Use of infrared thermography to detect water deficit response in an irrigated cotton crop

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Abstract

Infrared thermography is a plant water stress sensing technique that allows acquisition of thermal infrared images of crop canopies with a thermal infrared camera at a high spatial resolution and a thermal resolution of 0.1 °C. Canopy temperature is considered as an indicator of plant water stress and is also used as a tool for irrigation scheduling. In this field study the potential of using infrared thermography to detect water deficit in cotton crop under various irrigation treatments was investigated and also the relationship between canopy temperature and soil water within root zone was explored. Irrigation treatments (T50-T85) were designed to allow soil water depletion down to 50%, 60%, 70% and 85% of the plant available water capacity in soil. Due to the variation in rainfall distribution over the growth period, T85 treatment did not receive any irrigation water. Measurements of profile soil water and canopy temperature were made in 3 replicated plots of 4 irrigation treatments using a randomized block design. In this field experiment we used infrared thermography to measure canopy temperature and profile soil water with a neutron probe on six occasions during the entire period of cotton growth.

Results indicated that thermal imagery was successful in distinguishing irrigated (i.e. T50) and unirrigated (i.e. T85) treatments, with a strong correlations between soil water within the root zone and canopy temperature as measured with the infrared camera. Due to the close correspondence between canopy temperature and soil water within root zone, estimation of crop water stress indices relating to stomatal conductance (I_G) and improved crop water stress index (ICWSI) may not be necessary for irrigation scheduling. Similarities in the pattern of spatial variation in canopy temperature and soil water over the entire crop field could be used to determine soil water deficit such that precise quantity of water can be delivered at various parts over the experimental field.

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Overall, thermography provided a more rapid and convenient approach to detection of crop water deficit stress with potential for commercial application.

Introduction

Mean global temperatures is expected to rise over the next few decades which will increase evaporation rates and cause expansion of arid regions. Thus water availability will be a major limitation to plant growth in the future (Houghton et al., 2001). As a result, irrigation of crops will become an increasingly common practice. The Australian cotton crop occupies some 500,000 ha of which around 85% of the area are irrigated (Dowling, 2001). Irrigation is essential to achieve potential yield in cotton grown in eastern Australia, as in season precipitation is inadequate to meet crop water demand (Tennakoon & Hulugalle, 2006). Cotton crop consumes over 2 million mega litres of irrigation water annually. Therefore water use is a critical issue for the Australian cotton industry. Water use is also important to the irrigator from the point of view of gaining maximum return from a limited resource. Irrigation scheduling is a farmer level decision process which includes when to irrigate and how much water to apply to a crop field. Jones (1990) suggested that greater precision in the application of irrigation can potentially be obtained by the using ‘plant stress sensing’. The most established method for detecting crop water stress remotely is through the measurement of a crop’s surface temperature (Jackson, 1982). When crops are experiencing water shortage, transpiration from the leaves decreases that is expected to reduce both stomatal conductance and water potential of leaves. A decrease in transpiration can also cause insufficient cooling of leaf surface which will ultimately lead to an increase in leaf temperature. Although there are a number of factors which affect actual level of water stress in a plant, leaf temperature is considered as one of the most important factors (Jackson, 1982).

Most of the past studies on detection of water stress in plants have been based on infrared thermometry which involves acquisition of thermal signal from the plant and its surrounding. Thermography, on the other hand, is the process of obtaining thermal images. 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 these to include background noise arising from soil or sky within the field of view in addition to plant canopy which can introduce some bias (Jones and Leinonen, 2003). Recent development 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). Rigorous testing of thermal imaging against more traditional physiological techniques under field conditions is still required for different types of crops (Grant et al., 2006). 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. Therefore, the experiment reported here was carried out to test (1) whether thermal imaging can be used to distinguish between cotton crops growing under different deficit irrigation treatments, (2) if there are any relationships between canopy or leaf temperatures with the soil water within root zone and (3) the usefulness of crop water stress indices: one which corresponds closely with the stomatal conductance (I_G) and an improved crop water stress index (ICWSI, suggested by Jones, 1999).

Materials and Methods

A field experiment with cotton (*Gossypium hirsutum* L.) was conducted at the Queensland Department of Primary Industries and Fisheries (Department of Employment, Economic development and Innovation) experimental station near Kingsthorpe (27°30'44"S, 151°46'55"E, and 431 m elevation). The soil at this site was a haplic, self-mulching, and black vertosol (Isbell, 1996). The field experiment consisted of four irrigation treatments and three replications of each treatment using a randomized block design. Bollgard II cotton variety Sicala 60 BRF was selected for the experiment.

Crop and Irrigation Management

The cotton seeds were sown at a depth of 5 cm on 12th November 2007. Row and plant spacing was maintained at 100 cm and 10 cm, respectively. During sowing, a starter fertilizer containing 10.5% N, 19.5% P and 2.2% S was applied at a rate of 188.4 kg ha^{-1} with an additional supply of 126 kg ha^{-1} of urea. The target planting density for the cotton crop was 11-12 plants m^{-1}. Most of the crop emerged 8 days after sowing and the measured planting density after emergence was 10.9 plants m^{-1}. For weed control, 1 kg ha^{-1} of Roundup was applied with additional mechanical cultivation in all the plots of the field on 9th December 2007. Additional 190 kg ha^{-1} of urea was applied 68 days after sowing. In order to control the pest pale cotton stainer, an insecticide Decis (deltamethrin) was applied at a rate of 200 ml ha^{-1} on 15th March 2008.

Irrigation was imposed within the experimental area when plant water available capacity (PAWC) depleted to 50%, 60%, 70% and 85% (denoted as T50, T60, T70 and T85, respectively). Plant available water capacity (PAWC) is the maximum amount of stored soil water that is available for plant growth (Godwin et al., 1984 and Gardner, 1985). Each replicate plot had a dimension of 13 m × 20 m, which was separated from adjacent plots with 4 m wide buffer. Each replicate plot was irrigated with bore water using a hand-shift solid sprinkler system (Fig. 1). Partial-circle sprinkler heads were used to avoid irrigation of adjacent plots. In order to monitor soil water content within experimental plots over time, neutron access tubes were installed in the centre of each plot. A neutron probe (CPN 503DR, Campbell Pacific Nuclear Inc., Martinez, CA, USA) was used to measure soil water content from surface to a depth of 1.5 m at 0.1 m depth increments. The neutron count ration (n) was converted to volumetric soil water content (θ, $m^3 m^{-3}$) using the calibration equation:

$$\theta = 1.36\,n - 0.44. \qquad (R^2 = 0.86) \qquad (1)$$

Measurements

Thermal images of plants located close to the neutron access tubes were taken from each plot with a thermal infrared camera (NEC TH7800 model, NEC, Japan) that operates within the waveband of 8-14 µm to acquire thermal image (Fig. 2). Images were analysed by Image Processor Pro II software (NEC). Assuming an emissivity of 1.0 for plants has been reported to induce an error of <1°C (Jackson, 1982). The emissivity for plant leaves usually varies from 0.92-0.99 (Rees, 2001, Idso et al., 1969, Sutherland, 1986). The emissivity for cotton canopy selected for this experiment was 0.97 (Wittich, 1997).

Figure 1. Hand shift solid sprinkler system used for application of irrigation water to the cotton crop.

Figure 2. Thermal images of cotton leaves taken by infrared camera.

During thermal imaging the position of thermal imagery in the field was recorded separately with the help of a hand-held GPS (Garmin, Kansas, USA) to allow measurements of spatial variation in canopy temperature within the experiment. Reference 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 for each irrigation treatment at the time of image acquisition of normal leaves. Grant et al. (2006) suggested that the average temperature of areas of canopies containing several leaves is more useful for distinguishing between irrigation treatments than the temperatures of individual leaves as average temperatures over several leaves per canopy is expected to reduce the impact of variation in leaf angles.

Soil moisture content was measured with a neutron probe on the same day as for thermal imaging to explore interrelationships between measurements. Both thermal imagery and soil moisture content measurements were taken 6 times (74, 81, 94, 135, 144, 155 days after planting (DAP)) during the entire cotton season.

Data collected from this experiment were analysed using the analysis of variance recommended for randomised block design (Snedecor and Cochran, 1989). Whenever a measured variable was found to be significantly affected by irrigation treatments ($p \leq 0.05$), mean values were compared with an estimate of least significant difference (LSD).

The temperatures of wet and dry reference leaves were used in the calculation of I_G and ICWSI as detailed below.

The crop water stress index (I_G) is expressed as

$$I_G = \frac{T_{dry} - T_c}{T_c - T_{wet}} \quad , \tag{2}$$

where T_{dry} (°C) is the temperature of the leaf covered with petroleum jelly on both sides, T_c (°C) is the canopy temperature of normal leaf measured with an infrared camera and T_{wet} (°C) is the temperature of leaf sprayed with water on both sides of the leaf. A modified crop water stress index (ICWSI) is given by

$$ICWSI = \frac{T_c - T_{wet}}{T_{dry} - T_c} . \tag{3}$$

It can be seen from Eqns. 2 and 3 that I_G and ICWSI are inversely related to each other.

Results and Discussion

Significant effects of irrigation treatments on canopy temperature and soil water within root zone were detected for 5 of the 6 measurement occasions. Mean values of canopy temperature and soil water within the root zone for these measurement periods are shown in Table 1. For these calculations, root zone depth was assumed to coincide with the depth at which changes in soil water content was negligible on successive measurement period. It can be seen from Table 1 that the canopy temperature for T50 irrigation treatment was consistently lower than the T85 treatment throughout the cotton season because plants under T50 treatment were irrigated more frequently than the plants under T85 treatment. Soil water within the root zone in Table 1 indicated that more frequently irrigated treatment (T50) also remained consistently wetter than the least irrigated treatment (T85). Thus, crop plants when irrigated frequently are not expected to develop high level of internal water deficit stress as soil water availability to plants is not impaired. Lack of significant internal water deficit stress in leaves should allow plants to maintain high transpiration rate that causes a reduction in canopy temperature.

Canopy temperature of cotton decreased linearly with increase in soil water within the root zone that could be represented with a single regression equation (Fig. 3). Regression parameters were also derived for each irrigation treatment separately. The slope, intercept and the coefficient of determination (R^2) value for individual irrigation treatments are shown in Table 2. It can be seen from Table 2 that the slope parameter for T50 was significantly lower than T85, with an intermediate slope for T60 and T70 treatments. Intercept parameters in these regression equations are of limited use as these indicate maximum canopy temperature that would theoretically be reached when soil water in the root zone drops to zero. As plants are expected to reach permanent wilting point at soil water content above this value, canopy temperature indicated by intercepts have little practical use. The extent to which leaves can be cooled below ambient temperature (i.e. air temperature surrounding leaves) due to transpiration is indicated approximately by the slope parameters (Table 2 and Fig. 3).

Table 1. Effects of irrigation treatments on the canopy temperature and soil water within the root zone of cotton at selected measurement dates (indicated as days after planting, DAP).

Measurement dates (DAP)	Root zone depth (cm)	Canopy temperature (°C)				Soil water within root zone (mm)			
		T50	T60	T70	T85	T50	T60	T70	T85
81	80	26.4^b	32.0^a	32.9^a	33.5^a	406.0^b	272.4^a	263.3^a	261.1^a
94	90	25.6^c	27.9^b	30.9^a	29.9^a	430.8^b	342.1^a	310.5^a	319.8^a
135	100	28.7^b	31.8^a	28.2^b	33.1^a	330.0^b	283.3^a	345.6^b	272.1^a
144	110	25.1^b	27.9^a	27.3^a	29.1^a	479.7^b	353.9^a	368.7^a	336.5^a
155	120	26.8^c	30.1^a	28.6^b	31.4^a	390.7^b	314.4^a	330.7^a	299.1^a

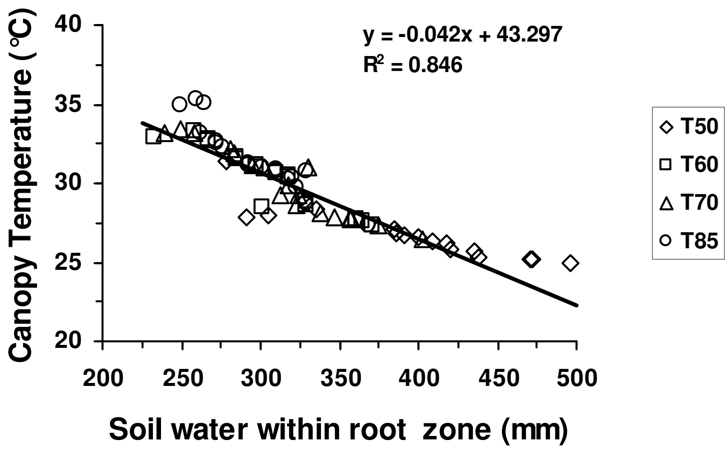

Figure 3. The dependence of canopy temperature on soil water within the root zone.

Table 2. Regression parameters (slope, intercept, R^2 and P-values) for the relationship between canopy temperature and soil water within root zone for individual irrigation treatments. SE indicates standard error (n = 18) of fitted regression parameters.

Treatment	Slope ± SE.	Intercept ± SE	R^2	P-value
T50	-0.024 ± 0.003	36.3 ± 1.0	0.84	≤ 0.001
T60	-0.048 ± 0.004	45.2 ± 1.4	0.88	≤ 0.001
T70	-0.049 ± 0.004	45.5 ± 1.2	0.91	≤ 0.001
T85	-0.064 ± 0.006	50.6 ± 1.7	0.89	≤ 0.001

The water stress index ICWSI commonly varies from 0 to 1 with 0 value indicating plants under no water stress to 1 for plants under maximum water stress. It can be seen from Fig. 4 that ICWSI value was low when the canopy temperature of cotton crop was low. In a similar way, the other water stress index I_G indicated high values when the plants were under less water stress or low canopy temperature (Fig. 5).

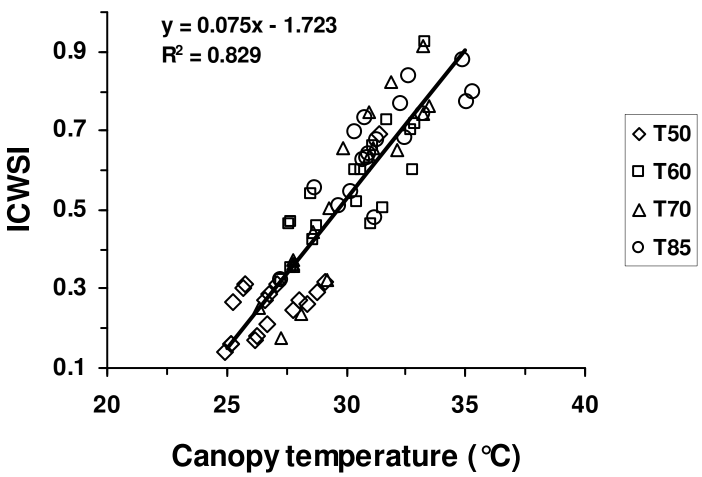

Figure 4. The relationship between canopy temperature and water stress index, ICWSI.

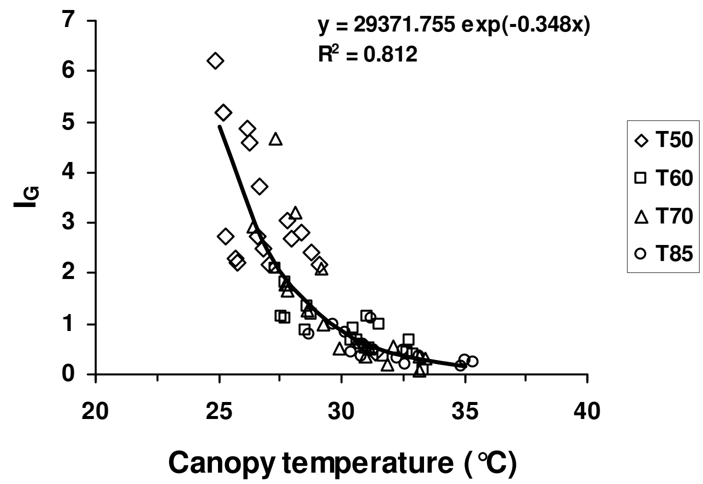

Figure 5. The relationship between canopy temperature and water stress index, I_G.

Figures 6 and 7 show the spatial variation in canopy temperature and root-zone soil water content within the experimental field of cotton. The cross symbols represent the plots which were frequently irrigated (T50) and plus symbols indicating the T85 (unirrigated) plots. We can observe from these figures that when soil water within root zone was high, corresponding canopy temperature was low for those locations. Earlier studies which have used infrared methods for irrigation scheduling are able to indicate stomatal closure or evaporation 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).

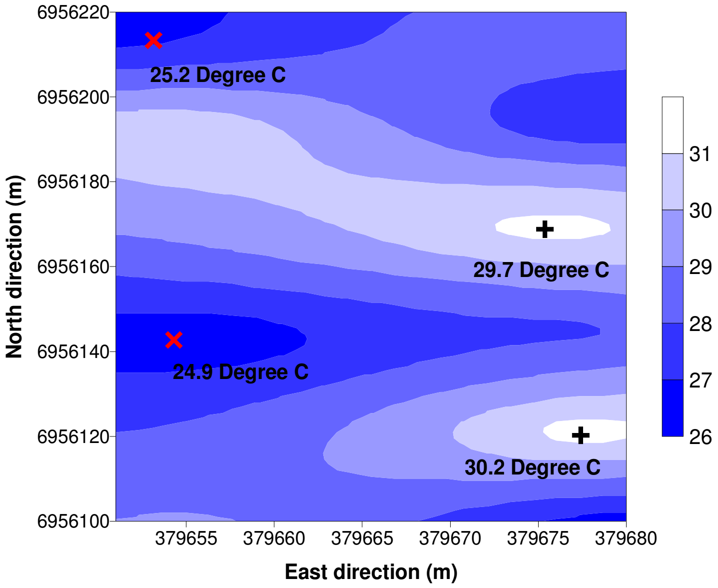

Figure 6. Spatial variation in canopy temperature for T50 and T85 treatments at 144 days after planting. Cross and plus symbols indicate the position of frequently irrigated (T50) and unirrigated (T85) plots, respectively.

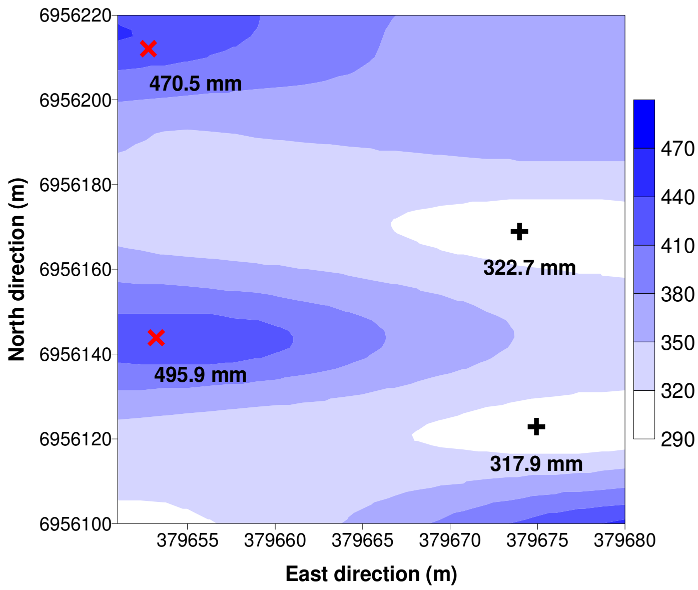

Figure 7. Spatial variation of soil water content within the root zone for T50 and T85 treatments at 144 days after planting. Cross and plus symbols are shown as for the previous figure.

Recent developments in thermal imaging and irrigation control systems are able to open up the possibilities for the development of irrigation control systems to be directly based on thermal imaging of crop water stress. Precision irrigation can be applied to fields of non homogeneous crop by combining thermal imaging so that information on soil water can be derived and used. Precision irrigation will also allow optimising the use of irrigation water by applying the right amount of water at right place so that water stress to crops and losses due to deep drainage can be avoided in the field.

Conclusions

In this study, we have shown that thermal imaging was able to consistently distinguish water deficit in cotton for frequently irrigated (i.e. T50 treatment) and unirrigated (i.e. T85 treatment). Canopy temperature differences found under various irrigation treatments are encouraging to apply thermal imaging for irrigation scheduling. Since empirical relationships between various parameters have been derived for specific crop and soil conditions these are site specific in nature. Further studies are required to obtain more general relationships between canopy temperature and soil water. General relationships will also overcome the need for estimation of ICWSI and I_G indices which require measurements of dry and wet reference leaves. Overall, thermography provides a more rapid and convenient approach to detection of crop water deficit stress with potential for commercial application.

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