to irrigation than θ_z and T_c.

In our experiment, stomatal conductance of leaves (g_s) was measured only during the second cotton season in 2008-2009 (Table 4). During this season, the temporal pattern of variation and sensitivity of g_s to irrigation treatments was similar to ψ_l (Table 3) with frequent application of irrigation (in T50) indicating significantly higher g_s than other irrigation treatments.

The stomatal conductance index I_G was found to be more sensitive to irrigation treatments than other physiological variables measured for leaves (Table 5). As this index is based on the temperature of non-transpiring and fully transpiring leaves (as detailed in Eq. 2), large variation in I_G was likely for various irrigation treatments. Plants irrigated more frequently (T50) with low canopy temperature (Table 2) deviated greatly from the temperature of a non-transpiring leaf and hence maintained high values of I_G compared with other irrigation treatments throughout the growth period in both seasons (Table 5).

4. Discussion

4.1 Sensitivity of canopy temperature to soil water

Canopy temperature (T_c) averaged over several leaves indicate the extent to which stomatal activity cools the leaves. Plants can regulate water potential of leaves to reduce transpiration rate (T_r) by controlling water inflow into leaf. However, water outflow from leaves is controlled by partial to full closure of stomata that influences stomatal conductance (g_s). The extent to which a plant is able to adjust internal water deficit within leaves is by modifying T_r, Ψ_l and g_s in response to available soil water within the root zone and atmospheric water deficit both diurnally and seasonally may be considered as a characteristic feature of the plant.

The sensitivity of stomata to humidity is known to be partly dependent on soil water content (Calvet, 2000). Significant effects of irrigation treatments on canopy temperature and soil water observed during both seasons of cotton (Tables 1 and 2) indicated a significant decrease in canopy temperature with an increase in soil water within the root zone (Fig. 3a and b). There are number of local and seasonal environmental factors (sunshine, air temperature, wind and humidity) which affect canopy temperature independent of transpiration causing a loss of soil water. Therefore, the nonlinear relationships between T_c and θ_z (shown as negative power functions in Table 6) may be circumstantial as it overlooks the effects of other environmental factors. The uncertainty in these relationships is shown in Fig. 3c which indicated that considerable variation in T_c - T_a (an indicator of cooling or warming of leaves) may occur at a given soil water within the root zone. For example, T_c - T_a varied from -4 to 10 °C at a θ_z of approx. 300 mm. Therefore, the effect of soil water on heat emission from leaves may depend on the physiological behaviour of the crop plant, local and seasonal environmental factors and soil properties affecting the availability of water at the root surface (e.g. unsaturated hydraulic conductivity).

4.2 Sensitivity of canopy temperature to physiological factors

Physiological factors that may influence T_c via leaf water relations were also examined in this work. Data in Fig. 4 and Tables 1 and 3 show that cotton canopies with high leaf water potential (Ψ_l) tend to maintain low canopy temperature (T_c). High leaf water potential should allow substantial cooling of leaves by supporting high transpiration rate to reduce T_c significantly (Fig. 4). During both seasons of cotton, the relationship between T_c and Ψ_l was linear and the slope of the relationship was similar (Table 6). Leaf water potential also increased with increase in θ_z (Fig. 4c) which suggests a hydraulic continuity and a hydrostatic equilibrium between soil and plant throughout the season.

When soil water within the root zone of a crop plant changes over time but within a certain limit (as with the irrigation treatments used in this work), stomatal conductance of leaves (g_s) tends to increase linearly with increase in soil water (θ_z) (Fig. 5). Since g_s is an instantaneous measure of the stomatal conductance of single leaves, it is strongly influenced by the atmospheric conditions (light or radiation, temperature, humidity and wind speed) at the time of measurement, especially vapour pressure deficit (VPD). When g_s is derived from thermography it has been shown to vary quite considerably with wind speed and exposure of leaves to sun and shade (Jones et al. 2002). Thus, a reasonable degree of scatter observed in Fig. 5 could be partly due to the variation in ambient weather conditions during the measurement of g_s at various times over the cotton season.

Since photosynthesis and transpiration are jointly influenced by stomatal conductance (Jarvis and Davies, 1998), occurrence of low values of g_s may adversely affect crop growth due to reduced photosynthesis. For plant growth to continue, plants need to assimilate sufficient CO_2 by optimising transpiration and photosynthesis which requires regulation of g_s by plants (Jones, 1998). Such regulation of g_s would also allow leaf temperature to be maintained within an optimal range as a given change in g_s to control transpiration can influence g_s itself through a feedback mechanism (Jarvis and Davies, 1998). Due to the complexity of the relationship between transpiration and stomatal conductance, transpiration rate (T_r) of single leaves may be dependent on leaf temperature, but spatial variability of T_r (arising from leaf to leaf variation at various positions within the canopy) can be substantial due to the spatial variability of g_s (Jones, 1999). Simultaneous measurements of g_s and T_r made with the porometer showed a declining trend in transpiration rate with an increase in leaf temperature (data not shown as these are parameters are correlated). The relationship of T_c (obtained as an average estimate of temperature of several leaves with the infrared thermography) with T_r of single leaves (obtained with porometer) showed a reduction in canopy temperature with increased transpiration rate (data not shown). The variability in T_c for a given T_r was considerable for modest values of conductance and transpiration rate. This supports the notion that T_c not only increases at low stomatal conductance, but its variability is also high (Fuchs, 1990; Leinonen and Jones, 2004). This may reduce the sensitivity of T_c as a measure of transpiration rate of the whole canopy of plant species.

4.3. Stomatal conductance index

The stomatal conductance index I_G can be considered as a good indicator of the transpiring ability of plants as it is used for the estimation of g_s (Jones 1999). Our experimental data for cotton showed that T_c decreased nonlinearly while I_G increased linearly with increase in g_s (Fig. 6a and b). Since the degree of scatter in the data for I_G and T_c in Fig. 6 were similar, T_c could be considered as good indicator of seasonal variation in stomatal conductance for cotton as the stomatal conductance index I_G. However, T_c may not be a reliable indicator as cooling/warming of leaves, i.e. T_c - T_a varies quite considerably at a given value of g_s (Fig. 6c). In order to derive useful information on soil water deficit affecting the transpiration ability of crop plants, it may be necessary to examine the variation of I_G with θ_z (Fig. 7). The relationship between I_G and θ_z was mostly linear with considerably greater dependence of I_G during the first season than the second season (as indicated by slope for the fitted regression equations in Table 6). This seasonal difference in the behaviour of I_G could be due to the amount of seasonal rainfall and irrigation given in each season. The first season (2007-2008) of cotton was relatively drier (approx. 200 mm less rainfall) than the second season (2008-2009) requiring larger amount of supplemental irrigation to maintain the necessary irrigation treatments (as detailed in Section 2). Since there were few values of I_G >2 in both seasons (Fig. 7), it may be useful to consider to apply irrigation to cotton when $I_G = 2$ so that the crop does not experience severe water deficit. As the maximum rooting depth during both seasons did not exceed 1.03 m, $I_G = 2$ corresponded with a θ_z of 315 mm in the first season and 340 mm in the second season. These values of θ_z corresponded with soil water deficit of 63 and 71% (similar to T60 and T70 treatments in our experiment), respectively. For these estimates the regression models shown in Table 6 and the upper and lower limit of plant available water content (PAWC) within 1.03 m depth of soil were considered.

4.4 Spatial correlation between soil water and canopy temperature

Spatial variability in soil and plant properties is perhaps present in many agricultural fields, but it is difficult to measure as soil properties tend to vary not only in horizontal direction, but most commonly vertically (with depth) due to the occurrence of distinct horizons. The depth of horizons in a field is not necessarily uniform in the horizontal direction. This spatial variability in soil properties may lead to uneven distribution and retention of water from rain or irrigation causing nonuniform crop growth and development. Nonuniform soil and plant management in crop fields, e.g. distribution of irrigation and fertilizers, or plant spacing adds further difficulty in identifying the nature and source of spatial variation the field. In this study, randomized allocation of irrigation treatments to various parts of the experimental field allowed soil water to vary spatially at various times during the growth of cotton.

Due to the close correspondence between canopy temperature and soil water that neglected the effects of other environmental variables observed in Fig. 3 and the contrasts between two of the four irrigation treatments (T50 and T85 in Tables 1 and 2), it was possible to identify wet areas (θ_z = 405 mm in T50 plots) from dry areas (θ_z = 315 mm in T85 plots) within the experimental field on the basis of canopy temperature of cotton (with a variation of around 4°C for T_c) at the time when the difference in soil water at various parts of the field was large, e.g. at 144 DAP of cotton in 2007-2008 (Fig. 8a and b). It was also possible to clearly identify these wet and dry areas in the field on the basis of canopy temperature when the difference in soil water was as small as 40 mm, e.g. at 88 DAP in 2008-2009 (Fig. 8c and d).

These analyses suggest that maps of canopy temperature in crop fields together with the stomatal conductance index or a similar type of crop water stress index that takes some of the environmental condition into account may be used to estimate available soil water within the crop's root zone so that soil water deficit can be quantified within the field for irrigation scheduling. Information on canopy temperature and other environmental variables can be readily utilised by mobile irrigation systems (e.g. centre pivot or lateral move systems) to apply the necessary amount of irrigation water at the time when it is needed by a growing crop. Using thermal infrared sensors, automatic irrigation has been successfully implemented for centre-pivot irrigated fields (O'Shaughnessy and Evett, 2010; Sullivan et al., 2007). Further accuracy with irrigation may be gained by using the infrared thermography approach shown in this work to assess soil water deficit in crop fields.

5. Conclusions

The response of an irrigated cotton crop to systematic variation in soil water deficit with various irrigation treatments described in this work indicates that thermal imagery or infrared thermography can provide a reliable measurement of canopy temperature that could be used with other environmental parameters or stomatal conductance index as a measure of water stress to plants to extract information on soil water within the crop's root zone. Further testing at other sites and crops is expected to increase confidence with these measurements to help distinguish well irrigated areas within a crop field from water deficient areas. Although our experimental data is specific to the crop (cotton) and the experimental site (clay soil) used, the measurement approach and analysis is expected to apply to other crops and sites.

Due to the existence of an apparent thermal equilibrium between the crop and soil water evident at the experimental field, irrigation scheduling should be based on the canopy temperature and a water stress index (using the traditional approach of Crop Water Stress Index, CWSI or more contemporary index I_G as used in this work). These indices are useful for estimation of ET and stomatal behaviour of crop plants.

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Table 1. Effects of four irrigation treatments (T50-T85) on soil water within the root zone of cotton on selected measurement dates (indicated as days after planting, DAP) during the 2007-2008 and 2008-2009 seasons. Mean values of soil water on a given DAP with the same superscript letter are not significantly different (P>0.05) as the difference is less than the least significant difference (LSD). NS indicates no significant effect of treatments on soil water.

DAP	Soil water within the root zone (mm) 2007-2008 season				LSD (mm)
	T50	T60	T70	T85	
74	277.2	265.9	262.0	271.1	NS
81	335.5^b	250.7^a	245.1^a	246.7^a	34.6
94	338.5^b	291.3^a	261.6^a	272.6^a	31.2
135	316.4^b	310.9^b	326.1^b	264.2^a	30.8
144	431.6^b	329.4^a	345.3^a	321.2^a	48.1
155	364.8^b	303.6^a	318.2^a	293.6^a	36.8
	2008-2009 season				
62	219.8	215.3	220.4	219.4	NS
76	266.1^b	252.4^{ab}	234.3^a	230.8^a	21.8
88	253.9^c	234.2^{bc}	220.2^{ab}	205.1^a	25.1
125	350.7^b	268.5^a	312.6^a	264.3^a	56.1
136	363.3^b	295.9^a	339.9^a	296.6^a	48.6
144	344.7^b	263.7^a	289.1^a	257.1^a	38.7

Table 2. Effects of four irrigation treatments (T50-T85) on canopy temperature of cotton on selected measurement dates (indicated as days after planting, DAP) during the 2007-2008 and 2008-2009 seasons. Mean values of canopy temperature on a given DAP with the same superscript letter are not significantly different (P>0.05) as the difference is less than the least significant difference (LSD). NS indicates no significant effect of treatments on canopy temperature. Whenever available, mean values and standard error (SE, $n = 12$) of air temperature (T_a) and temperatures of wet (T_{wet}) and dry (T_{dry}) reference leaves for a given DAP are given.

DAP	Canopy temperature (°C) 2007-2008 season				LSD (°C)	T_a (°C)	T_{wet} (°C)	T_{dry} (°C)
	T50	T60	T70	T85				
74	30.4	31.8	31.7	31.5	NS	27.0	27.5±0.05	34.7±0.06
81	26.4^b	32.0^a	32.9^a	33.5^a	1.6	29.1	26.6±0.43	35.7±0.29
94	25.6^c	29.1^b	30.9^a	29.9^a	1.7	24.4	24.0±0.33	33.1±0.35
135	28.5^b	28.7^b	28.2^b	33.9^a	2.8	29.4	25.6±0.29	36.3±0.30
144	25.1^b	27.9^a	27.3^a	29.1^a	2.1	24.0	24.3±0.21	35.5±0.21
155	26.8^c	30.1^a	28.6^b	31.4^a	1.7	22.1	24.7±0.21	34.4±0.20
	2008-2009 season							
62	31.8	32.0	31.9	31.7	NS	28.2	-	-
76	27.4^b	27.6^a	28.2^a	28.4^a	0.6	26.1±0.11	25.4±0.07	31.8±0.05
88	27.7^c	29.0^b	29.4^b	31.4^a	1.0	32.4	26.1±0.24	32.8±0.27
125	26.2^b	27.9^a	27.1^{ab}	28.3^a	1.4	30.3±0.05	25.0±0.21	30.8±0.10
136	25.9^b	27.6^a	26.9^{ab}	27.8^a	1.1	28.9±0.14	24.8±0.14	31.0±0.13
144	27.1^b	28.3^a	28.0^a	28.4^a	0.8	28.3±0.11	25.8±0.07	31.0±0.13

Table 3. Effects of four irrigation treatments (T50-T85) on leaf water potential of cotton on selected measurement dates (indicated as days after planting, DAP) during the 2007-2008 and 2008-2009 seasons. Mean values of leaf water potential on a given DAP with the same superscript letter are not significantly different (P>0.05) with respect to irrigation treatments as the difference is less than the least significant difference (LSD). NS indicates no significant effect of irrigation treatments on leaf water potential (P>0.05).

DAP	Leaf water potential (-MPa) 2007-2008 season				LSD (MPa)
	T50	T60	T70	T85	
74	2.3	2.6	2.5	2.5	NS
94	1.5^{b}	1.9^{a}	2.1^{a}	2.0^{a}	0.3
	2008-2009 season				
62	2.6	2.8	2.7	2.7	NS
76	1.9^{b}	2.0^{a}	2.1^{a}	2.1^{a}	0.1
88	2.0^{c}	2.2^{b}	2.3^{b}	2.9^{a}	0.1
125	1.7	2.1	1.9	2.3	NS

Table 4. Effects of four irrigation treatments (T50-T85) on stomatal conductance of cotton leaves on selected measurement dates (indicated as days after planting, DAP) during the 2008-2009 season. Mean values of stomatal conductance on a given DAP with the same superscript letter(s) are not significantly different (P>0.05) as their difference is less than the least significant difference (LSD). NS indicates no significant difference between irrigation treatments (P>0.05).

	Stomatal conductance (mmol m^{-2} s^{-1})				LSD
DAP	T50	T60	T70	T85	(mmol m^{-2} s^{-1})
76	38	32	35	32	NS
88	33^{a}	29^{b}	30^{ab}	27^{b}	3.7
125	45^{a}	33^{b}	32^{b}	32^{b}	5.9
136	43^{a}	36^{bc}	39^{ab}	30^{c}	6.8
144	38	32	33	31	NS

Table 5. Effects of four irrigation treatments (T50-T85) on I_G of cotton on selected measurement dates (indicated as days after planting, DAP) during the 2007-2008 and 2008-2009 seasons. Mean values of I_G for a given DAP with the same superscript letter(s) are not significantly different (P>0.05) with respect to irrigation treatments as their difference is less than the least significant difference (LSD). NS under the LSD values indicate no significant differences between irrigation treatments (P>0.05).

DAP	I_G 2007-2008 season				LSD
	T50	T60	T70	T85	
74	1.90	0.74	0.80	0.87	NS
81	4.40^{a}	0.58^{b}	0.40^{b}	0.32^{b}	0.60
94	2.41^{a}	0.71^{b}	0.36^{b}	0.53^{b}	0.42
135	2.71^{a}	2.60^{a}	3.27^{a}	0.54^{b}	1.60
144	5.53^{a}	1.76^{b}	2.16^{b}	1.30^{b}	1.27
155	2.46^{a}	0.78^{bc}	1.30^{b}	0.46^{c}	0.55
	2008-2009 season				
76	1.91^{a}	1.67^{ab}	0.79^{b}	0.87^{b}	0.91
88	1.66^{a}	1.03^{a}	0.40^{b}	0.32^{b}	0.62
125	2.60^{a}	1.23^{b}	0.36^{b}	0.53^{b}	1.35
136	2.77^{ab}	1.33^{bc}	3.27^{a}	0.55^{c}	1.51
144	5.53^{a}	1.76^{b}	2.05^{b}	1.21^{b}	1.01

Table 6. Details of regression model parameters and related statistics used to derive relationships between the measured variables presented within various figures. n indicates the no. of data pairs, R^2 the coefficient of determination for the fitted regression. P-values for all regression models was <0.001. Variables shown for the regression models are explained in text.

Season	Source figure	Regression model	n	R^2
2007-2008 season	Fig. 3a	$T_c = 612.13\ \theta_z^{-0.532}$	72	0.83
2008-2009 season	Fig. 3b	$T_c = 152.81\ \theta_z^{-0.301}$	72	0.73
2007-2008 season	Fig. 4a	$T_c = 4.7\ \Psi_l + 19.8$	24	0.84
2008-2009 season	Fig. 4b	$T_c = 5.2\ \Psi_l + 17.4$	48	0.90
2007-2009 season	Fig. 4c	$\Psi_l = 293.05\ \theta_z^{-0.882}$	72	0.58
2008-2009 season	Fig. 5	$g_s = 0.085\ \theta_z + 10.4$	60	0.63
2008-2009 season	Fig. 6a	$T_c = 67.04\ g_s^{-0.249}$	60	0.72
2008-2009 season	Fig. 6b	$I_G = 0.11\ g_s - 2.2$	60	0.76
2007-2008 season	Fig. 7a	$I_G = 0.026\ \theta_z - 6.2$	72	0.69
2008-2009 season	Fig. 7b	$I_G = 0.01\ \theta_z - 1.4$	72	0.61

Figures

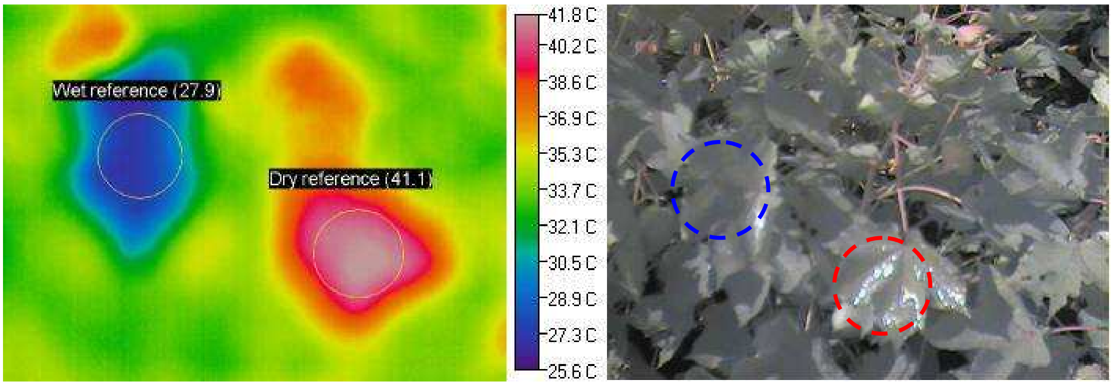


Figure 1. Variation in the temperature of wet and dry reference leaves for cotton. Number in parenthesis indicates average temperature (°C) of the enclosed circular area for the thermal image (left) and the corresponding visual image (right). Red circle represents the leaf covered with petroleum jelly and blue circle represents the leaf sprayed with water.

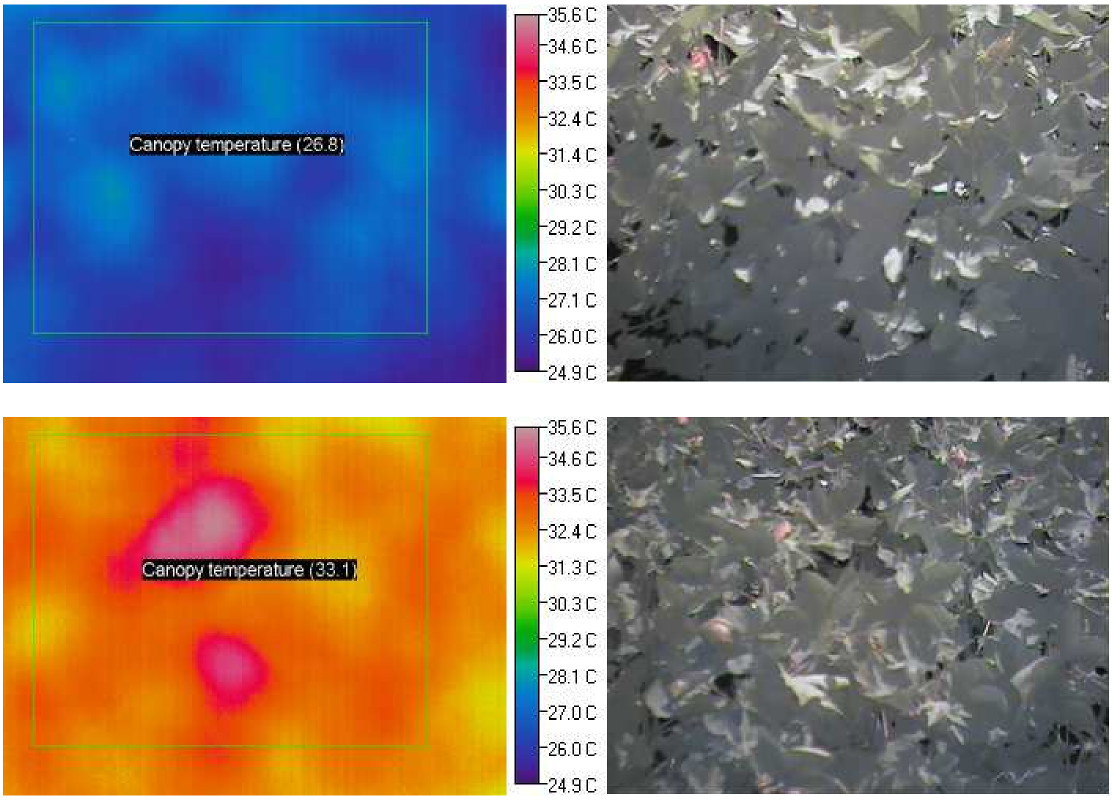


Figure 2. Thermal (top left) and visual (top right) images of the canopy of cotton plants for T50 irrigation treatment at 81 DAP during 2007-2008 season. Similar thermal (bottom left) and visual (bottom right) images for T85 irrigation treatment around the same time are shown for comparison. Numbers in parenthesis on the thermal images (top and bottom left) indicate canopy temperature (°C) of the rectangular area on the thermal image that corresponds with the visual images shown on the right.

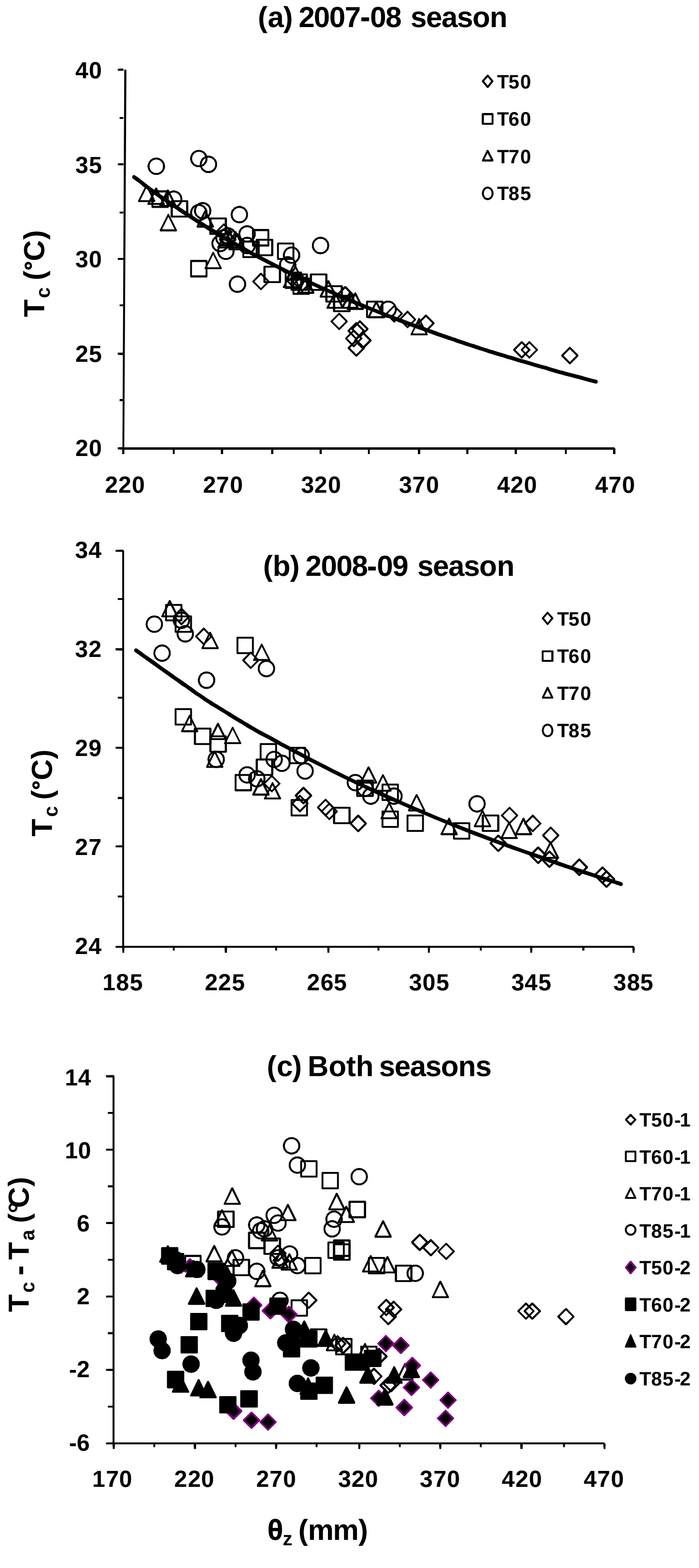


Figure 3. The relationship between canopy temperature (T_c) and soil water within the root zone (θ_z) for various irrigation treatments of cotton during (a) 2007-2008 and (b) 2008-2009 seasons. The difference between T_c and air temperature (T_a) as a function of θ_z for both seasons is shown in c.

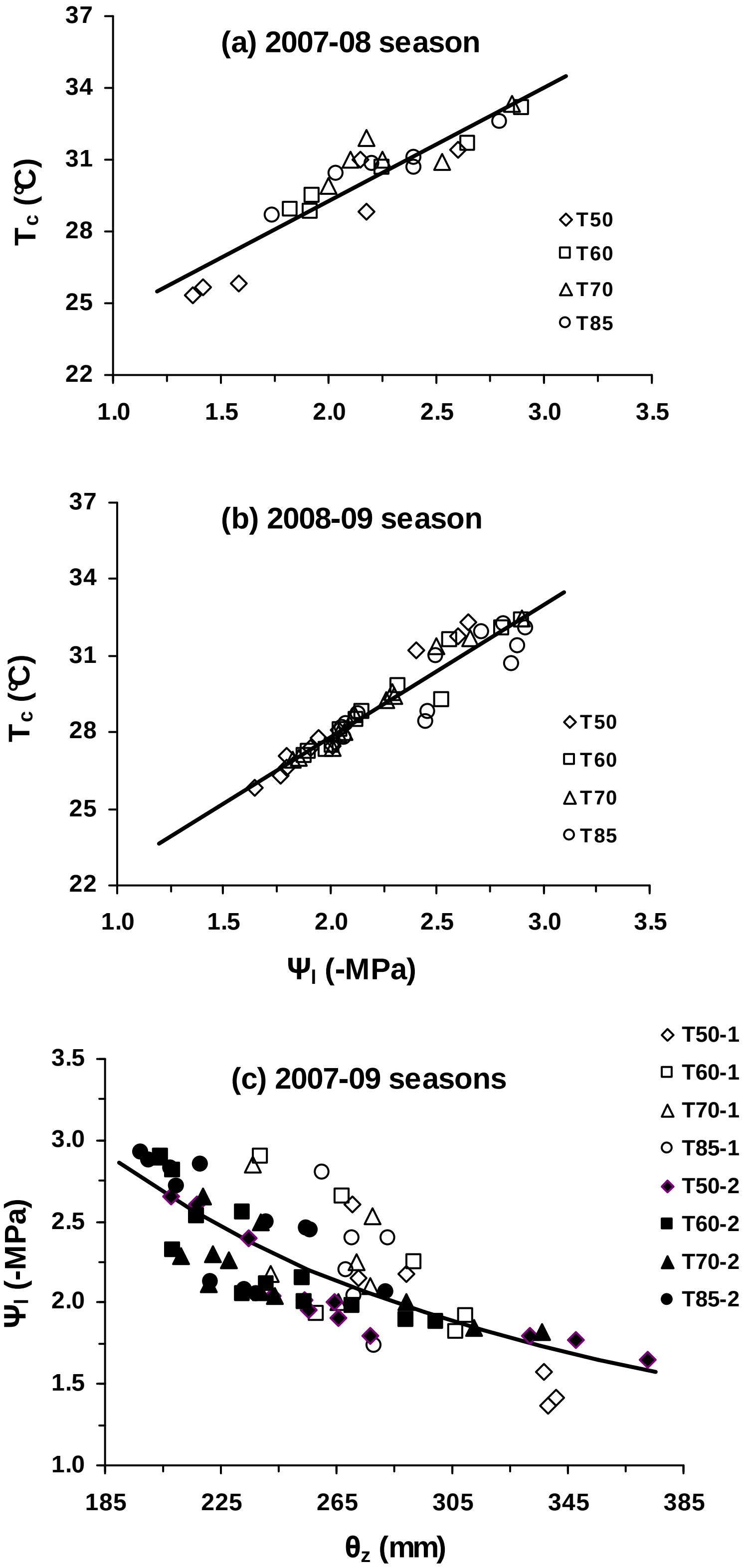


Figure 4. The dependency of canopy temperature (T_c) on leaf water potential (Ψ_l) of cotton for various irrigation treatments at (a) 74 and 94 DAP in 2007-2008 and (b) 62 and 125 DAP in 2008-2009. The relationship between leaf water potential (Ψ_l) with soil water within the root zone (θ_z) for both seasons of cotton is shown in c.

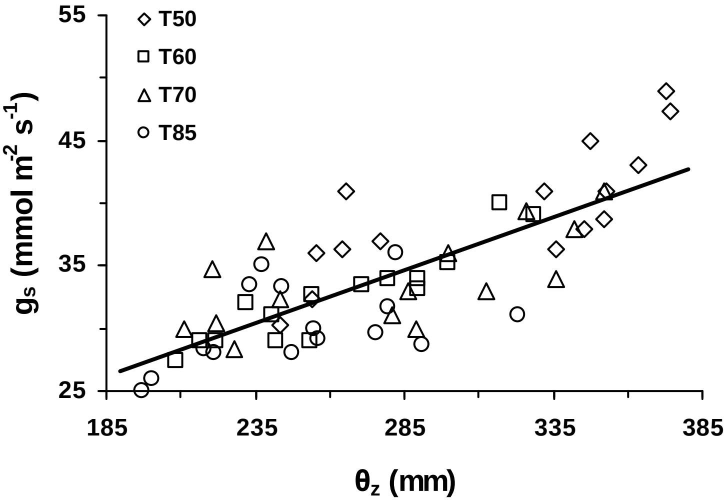


Figure 5. The relationship between stomatal conductance (*g_s*) and soil water within the root zone (*θ_z*) for various irrigation treatments of cotton during the 2008-2009 season.

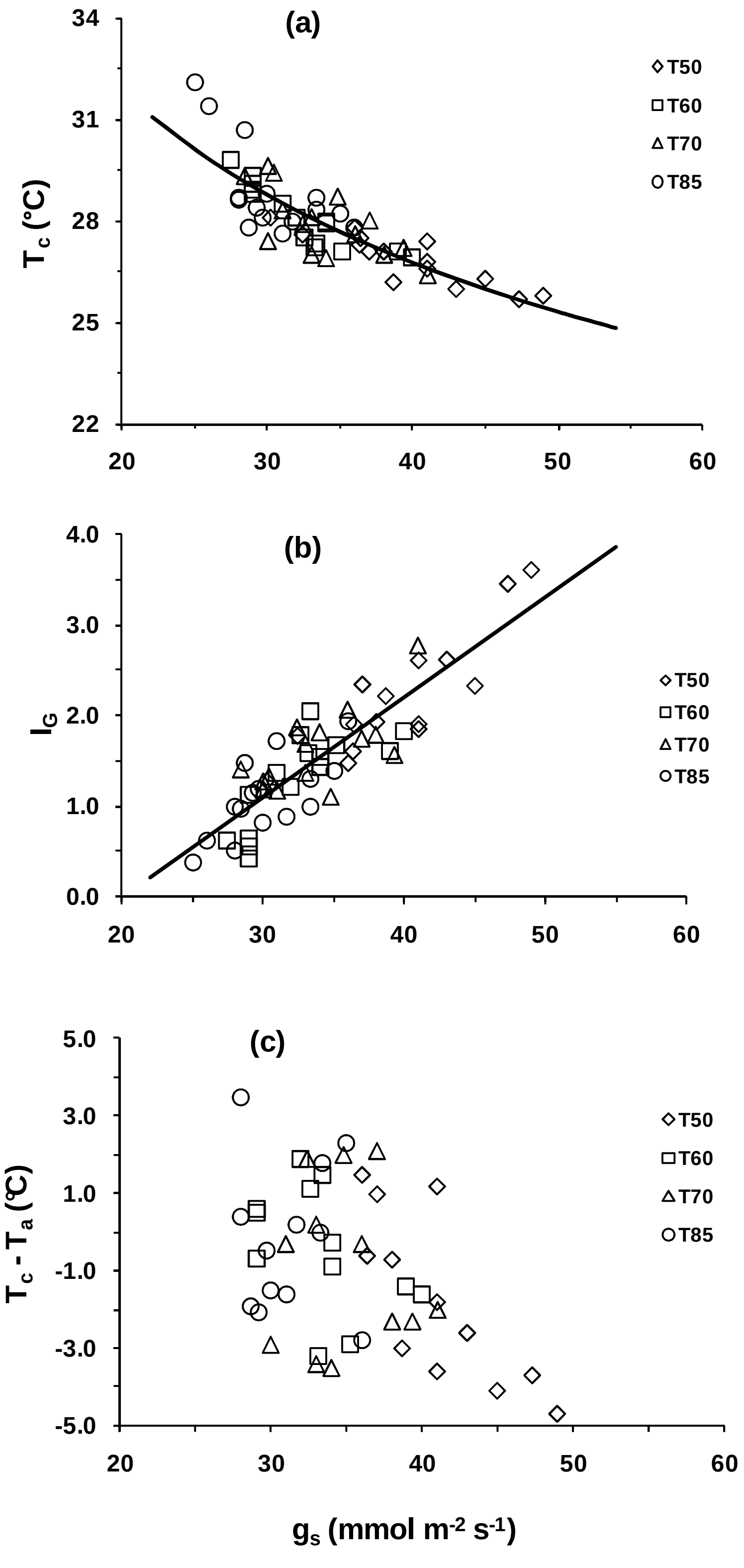


Figure 6. The relationships between (a) canopy temperature (T_c) and (b) stomatal conductance index (I_G) with stomatal conductance (g_s) for various irrigation treatments of cotton during 2008-2009. The difference between T_c and air temperature (T_a) as a function of g_s for the same season is shown in c.

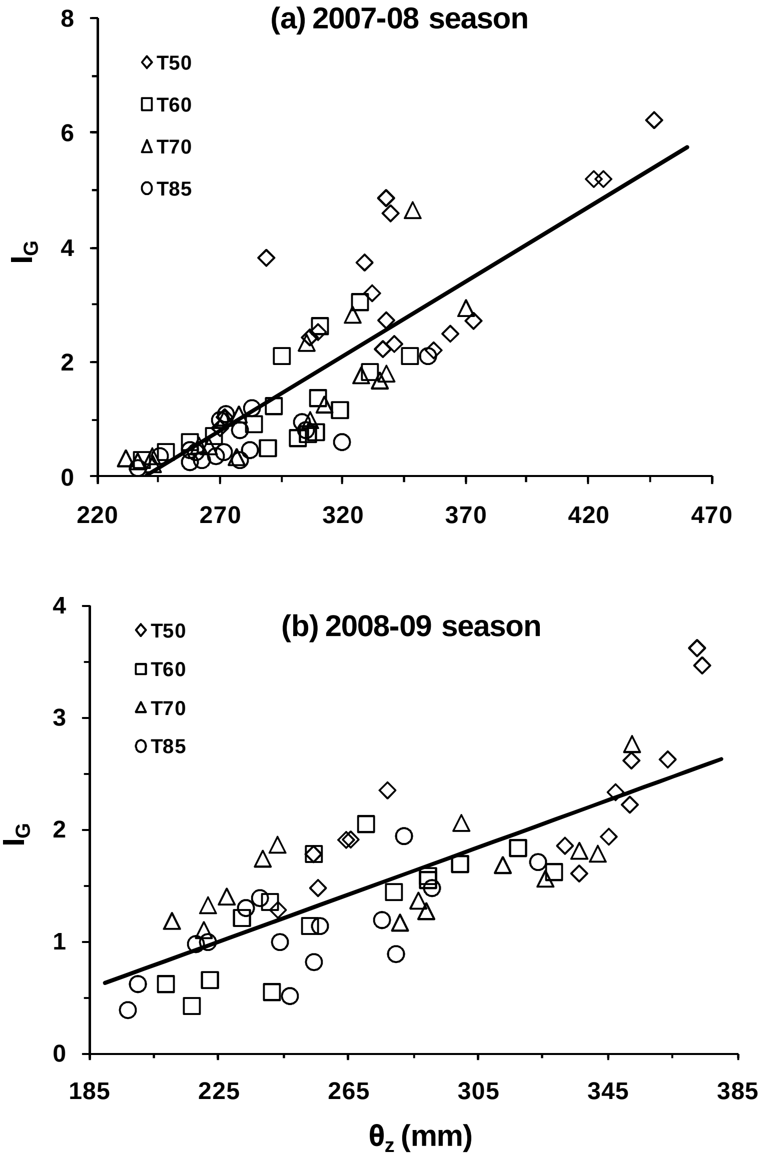
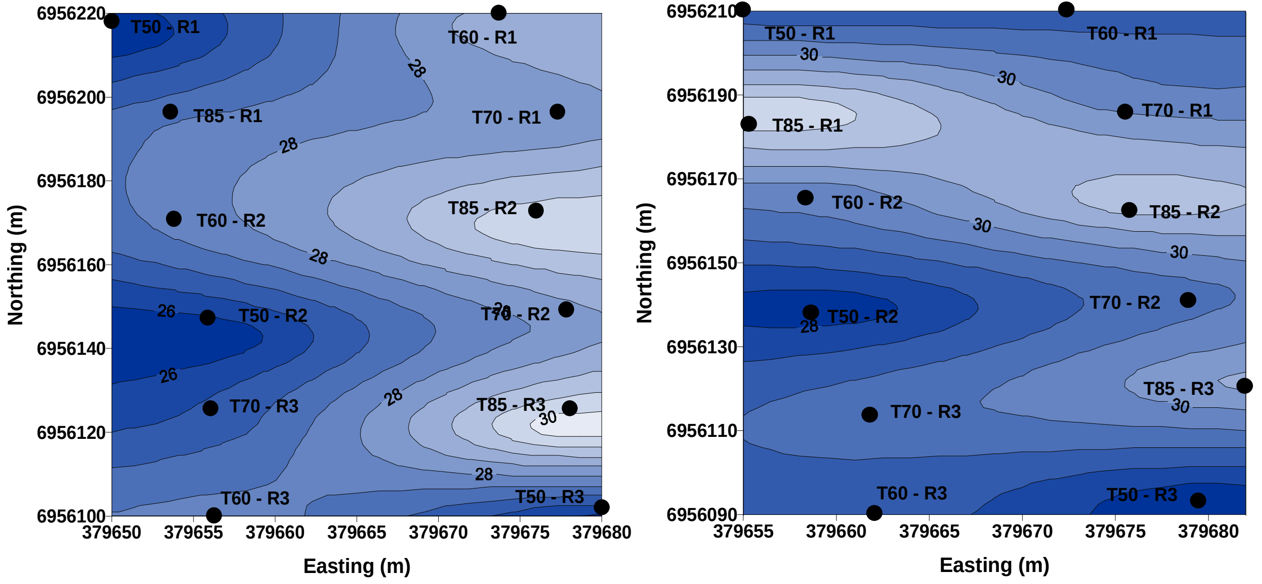
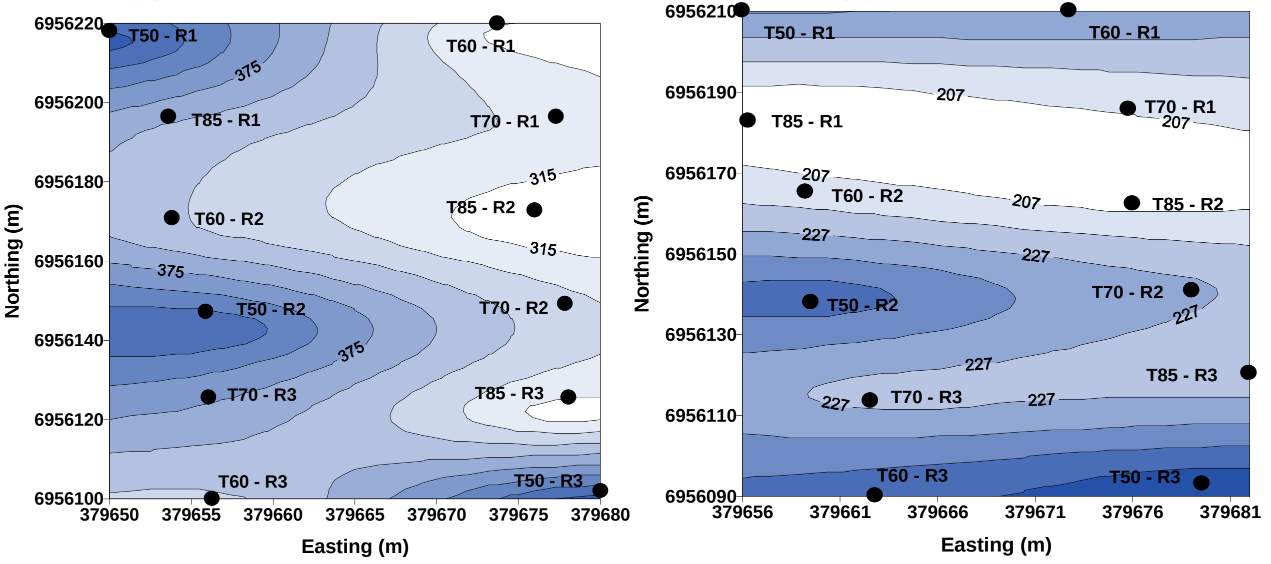


Figure 7. Variation in stomatal conductance index I_G with soil water within the root zone (θ_z) for various irrigation treatments of cotton during (a) 2007-2008 and (b) 2008-2009 seasons.



(a) T_c 2007-08 season

(c) T_c 2008-09 season



(b) θ_z, 2007-08 season

(d) θ_z, 2008-09 season

Figure 8. Spatial variation in canopy temperature (T_c, °C) and soil water within the root zone (θ_z, mm) within the irrigated cotton field (Figs. a, b) at 144 DAP during the 2007-2008 season and (Figs. c, d) at 88 DAP during the 2008-2009 season. Solid circles indicate the position of each measurement for the replicate plots R1, R2 and R3 of irrigation treatments T50, T60, T70 and T85.