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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), **s** is the rate of change of saturation vapour pressure with temperature (Pa K^{-1}), and D is the vapour pressure deficit (Pa). There are slight differences in formulation when this is used to determine the overall canopy conductance of a single leaf or a canopy, owing to the fact that single leaves have two sides, here we use the one-sided version appropriate for canopies. The overall canopy conductance is partitioned into the conductance (g_s) relating to transpiration through the stomata and the transfer through the boundary layer (g_a), though for a leaf with differing stomatal conductances on the two surfaces the two terms cannot be completely separated (Jones, 1973).

Where one has a dry reference temperature, Equation (2) reduces to (Leinonen et al., 2006)

$$g_W = g_{HR}\gamma(T_{dry} - T_s)/(\mathbf{s}(T_s - T_a) + D) \quad (3)$$

where T_{dry} is the temperature of the dry reference. Note that this equation eliminates the need for an accurate estimate of the net radiation.

2.3. Estimation of boundary layer conductance

A critical variable for the above equations is the boundary layer conductance (g_{aH}). Conventionally g_{aH} is estimated at a leaf scale from aerodynamic theory using the relationships between wind speed and leaf size using

$$g_{aH} = 6.62(u/l)^{0.5} \quad (4)$$

where u is the wind speed (m s^{-1}) and l is the characteristic dimension of the leaf (m), assumed equal to 0.05 m for cotton. In this study, we used wind profile theory (Jones, 2014; Monteith & Unsworth, 2008) to estimate wind speed at the top of the canopy (u_z) from that at a nearby anemometer at a height of 4.5 m ($u_{4.5}$), according to

$$u_z = u_{4.5}{*}\ln((z - d)/z_o)/\ln((4.5 - d)/z_o) \quad (5)$$

where u_z is the wind speed at canopy height z, z_o is the roughness length (assumed equal to 0.64*z for cotton), and d is the zero plane displacement (assumed equal to 0.13*z for cotton) and then estimated boundary layer conductance using Equation (4). As an alternative, at the canopy scale, it is possible to estimate g_{aH} from wind profile theory (Jones, 2014; Monteith & Unsworth, 2008) as

$$g_{aH} = k^2u_z\Big/[\ln((z - d)/z_o)]^2 \quad (6)$$

where κ is von Karman's constant (=0.41).

An alternative approach that is well adapted to the leaf scale and for continuous monitoring in the field would be to calculate g_{aH} from the temperatures of heated and unheated replica leaves mounted in the canopy (Brenner & Jarvis, 1995).

3. Materials and methods

3.1. Sensor construction

The ArduCrop wireless canopy temperature system comprises wireless infrared temperature sensors specifically designed for continuous measurement of crop canopy temperature under harsh field conditions. An individual ArduCrop sensor (Fig. 1) is similar in design to that described by O'Shaughnessy, Evett, Coliazzi, and Howell (2011), O'Shaughnessy, Hebel, Evett, and Colaizzi (2011) and uses an infrared thermometer sensor (MLX90614-BCF from Melexis, Ypres, Belgium) with a 35° field of view, resolution of 0.02 °C and an accuracy of ±0.5 °C from 0 to 50 °C. This specification was checked for each ArduCrop sensor before and after deployment with a Landcal P80P black body radiation source (Land Instruments, Leicester, United Kingdom). Temperature data are recorded at 1 s intervals on an Arduino microcontroller and 1 min averages are transmitted via ultra-high frequency (UHF) radio to a base station in the field. The base station, equipped with a 3G modem, sends data every 15 min directly to the SensorDB website (http://sensordb.csiro.au, see Salehi et al., 2015) for real time data access and preliminary visualisation and analysis through an online web portal. The ArduCrop sensor is height adjustable to ensure that a consistent height above the crop canopy is maintained throughout the crop growing season. An individual ArduCrop sensor is normally positioned so as to view the canopy from an angle to the individual rows to minimise the chance of viewing background soil, and facing approximately North (Southern hemisphere) to give the most consistent canopy temperature by avoiding the sunlit side of the canopy (see Jones et al., 2002). An online 11 min video of the installation method is available here (https://www.youtube.com/watch?v=8iMr03X6y7g).

3.2. Development of a reference surface

A wide range of approaches to obtaining reference temperature data have been proposed, from the use of reference crops growing under the same environmental conditions (Idso, 1982), through various physical references (see Maes and Steppe (2012) for a review). Most previous workers have used flat reference surfaces, but their disadvantage is that they cannot well represent the range of illumination experienced by typical leaves in a crop canopy. For the temperature data from the reference sensor to be valid, solar radiation absorptance and emissivity need to be similar, and it also needs to match the illumination distribution of the actual canopy (Jones et al., 2009). To this particular end, a hemispherical reference surface, developed from an original idea by Dr Brian Loveys (personal communication) was prototyped in this study (Fig. 1), alias “ArduCrop dry reference”. The ArduCrop dry reference sensor comprises two infrared thermometer sensors (35° field of view, MLX90614-BCF from Melexis, Ypres, Belgium): 1) a downward-looking sensor to measure the canopy temperature and; 2) the dry reference, based on an upward-looking sensor mounted inside a green hemispherical dome made of thin plastic (based on a half table-tennis ball, <0.5 mm thick). Though not directly measured, the effective emissivity of the inside of the dome was likely to be close to unity as it comprises part of an enclosed near-isothermal surface (Jones & Vaughan, 2010). The ArduCrop dry reference used the same data recording and data transmission system as described above for the ArduCrop sensor. A key feature of the dry reference surface is the solar absorptivity of its surface, which depends on the choice of paint; results of some tests of different colour paints are outlined in Section 4.2 below.

Fig. 1 – Custom developed ArduCrop wireless infra-red canopy temperature sensor (left) and ArduCrop dry reference sensor (right). The ArduCrop dry reference sensor comprises two infrared thermometer sensors (MLX90614-BCF from Melexis, Ypres, Belgium): 1) a downward-looking sensor to measure the canopy temperature (obscured) and; 2) an upward-looking sensor mounted inside a green hemispherical dome made of plastic, the dry reference. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The effect of directional solar radiation on the temperature distribution across the hemispherical surface of the dry reference sensor is illustrated for hot dry conditions in Fig. 2. Under such conditions the temperature ranged from 28.5 °C to 32.6 °C, depending on the orientation of the particular part of the surface. The average temperature over the hemisphere was 30.7 °C.

3.3. *Data handling*

Data were uploaded to SensorDB (Salehi et al., 2015) for archiving, visualisation and preliminary analysis. Other analyses used Microsoft Excel and Python 3.5 (Python Software Foundation, https://www.python.org). Reference evapotranspiration, *Et0* was calculated using the standard meteorological station data according to FAO56 (Allen et al., 1998). Canopy conductance (g_W) was estimated either from the ArduCrop canopy temperature and meteorological data using the full energy balance (Equation (2); referred to as Cond. (energy balance)) or from both the canopy temperature and the dry reference temperature using Equation (3) (referred to Cond. (T_{dry})). Canopy evapotranspiration (*Et*) was calculated from Equation (1) and referred to as *Et* (T_{dry}). Canopy evapotranspiration and conductance were calculated from Equations (1) and (3)) respectively, by approximating T_{dry} as $T_a + 5$ °C (Ben-Gal et al., 2009; Irmak, Haman, & Bastug, 2000; Meron, Tsipris, Orlov, Alchanatis, & Cohen, 2010) and are referred to as Cond. ($T_{dry} = T_a + 5$) and *Et* ($T_{dry} = T_a + 5$). Further, T_{dry} was calculated from the full energy balance by solving Equation (3) for T_{dry} and setting g_W to Cond. (energy balance), derived from Equation (2).

3.4. *Experimental details*

i) Three ArduCrop dry reference sensors, together with a standard Meteorological station (Hussat Pty., Hanwood 2680, NSW, Australia), were deployed over representative areas of a commercial cotton crop (variety: 71BRF; spacing: 18 seeds m^{-1}; row spacing: 1 m) near Darlington Point, NSW, Australia, "Kulki farm", from 8 Dec 2014 to 16 March 2015. The ArduCrop dry reference sensors were placed at three sites across the cotton field. The cotton crop was sown on 3 Dec 2014. Aside from missing data from 26 to 30 Jan 2015 for the Meteorological station, data recovery from the ArduCrop dry reference sensor and Meteorological station were excellent. Data are presented as the mean and standard deviation of the three ArduCrop dry reference sensors. For this experiment a value 0.5 for α was found to scale *ET* appropriately to *Et0* for the fully irrigated crop after achievement of full ground cover (around 22 Dec 2014).
ii) Another cotton crop was grown at the Australian Cotton Research Centre at Narrabri, NSW, Australia. The cotton crop was sown on 15 Oct 2015 on furrow beds with 1 m spacing between planting rows. This was used for some tests of the ArduCrop deployment. In particular, we tested sensor orientation effects and compared ArduCrop dry reference readings with the temperature of the untreated (well-irrigated) field crop, and with a non-transpiring crop

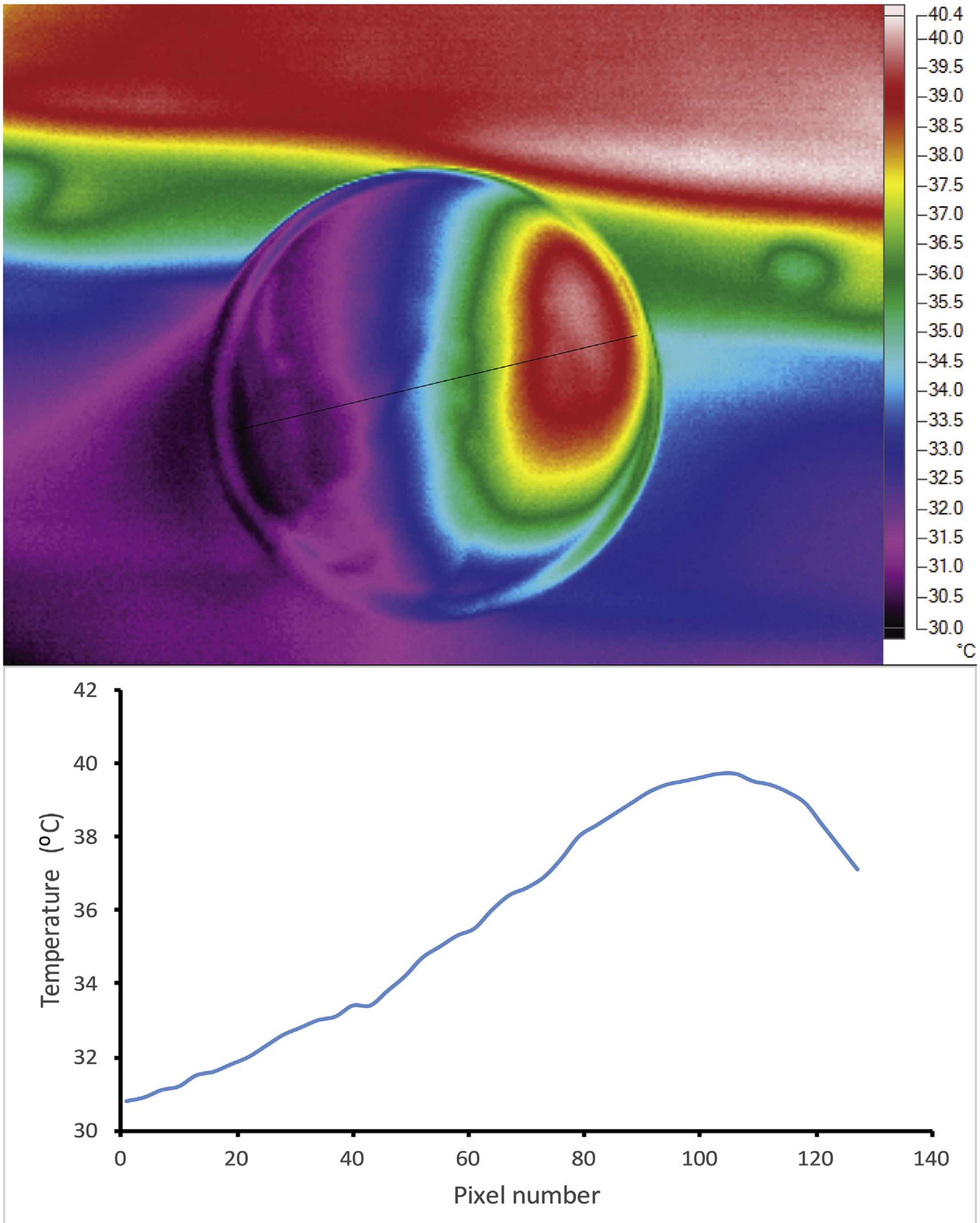

Fig. 2 – The upper panel shows the temperature distribution across a dry reference hemisphere in bright sunlight and low wind conditions, as recorded by the thermal camera. The temperature profile along the line across the centre of the dome is plotted in the lower panel.

where transpiration had been inhibited by covering leaves within the infrared sensor field of view with petroleum jelly (Vaseline). All measurements were taken within 12 h of the Vaseline treatment, before tissue death was apparent. Other areas of canopy were sprayed with water (containing a wetting agent) as a wet reference crop (Jones, 1999b) with temperatures recorded within a couple of minutes of spraying (but avoiding the first 30 s). For this crop, ground cover was complete so no correction for background soil was necessary.

Thermal images were obtained using a FLIR SC660 (FLIR Systems, Oregon, USA) longwave infrared camera (spectral range of 7.5–13 μm), having a spatial resolution of 640 pixels × 480 pixels, accuracy of ±2 °C or ±2% of reading; <0.05 °C pixel sensitivity; and temperature range from −40 °C to +1500 °C. Images were analysed using FLIR Thermacam ResearcherIR software. These images were obtained from a comparable view angle and distance to ArduCrop data, with data only used for a comparable field of view selected in the ResearcherIR software. These data were used as an independent check on ArduCrop readings.

4. Results

4.1. *Relationship between temperature readings from ArduCrop and thermal camera*

The relationship between the canopy temperature readings obtained by the ArduCrop and the thermal camera for similar areas of canopy are shown in Fig. 3. Although the camera on average tended to give a slightly higher temperature than the ArduCrop, this difference may have related to a small difference in calibration, or possibly to slight differences in orientation of sensors. The larger difference between instruments for the dry canopy may have been because of incomplete Vaseline cover in the ArduCrop field of view, while the camera selected only clearly treated leaves. Where tested, the temperature recorded by the ArduCrop dry reference was compared with the average temperature of the dome as recorded by a camera. Overall the agreement was good with the average difference between camera and ArduCrop ranging from −0.5 °C (when the average dome temperature was 38.8 °C) to 1.8 °C (when the average dome temperature was 26.0 °C) over three separate occasions with three reference domes in operation.

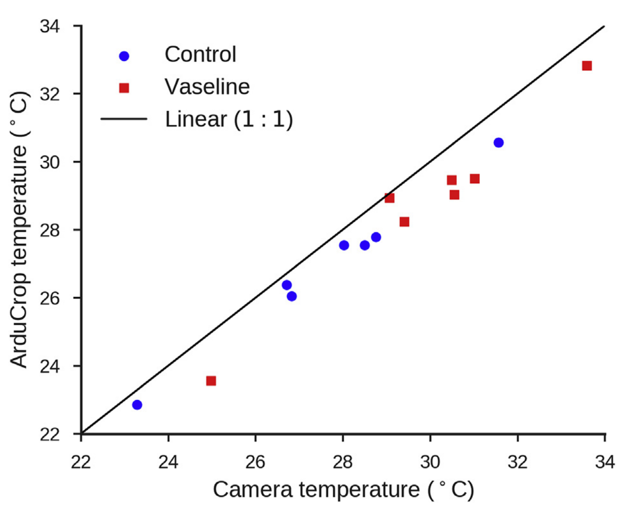

Fig. 3 – Relationship between ArduCrop estimates of canopy temperatures and camera estimates of temperatures of the same areas of canopy from the same view angle (data from 4th, 5th and 12th February, 2016). Each point represents the average of 16 measurements over 20–30 min periods (representative of a range of environmental conditions) with two separate ArduCrops at different representative positions in the crop (newly selected on each date). On average the camera estimate was 1.08 °C higher than the ArduCrop for the Vaseline canopy (red squares) and 0.71 °C for the control canopy (blue circles). The solid line denotes the 1:1 relationship. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.2. *Choice of colour/absorptance for dry reference*

A number of preliminary tests were conducted to compare the temperatures of reference domes and the temperature of non-transpiring canopies. Initial testing of colours for reference surfaces used flat paper references printed with different densities of green. Across a range of lightness from black to white through shades of green the temperatures ranged from 16 °C to 38 °C on a clear sunny day at midday at Griffith, NSW, Australia (data not shown). Comparison of these results with the temperature of a non-transpiring crop obtained by covering the leaves with petroleum jelly allows one to determine rigorously the appropriate colour density for any particular crop. Unfortunately the appropriate colour density for a flat surface varies with the time of day as the proportion of sunlit leaves in a canopy changes. Therefore further work emphasised the need for hemispherical dry reference surfaces.

The first set of colours tested for the hemispherical sensors (4, 5 February 2016, for the cotton crop at Narrabri) led to dome temperatures substantially greater than Vaseline-covered canopy (by as much as 5.4 °C). A second lighter set of colours was found to provide a much better approximation of the non-transpiring cotton canopy temperature (within 0.5 °C). These latter paints included Fresh Lime (RGB value R234, G245, B224), Grey (RGB value R211, G211, B211) and Green Trance (RGB value R242, G255, B242) (all from Taubmans, Chester Hill, NSW, Australia (http://www.taubmans.com.au)).

4.3. *Seasonal study on farm crop*

The data recorded at Kulki farm were used to calculate reference *Et0* (according to FAO56 using the meteorological station records), and to estimate *Et* (T_{dry}), *Et* ($T_{dry} = T_a + 5$), Cond. (T_{dry}), Cond. ($T_{dry} = T_a + 5$) and Cond. (energy balance). Figure 4 shows the daily trends of these quantities for the period 14–23 Dec 2014, together with solar radiation, T_{dry}, $T_{dry} = T_a + 5$ and T_{dry} (energy balance) (calculated from the full energy balance by solving Equation (3) for T_{dry} and setting g_W to Cond. (energy balance), derived from Equation (2)). This period covers several days before and after the first irrigation of the season. Over this period Cond. (T_{dry}) and Cond (energy balance) were generally well correlated, though the energy balance calculation for conductance did not generally show as high an early morning peak as did the dry reference method (Fig. 4a).

In the several days prior to the irrigation event, Figs. 4b and 5a show that there was a clear and increasing difference between *Et0* and *Et* (T_{dry}), presumably resulting from soil drying. Following the irrigation event, however, *Et* (T_{dry}) recovered to close to *Et0*.

Further, this panel also shows that the diurnal pattern of *Et* (T_{dry}) changed after the irrigation event, with an increasing tendency for *Et* to be maintained into the afternoon. This contrasts with the days preceding the irrigation event, where *Et* (T_{dry}) tended to decrease substantially in the afternoon. This

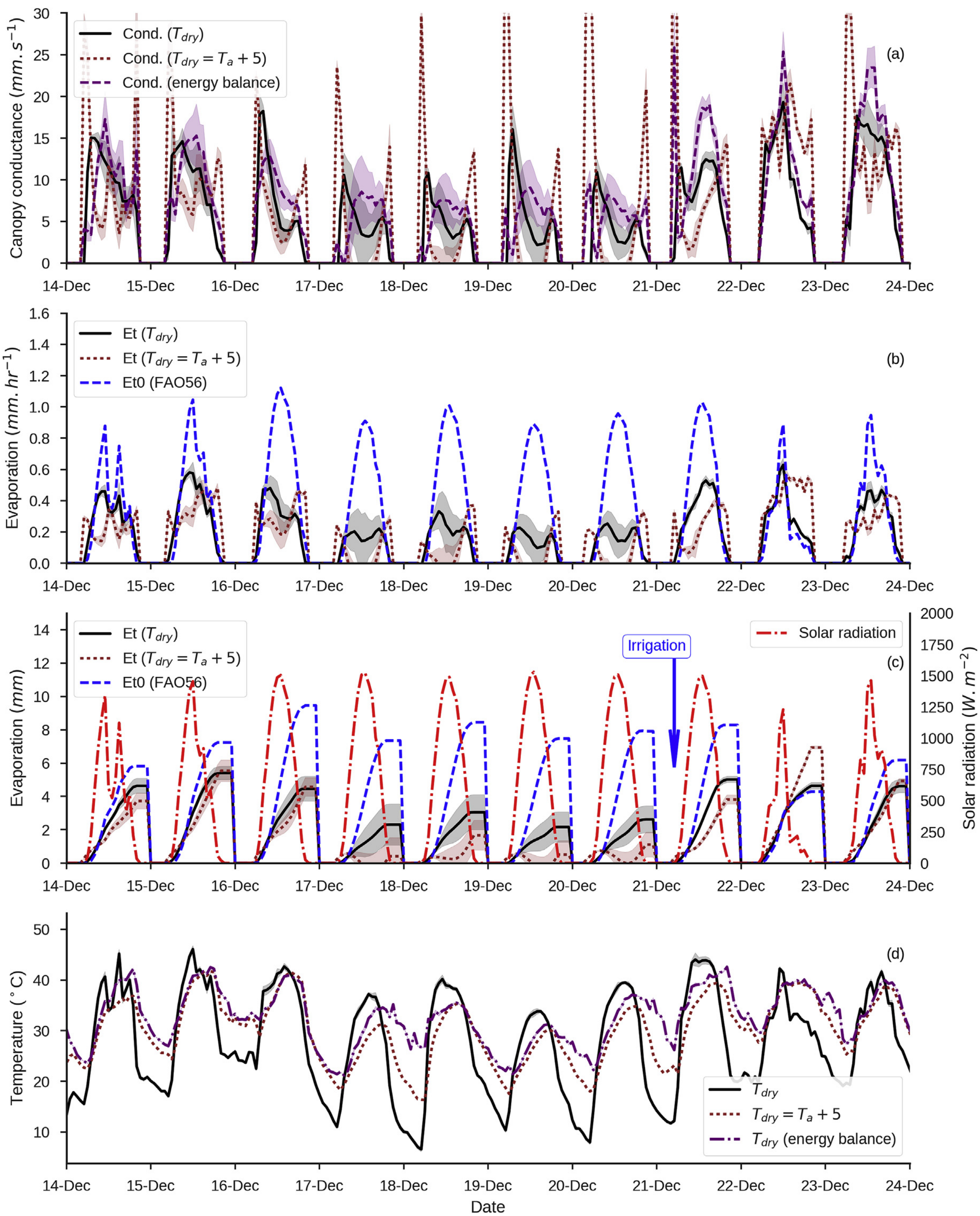

Fig. 4 – Canopy conductance (T_{dry}, solid black line, $T_{dry} = T_a + 5$, dotted brown line and energy balance, dashed purple line) (a), hourly *Et* (T_{dry}, solid black line, $T_{dry} = T_a + 5$, dotted brown line) and *Et0* (FAO56, dashed blue line) (b), cumulative daily Et (T_{dry}, solid black line, $T_{dry} = T_a + 5$, dotted brown line) and *Et0* (FAO56, dashed blue line) together with solar radiation (red dot-dash line) (c), and temperature for: T_{dry}, solid black line; $T_{dry} = T_a + 5$, dotted brown line; T_{dry} (energy balance), dotted purple line, (calculated from the full energy balance by solving Equation (3) for T_{dry} and setting g_W to Cond (energy balance), derived from Equation (2)) (d), for cotton (Kulki farm) for 14–23 Dec 2014. The scaling factor, α, in Equation (1) was set equal to 0.5, being the value that scaled the calculated *Et* to *Et0* according to FAO56. The date of the first irrigation event of the season is indicated. With the exception of *Et0* (FAO56), solar radiation and $T_{dry} = T_a + 5$, the lines and shaded regions represent the mean and standard deviation, respectively, of three values (three ArduCrop dry reference sensors). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

behaviour indicates a clear midday stomatal closure before the irrigation event, disappearing after irrigation. Figure 5 shows the seasonal trends of Daily *Et* (T_{dry}), *Et* ($T_{dry} = T_a + 5$), and *Et0* for the complete deployment on cotton (Kulki farm), together with the daily fraction of potential ($Et.Et0^{-1}$). The discrepancy between *Et0* and calculated *Et* early in the season can be attributed to the incomplete ground cover for this crop before about 22 December. Across the season, the average absolute difference between daily *Et* ($T_{dry} = T_a + 5$) and daily *Et* (T_{dry}) was 30% and for 75 out of 98 days, *Et* (T_{dry}) was greater than *Et* ($T_{dry} = T_a + 5$).

5. Discussion

The results presented here provide good evidence that a WSN of thermal sensors, when combined with limited meteorological data, can provide useful continuous monitoring of crop water use and canopy conductance that will be of great value for irrigation management and for crop phenotyping applications. The use of dry references greatly enhances the value of thermal sensing data, providing the possibility of obtaining useful absolute information on the continuous variation of canopy conductance and evapotranspiration.

It has been suggested that the use of dry references is unnecessary and that the temperature of a non-transpiring reference surface can simply be approximated as $T_a + 5$ °C, both for cotton (e.g. Cohen et al., 2016; Cohen, Alchantis, Meron, Saranga, & Tsipris, 2005; Meron et al., 2010; O'Shaughnessy, Evett et al., 2011) and for other crops (e.g. Ben-Gal et al., 2009; Irmak et al., 2000). However, as some of these authors themselves acknowledge, deviations from this (empirical) value can be substantial; simple inspection of the energy balance equation shows, for example, that much smaller deviations from air temperature are found in environments with low incoming radiation or high wind speeds.

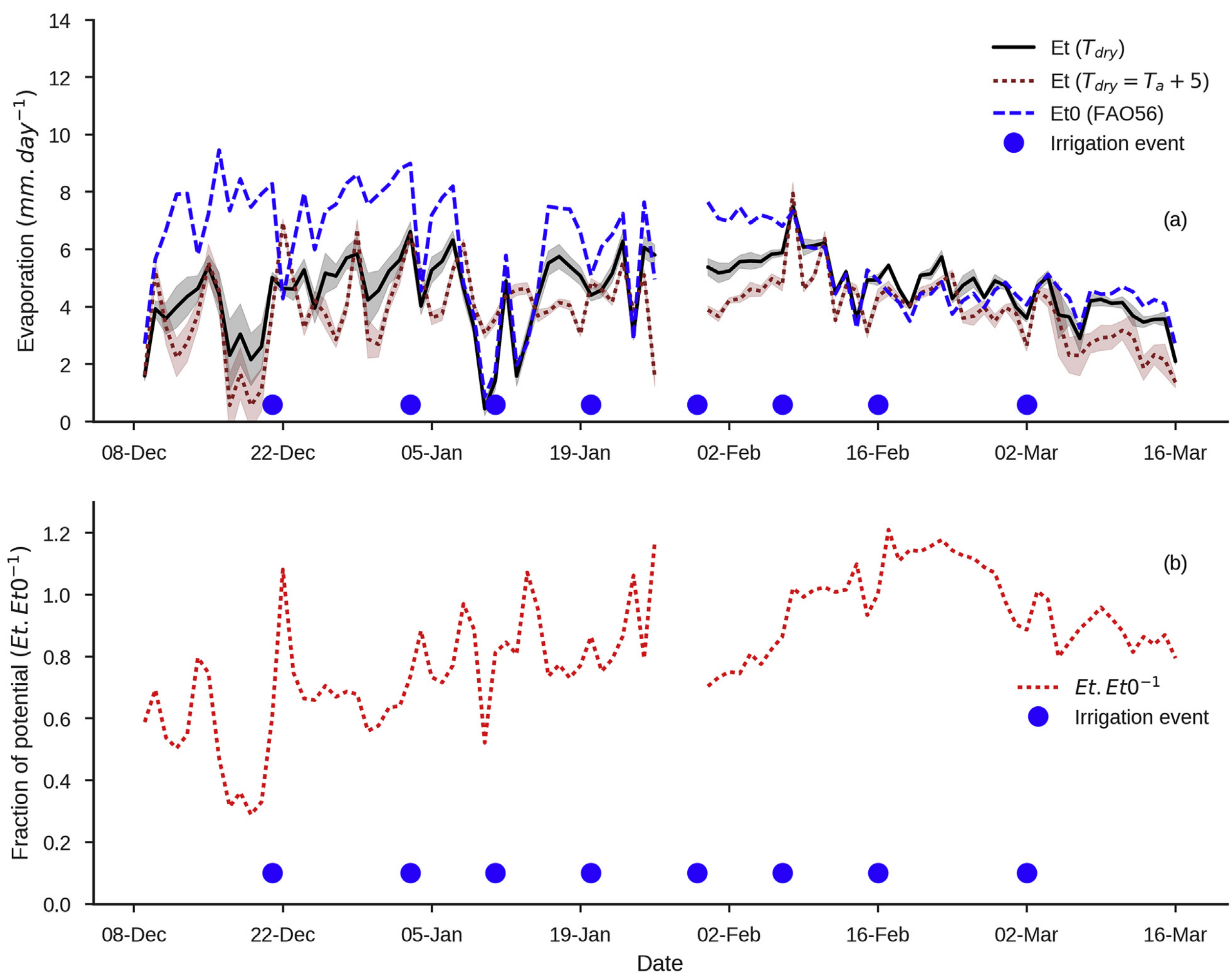

Fig. 5 – Daily *Et* (T_{dry}, solid black line and $T_{dry} = T_a + 5$, dotted brown line) and *Et0* (FAO56, dashed blue line) for the complete deployment on cotton (Kulki farm) (a) and the daily fraction of potential ($Et.Et0^{-1}$, dotted red line) (b). The scaling factor, α, in Equation (1) was set equal to 0.5, being the value that scaled the calculated *Et* to *Et0* according to FAO56. Note the missing meteorological data from 26 to 30 Jan 2015. The dates of irrigation events are indicated by blue circles. For *Et* (T_{dry}) and *Et* ($T_{dry} = T_a + 5$), the lines and shaded regions represent the mean and standard deviation, respectively, of three values (three ArduCrop dry reference sensors). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The alternative approach involving estimation of the dry reference temperature using a full energy balance calculation (Grant, Ochagavía, Baluja, Diago, Tardáguila, 2016), though it is an advance over a constant temperature enhancement, was found by these authors not to be as accurate as the use of a physical dry reference.

We compared three approaches to the estimation of T_{dry} in Fig. 4d. It is clear from this figure that the three independent approaches (dry reference sensor, $T_a + 5$ °C and the energy balance calculation) showed rather different diurnal trends, with $T_a + 5$ substantially overestimating temperatures outside the midday period, but potentially underestimating under the highest radiation. Although the simple approximation of the dry reference temperature as $T_a + 5$ °C may be appropriate around midday in semi-arid environments, it is clearly not appropriate for diurnal studies or for more humid climates. The resulting calculated values for *Et* ($T_{dry} = T_a + 5$) was often substantially less than *Et* (T_{dry}) (Fig. 4b, c and 5a). Further, large spikes in calculated Cond. ($T_{dry} = T_a + 5$) were evident at the beginning and end of the day (Fig. 4a). These spikes were far smaller for Cond. (T_{dry}) and Cond. (energy balance). Together, these observations highlight the sensitivity of *Et* and conductance, as calculated from Equations (1) and (3) respectively, to the dry reference temperature. Good estimates of T_{dry} are therefore critical for accurate work because calculated transpiration, and even more so conductance, are very sensitive to the value of the dry reference temperature. It is likely that the reason the arbitrary scaling factor, $\alpha = 0.5$ (required for Equation (1) to give estimates of *Et* that fit with the calculated *Et*0), did not equal unity in the Kulki farm study (performed before the calibration studies at Narrabri), was because in this early study the solar absorptance of the dry reference was somewhat higher than that of the canopy. This gave too high reference temperatures, especially under high radiation.

A number of other factors need to be considered in the application of the sensor network approach described here in practical situations. One particular problem for estimates of evaporation is the requirement that the sensor views only the crop canopy, otherwise temperatures will be biased towards the temperature of the background soil. This is one reason why CSIRO recommend that the ArduCrop is mounted at 45° from the vertical to ensure better coverage in erect or sparse-leaved canopies. Some possible approaches to correction for such a 'mixed pixel' effect have been discussed elsewhere (Jones & Sirault, 2014), and can be applied where information on the proportion of the field of view that is leaf is available. Further problems arise when a significant fraction of the field of view is occupied by flowers, fruit or stems that are unlikely to have the same conductance (or spectral absorptance) as the leaves.

Another important consideration is the orientation of the canopy sensor, though for fixed mounting systems, it follows that the bi-directional reflectance distribution (BRD) changes during the day. When the sensor is pointing in a similar orientation to that of the sun, most leaves will be sunlit and hence the observed canopy temperature will be substantially higher than when the sensor is oriented towards the sun. The theory outlined above assumes that the radiative temperature observed using the IRT is actually equivalent to the aerodynamic temperature that relates to the full temperature distribution of the evaporating surfaces; this is clearly only an approximation. Orienting the IRT canopy sensor to view north in the southern hemisphere, or south in the northern hemisphere, is probably the best compromise for a fixed orientation as it avoids excessive direct sunlight that would be obtained at midday when viewing the 'hotspot'.

For the dry reference hemisphere, setting it horizontal (looking directly upwards as shown in Fig. 1) is probably generally best as this mimics the orientation of the canopy. As an alternative it could be aligned in the opposite direction to the canopy sensor, so it is representative of the leaves viewed by the sensor. A particular advantage of the hemispherical sensor introduced here, however, is that for randomly oriented leaves the distribution of irradiance over its surface depends on solar elevation in a similar way to the proportion of sunlit leaves.

A further consideration is the mounting level of the dry reference. The instrument described here, the ArduCrop dry reference, combines a dry reference and a downward-pointing sensor for canopy measurements. An unfortunate consequence of this arrangement is that the dry reference is mounted above the canopy and exposed to a different radiation and wind regime than the canopy leaves, with the dry reference being illuminated earlier than the canopy. This probably partly explains the peaks in apparent conductance in the early mornings (Fig. 4). We recommend, therefore, that for future work the dry reference should be mounted in the canopy at the level of the predominant leaves that are sensed by the canopy temperature detector. One conclusion from the Kulki study, therefore, is that there is little need to have both the dry reference and a canopy sensor in the same instrument. Greater flexibility in deployment can be obtained by having them in separate units.

Although the estimates of canopy conductance could potentially be improved by the additional use of freely-evaporating wet reference surfaces (Jones, 1999a, 1999b; Leinonen et al., 2006), as this eliminates the need for a humidity measurement, the difficulties of preparing and maintaining a wet reference surface for hot arid environments suggests that sensors just using the dry reference surface are likely to be more generally robust. Nevertheless progress has recently been made in the development of such wet reference surfaces (Grant et al., 2016; Maes et al., 2016) that may allow improved accuracy for future sensor networks.

Some potential future developments of the approach can be envisaged. In particular, the advent of very cheap temperature sensing arrays (Melexis MLX90621, Melexis, Ypres, Belgium) means that there is potential for replacement of simple single radiometer thermal sensors. These would potentially allow one to overcome the limitations of single field of view sensors (especially caused by non-homogeneous crops and incomplete cover of the field of view by the canopy of interest). Once such sensors are incorporated into WSNs it should become straightforward to derive algorithms to use only relevant pixels for any irrigation scheduling or other calculation.

While deployment of the ArduCrop dry reference sensor on a commercial farm seems plausible, the deployment and maintenance of a high quality Meteorological station in such situations may not be so practical. Yet weather data is required, along with canopy and dry reference temperatures, to calculate canopy conductance and water use. In such situations, services providing interpolated weather data may be sufficient (e.g. SILO climate data: https://www.longpaddock.qld.gov.au/silo/data_available.html).

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