Field Crops Research 126 (2012) 45–55

Contents lists available at SciVerse ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

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

J. Padhi[a], R.K. Misra[a,*], 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

ARTICLE INFO

Article history:
Received 30 April 2011
Received in revised form
22 September 2011
Accepted 23 September 2011

Keywords:
Canopy temperature
Irrigation
Leaf water potential
Soil water deficit
Stomatal conductance
Stomatal conductance index
Thermal imagery

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.

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 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,

---

* Corresponding author. Tel.: +61 7 46312805; fax: +61 7 46312526.
E-mail address: misrar@usq.edu.au (R.K. Misra).

0378-4290/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.fcr.2011.09.015

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 (De Tar 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