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Research Paper

A practical method using a network of fixed infrared sensors for estimating crop canopy conductance and evaporation rate[☆]

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We describe the development and testing of a novel thermal infrared sensor incorporating a dry reference surface for incorporation into field wireless sensor networks (WSNs) that allows the estimation of absolute transpiration rates and canopy conductance. This 'dry reference' sensor provides a physical reference surface that mimics the temperature of a non-transpiring canopy and can therefore be used in conjunction with canopy temperature to estimate either canopy transpiration or canopy conductance. The dry reference sensor is based on a hemispherical surface that mimics the distribution of shaded and sunlit leaves in non-transpiring canopy. Three dry reference sensors were deployed in a commercial cotton crop from which canopy transpiration and conductance was estimated for the entire season. We provide evidence that fixed infrared sensors with a dry reference surface, when combined with limited meteorological data, can provide useful continuous monitoring of crop water use and canopy conductance that is potentially of value for irrigation management and crop phenotyping applications. Key to the success of this dry sensor application is the requirement that the spectral absorptance of the sensor is tailored to match the crop of interest.

1. Introduction and theory

Evapotranspiration from crops is a critical determinant of crop water balance and the transpiration component has also been widely used (see e.g. Jones, 2014) as an indicator of crop water deficits and a need for irrigation. This is because an early response to any water deficit is often stomatal closure (especially in so-called anisohydric plants) and hence reduced

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transpiration. Because evaporation of water requires energy, increases in evaporation rate tend to lower canopy temperature; this has led to the widespread use of thermal infrared sensing of canopy temperature as an indirect tool for estimation of both evaporation from crops (Allen, Tasumi, & Trezza, 2007; Bastiaanssen, Menenti, Feddes, & Holtslag, 1998; Jones & Vaughan, 2010; Kalma, McVicar, & McCabe, 2008) and of stomatal conductance (Blonquist, Norman, & Bugbee, 2009; Guilioni, Jones, Leinonen, & Lhomme, 2008; Leinonen, Grant, Tagliavia, Chaves, & Jones, 2006; Qiu, Momii, & Yano, 1996; Qiu, Yano, & Momii, 1996).

Most early measurements of canopy temperature utilised simple inexpensive radiometers with a single field of view. These have been widely used since the 1980s, both for irrigation scheduling using approaches such as the Crop Water Stress Index (Idso, Jackson, Pinter, Reginato, & Hatfield, 1981; Jackson, 1982) and for screening genotypes for stomatal differences (Amani, Fischer, & Reynolds, 1996; Rebetzke, Rattey, Farquhar, Richards, & Condon, 2013; Reynolds et al., 1998; Saint Pierre, Crossa, Manes, & Reynolds, 2010). The recent development of relatively affordable thermal cameras has greatly stimulated the use of thermal imaging as an important tool for the study of plant water relations and for irrigation scheduling and in many applications has largely replaced the use of simple thermal radiometers (Deery et al., 2016). The fact that canopy temperature is determined at any time not only by transpiration rate, but also by a wide range of environmental factors including air temperature, irradiance, wind speed and humidity, has led to the development of a number of approaches for normalising the data (see e.g. Maes & Steppe, 2012), often based on the use of reference surfaces designed to simulate the radiative and aerodynamic properties of the leaves in the canopy (Grant, Ochagavía, Baluja, Diago, & Tardáguila, 2016; Jones, 1999a, 2004; Leinonen et al., 2006; Maes et al., 2016).

Although the use of thermal imaging systems is becoming increasingly widespread, there are, however, many applications both for plant breeding and for irrigation management where there can be substantial advantages in being able to record canopy temperatures continuously using fixed thermal sensors. The development of simple infrared thermometers (IRT) for field application that can be incorporated into a wireless sensor network (WSN) has been described previously (Rebetzke, Jiminez-Berni, Bovill, Deery, & James, 2016). Although such sensors can give continuous comparative canopy temperature records, they cannot be used to estimate absolute evaporation rates or conductance without further information.

In this paper we outline an extension to the use of these IRT networks for the estimation of absolute crop evaporation rates and of crop canopy conductance that makes use of novel dry reference surfaces (Jones, 1999a) that better mimic the radiative properties of the crop canopy.

2. Theory

Remote sensing from satellites is widely used to estimate evaporation based on the energy balance, but because of the difficulty of estimating the transfer resistances, evaporation is usually estimated only as the residual term in the energy balance, assuming that radiation and heat transfer are known (Allen et al., 2007; Bastiaanssen et al., 1998; Jones & Vaughan, 2010). In this study we concentrate on the potential of proximal sensing of canopy temperature for the accurate estimation of transpiration or canopy conductance from canopy temperature measurements.

One approach is to combine IRT measurements of canopy temperature with simultaneous recordings from a local meteorological station of air temperature, net radiation absorbed, wind speed (and hence boundary layer conductance) and humidity, and to substitute these values into the full energy balance equation (Berni, Zarco-Tejada, Sepulcre-Cantó, Fereres, & Villalobos, 2009; Jones & Vaughan, 2010; Jones, 2004). An alternative approach that can reduce the requirement for meteorological data, especially the somewhat difficult-to-measure net radiation, is to measure the temperatures of simple fully transpiring or non-transpiring physical reference surfaces that mimic the radiative and aerodynamic properties of the plants being studied (Jones, 1999a, 1999b). The theory for estimation of transpiration/evaporation or leaf conductance from leaf temperature using references has been developed previously (Guilioni et al., 2008; Leinonen et al., 2006) but will be briefly summarised below. The relevant equations have been incorporated into a Python programme for data calculation and presentation.

2.1. Evaporation rate

The evaporation or transpiration rate (Et) can readily be shown to be linearly related to the difference between the temperature of a dry non-transpiring surface having similar radiative and aerodynamic properties to the canopy, and the actual canopy temperature according to the following (Jones, 2014)

$$Et = \alpha g_{HR}(\rho c_p)(T_{dry} - T_s) \quad (1)$$

where α is an scaling factor, g_{HR} (m s^{-1}) is the parallel conductance (Jones, 2014) to heat (g_{aH}) and radiative transfer ($g_R = 4\varepsilon\sigma T_a^3/\rho c_p$), ρ and c_p are the density and specific heat of air, ε is the surface emissivity, σ is the Stefan-Boltzmann constant, and T_{dry} and T_s, respectively, are the temperatures (K) of a dry reference surface and the canopy. In practice, the value of Et obtained from Equation (1) was multiplied by a scaling factor, α, chosen to achieve consistency with reference evapotranspiration ($Et0$) as derived from meteorological data according to FAO56 (Allen, Pereira, Raes, & Smith, 1998) (i.e. reaching but not exceeding $Et0$). This scaling factor corrects for errors in T_{dry} arising from sensor calibration errors including incorrect spectral absorptance of the dome.

2.2. Canopy conductance

The theory for the estimation from canopy temperature of the canopy conductance to water vapour transfer (g_W) has been described previously (Guilioni et al., 2008; Leinonen et al., 2006), giving rise to the following full energy balance equation

$$g_W = \gamma((R_{ni}/\rho c_p) - g_{HR}(T_s - T_a))/(\mathbf{s}(T_s - T_a) + D) \quad (2)$$

where γ is the psychrometric constant (Pa K^{-1}), R_{ni} is the net isothermal radiation (W m^{-2}), T_a is the air temperature (K), $\mathbf{s}$ is