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The relationship between cotton canopy temperature and yield, fibre quality and water-use efficiency

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ABSTRACT

Crop canopy temperature (T_c) is associated with transpiration and T_c has been used in crop water stress detection. This study investigates the effect of surface drip and furrow irrigation regimes on cotton T_c. It outlines the relationship between T_c and lint yield, fibre quality and both agronomic (WUE$_a$, kg ha^{-1} mm^{-1} total applied water) and leaf level water-use efficiency (WUE$_l$, μmol[CO$_2$] mmol[H$_2$O]$^{-1}$) in a high input, high yielding (>1800 kg ha^{-1}) cotton system. Canopy temperature between flowering and crop maturity was monitored. Yield reductions occurred when T_c exceeded 28 °C. Reductions in fibre length outside the ideal range (>28.6 mm) occurred when T_c exceeded 31 °C, while desirable micronaire (3.8–4.5) was observed at T_c between 25 and 32 °C. Desirable fibre quality and peak lint yield can be realised if an irrigation scheduling protocol maintains average canopy temperatures below 28 °C. However, maximum WUE$_a$ was observed at a higher average T_c (30 °C) than peak lint yield (28 °C), which would correspond to a predicted 23% reduction in lint yield from the peak (3030 kg ha^{-1}). Therefore, the trade-off between peak yield and WUE$_a$ needs to be considered in conjunction with irrigation water costs and availability when scheduling irrigations based on canopy temperature.

1. Introduction

Plants are natural integrators of their environment and stress conditions. The use of plant-based stress detection tools should provide accurate insights into plant stress response, especially when used in combination with the monitoring of soil and climatic conditions (Conaty et al., 2014). By placing the focus on the crop, greater accuracy in water stress detection, and hence irrigation scheduling may be made. This is because a plant-based measure of water stress will indicate when it is best to irrigate in the context of the crop, while knowing the soil water deficit does not directly provide this information. Thus, a more detailed picture of crop water deficits and stress within a cropping system can be obtained. Plant based stress detection tools may be particularly useful in those instances where measurements can be made near-continuously over seasonal timeframes (Mahan et al., 2014). This is important as water stress fluctuates over diurnal and seasonal timescales within a continuously variable environment. Water stress develops and is alleviated in a cyclic manner over a growing season, with crops experiencing water stress of varying intensity and duration at all developmental stages. Continuous data collection ensure that the magnitude and intensity of water deficits can be monitored over discrete and extended timeframes, providing a full season stress signature (Mahan et al., 2010).

The focus of this paper is the interpretation of continuously collected crop canopy temperature (T_c) data for use as an indicator of field crop water stress. The basis of using T_c for crop water stress detection is that transpiration (the evaporation of water from the leaf) results in cooling of the leaf, providing a platform for determin-

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Abbreviations: Avg., average; DAP, days after planting; IRT, infra-red thermometer; T_a, ambient temperature; T_{max}, maximum ambient temperature; ET$_c$, crop evapotranspiration; ET$_o$, grass reference (standard conditions) evapotranspiration; K$_C$, crop factor; NAM, neutron attenuation meter; T$_c$, canopy temperature; VPD, vapour pressure deficit; WUE$_a$, agronomic water-use efficiency (kg [lint] ha^{-1} mm^{-1} total applied water); WUE$_l$, leaf level water-use efficiency or transpiration ratio (μmol[CO$_2$] mmol[H$_2$O]$^{-1}$).

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ing plant water status from canopy temperature measurements. As the soil water available to the plant declines, the transpirational cooling of the plant is reduced, which results in an increase in plant temperature. The use of plant temperature as an indicator of plant water status has historically been defined with respect to a reference temperature such as air temperature (T_a), or the temperature of a well-watered plant (Idso 1982; Fuchs, 1990; Jackson et al., 1981). However, this study investigated the relationship between irrigation regime and canopy temperature in the context of a biological optimum plant temperature.

The biological optimum temperature concept (Mahan et al., 2005) was assessed in the context of water stress. Previous studies have evaluated the optimum thermal environment for growth and metabolism, placing the thermal optimum for cotton at 28 °C, over a range of 25–31 °C (Burke, 1990; Burke et al., 2004; Conaty et al., 2012; Hatfield and Burke, 1991; Mahan et al., 2000). The risk associated with inefficient irrigation management is that plants will be unable to maintain *in vivo* temperatures at an optimum for metabolic functions, resulting in plant stress and potential yield reductions. When plants are grown at ambient temperatures exceeding their optimum, reductions in vegetative and reproductive growth, reduced pollen viability and high rates of fruit abscission can occur (Reddy et al., 1991; Singh et al., 2007). Although the growth and development of cotton is thermally dependent (Constable, 1976), heat unit assessments in cotton become less useful under water deficit conditions (Peng et al., 1989) and the relationship between air and canopy temperature becomes more variable under water deficits (Mahan et al., 2012; Jackson et al., 1981). Thus, the use of canopy temperature to assess plant growth and development in a limited water context may be more reliable than air temperature alone (Mahan et al., 2014).

This study aimed to assess the use of canopy temperature as a means of providing a measure of water stress, which can account for seasonal differences in temperature, evaporative demand and soil water availability. This was achieved by determining the effect of irrigation practices on canopy temperature and the subsequent relationship between canopy temperature and lint yield, fibre quality and water-use efficiency. Canopy temperature was evaluated in the context of a specific thermal optimum for a given crop. To the best of our knowledge, there has been limited research of this nature conducted under deficit irrigation practices, particularly furrow irrigation systems.

2. Materials and methods

This study investigates canopy temperature and how it related to lint yield, fibre quality and water-use efficiency. Experiments were established in the summer growing seasons of 2007/08 and 2008/09 at the Australian Cotton Research Institute (ACRI) (30° 12′s, 149°36′E), 22 km north–west of Narrabri NSW, Australia. Experiment 1 was planted on Oct. 5th 2007, Experiment 2 was planted on Oct. 14th 2008 and Experiment 3 was planted on Oct. 15th 2008. A row spacing of 1 m was used with a planting density of 10 plants m^{-2}.

Management for all field experiments followed current high-input commercial practices with weed and insect control as per standard recommendations for Bollgard II®, Roundup Ready Flex® cultivars (Monsanto Australia Ltd., 2012a,b). Each experiment was managed according to its individual requirements for fertiliser and pest control, with all plots receiving the same management regime except for the irrigation treatments imposed.

2.1. Genotype selection

All experiments used the Commonwealth Scientific and Industrial Research Organisation (CSIRO) developed cultivar Sicot 70BRF. Sicot 70BRF was chosen to represent a standard, modern, commercial Australian cultivar as it (and its related replacement, Sicot 71BRF) have been the most widely grown cultivars in Australia between 2007 and 2010 (Cotton Seed Distributors, Personal Communication, 2010). Sicot 70BRF is a full season cultivar with compact growth habit, high yield potential, good disease resistance and good fibre quality, performing well in all Australian production regions (Cotton Seed Distributors, 2009). Sicot 70BRF is reported to have a high lint proportion (0.41), medium fibre length (30.0 mm), high strength (31.0 g Tex^{-1}) and a good micronaire (4.3) (Cotton Seed Distributors, 2009). Sicot 70BRF is a *Bt* transgenic Bollgard II®™ variety (producing the Monsanto Cry1Ac and Cry2Ab proteins) for resistance to *Helicoverpa* spp. larvae damage and tolerance to the glyphosate (Roundup®) family of herbicides (Monsanto Australia Ltd., 2012a,b).

Table 1
Weather conditions observed during 2007/08 and 2008/09 from planting to maturity (0 to ~2050 day degrees; 60% open bolls).

	2007/08	2008/09
Avg. maximum T_a (°C)	30.5	32.1
Avg. minimum T_a (°C)	15.8	17.0
$T_{max} > 35$ °C (d)[a]	20	38
Avg. total solar radiation (MJ m^{-2} d^{-1})	23.7	25.1
Total rain (mm)	353.6	354.0
Avg. air wind speed (m s^{-1} d^{-1})	4.1	4.3
Avg. maximum air VPD (kPa d^{-1})	3.1	3.8
Days to 2050 day degrees[b] (d)	180	162
Grass reference evapotranspiration (mm) (ET_o)	920	905

[a] Represents temperature stress days, where the maximum $T_a > 35$ °C (Bange et al., 2010b).
[b] Calculated from a base temperature of 12 °C.

2.2. Site description

The study region is semi-arid, characterised by mild winters, hot summers and summer-dominant rainfall patterns, with an annual average precipitation of 646 mm (Aust. BOM, 2014). The soil of the site is a uniform grey cracking clay (USDA soil taxonomy: Typic Haplustert; Australian soil taxonomy: Grey Vertosol). Weather data from season 1 (2007/08) and season 2 (2008/09) was monitored with a weather station using the recommendations of the ASAE (Allen et al., 2005). The weather station was located above a grass reference 400 m from the field experiments and weather data are presented in Table 1. Plant available soil water to 1.2 m at the site is between 160 and 180 mm (Tennakoon and Hulugalle, 2006).

2.3. Experimental design and plot management

2.3.1. Surface drip irrigation

A randomised complete block design with five replicates of five irrigation treatments was used for surface drip irrigation experiments (Experiments 1 and 2). Surface drip irrigation tape (T-Tape, T-Systems Australia Pty Ltd., Brendale, QLD, Australia) was installed adjacent to the plant line, i.e., the ridge of the 1 m spaced beds. Irrigation treatments were imposed to generate differences in canopy temperature. These treatments were based on daily reference evapotranspiration (ET_o) rates, which include a control or theoretical optimum, an excessive and three deficit irrigation regimes (Table 2). Daily irrigation rates were calculated according to Allen et al. (1998) where the daily crop evapotranspiration (ET_c) is equal to the product of a grass reference ET_o and a locally calibrated crop factor (K_C). ET_o was calculated using on-site weather station data and the Penman–Monteith equation (Allen et al., 1998). The K_C used was based on recent experimental data by the CSIRO cotton agronomic management program over a number of growing seasons at the same site (Yeates, 2009). A validation of the crop factor using

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