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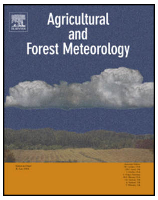

A new wet reference target method for continuous infrared thermography of vegetations

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ABSTRACT

Although infrared thermography for stress detection in plants is popular in scientific research, it is rarely used in continuous and automated applications. One of the main reasons for this is that the most precise method for generating wet reference targets, used for normalizing the leaf or canopy surface temperature for microclimatic conditions, requires manual wetting before each image capture. In this article, we present and evaluate a new type of wet reference target that remains wet while having an energy balance as similar as possible to that of the canopy. This reference target consists of a cloth knitted around a solid frame whose shape and dimensions mimic those of the leaves. The cloth remains wet by constantly absorbing water from a reservoir.

The new reference target was evaluated on grapevine and kiwifruit plants in greenhouse and orchard conditions. In greenhouse conditions, measured stomatal conductance was consistently more highly correlated with the stomatal conductance index I_g when I_g was calculated with the new wet reference rather than the manually wetted reference target. Furthermore, the temperature difference between leaves and the new reference target remained stable for as long as measured, in contrast with the manually wetted leaves. I_g obtained with the new reference target method was also highly correlated with stomatal conductance (g_s) of both crops in orchard conditions.

A new empirical regression model to estimate g_s from I_g in greenhouse conditions was introduced and evaluated. This regression model incorporates the background temperature, a parameter that needs to be included in thermographic measurements for obtaining correct surface temperatures, thus avoiding the need for any additional measurements. The same regression model can be applied on different days with differing conditions. The model performed better than other tested empirical models and provided unbiased estimates of g_s on days with different conditions, resulting in a root mean square error of 22–25% of g_s. Thus, it provides a promising method for continuous remote sensing of stomatal conductance or drought stress detection of plants and vegetations.

1. Introduction

Ground-based thermal remote sensing is an established method for estimating evapotranspiration and assessing drought stress of plants and terrestrial vegetations, with applications in irrigation scheduling, plant breeding and disease detection (see reviews of Maes and Steppe, 2012 and Costa et al., 2013). These methods are based on the linear relationship between leaf or canopy surface temperature (T_l or T_c) and evapotranspiration.

For most applications, a mathematical normalisation of T_l or T_c is necessary because of the large influence of microclimatic conditions on T_l or T_c (Maes and Steppe, 2012). The most successful normalisation makes use of a minimum and maximum temperature for given conditions. In the crop water stress index (CWSI), where this approach was first introduced, the upper and lower temperatures corresponded to the measured canopy that is either not transpiring (maximum temperature) or that is transpiring at

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the maximal rate (minimum temperature). CWSI has mainly been applied in an empirical form, in which the minimum temperature is calculated as a linear function of vapour pressure deficit, the so-called non-water stressed baseline (NWSB). Although this method is widely applied, particularly at orchard or field scale (e.g. Gonzalez-Dugo et al., 2014; Sezen et al., 2014; Taghvaeian et al., 2014; Gonzalez-Dugo et al., 2015), it requires very stable weather conditions and depends on the availability of the NWSB for the specific crop and crop stage (Maes and Steppe, 2012; Prashar and Jones, 2014).

Thermal cameras have facilitated a new approach, in which the minimum and maximum temperatures are estimated directly from reference targets included within the image. This direct approach requires no external microclimatic measurements or plant property data, but still normalizes the thermal data for radiation, humidity and, to a large extent, wind speed (Maes and Steppe, 2012). Different from the empirical approach, the bias of the thermal sensor does not need to be corrected either (thus only requiring corrections for emissivity and background radiation), which further reduces errors (Prashar and Jones, 2014). The direct approach has become a popular method for assessing drought stress or estimating evapotranspiration (Maes et al., 2011; Fuentes et al., 2012; Grant et al., 2012; Maes and Steppe, 2012; Agam et al., 2013; Ballester et al., 2013; Agam et al., 2014; Maes et al., 2014; Pou et al., 2014; Rud et al., 2014).

The direct approach allows calculating the direct version of CWSI ($CWSI_d$) or the stomatal conductance index I_g (Jones, 1999). Although $CWSI_d$ is most commonly used, it is not linearly related to evapotranspiration or stomatal conductance (Maes and Steppe, 2012). I_g, on the other hand, is linearly related with leaf stomatal conductance, at least for isolateral, hyper- or hypostomatous leaves and when the correct wet reference target is used (Guilioni et al., 2008; see Section 2.1):

$$I_g = \frac{\left(T_{dry} - T_l\right)}{\left(T_l - T_{wet}\right)} = Gg_s \qquad (1)$$

with T_{dry} and T_{wet} the surface temperature of the maximum and minimum reference targets (K or °C) and g_s the stomatal conductance ($\text{mmol}\,\text{m}^{-2}\,\text{s}^{-1}$). G ($\text{m}^2\,\text{s}\,\text{mmol}^{-1}$) is a function of the air temperature and of the boundary layer resistance to moisture (r_{aV}) and to heat (r_{aH}) transfer. G is independent of radiation or humidity but changes with air temperature and wind speed. The linear relation between I_g and g_s has been confirmed empirically in several studies (Maes and Steppe, 2012).

Despite its potential, the direct approach has so far not been applied outside scientific research, for instance in irrigation scheduling or automated stress detection in agriculture. Probably the most important reason for this is related to the practical aspects of the creation of the reference targets (Jones et al., 2009; Maes et al., 2011). Indeed, to obtain precise results, it is vital that the reference targets have leaf properties and experience microclimatic conditions as similar to those of the leaf or canopy as possible (Kaukoranta et al., 2005; Leinonen et al., 2006; Maes et al., 2011; Maes and Steppe, 2012).

Developed at plant scale, Jones and his co-workers recommended creating dry reference targets by covering leaves of the plant with petroleum jelly on the stomatal side(s) and wet reference surfaces by spraying one (hypo-/hyperstomatous leaves) or two (isolateral leaves) leaf sides with water before image capture (Jones, 1999; Jones et al., 2002; Leinonen and Jones, 2004).

The practical problems with dry reference target leaves are restricted to the distinction of the leaves in the image, particularly at larger scale (Jones et al., 2009; Maes et al., 2011). In contrast, the creation of the wet reference target leaves poses a range of issues, which is why the focus of this article is on these wet reference target leaves. These issues are: (1) the manual spraying hinders the whole process from being fully automated, an important requirement for continuous application; (2) manual spraying is labour-intensive and unpractical. Plants can be damaged and their temperature affected by disturbance; (3) wet leaves should be sprayed about one minute before image capture. However, it is unclear whether this prevails in all conditions and to what extent the method is still reliable when images are taken earlier or later; and (4) this method cannot be applied at larger scale, where single leaves are not distinguishable on the thermal images.

A few alternative reference targets have been used. At small scale, Pou et al. (2014) used the temperatures of an evaporimeter placed at the leaf angle. T_{dry} is estimated as the temperature of a thin black metal plate (5 × 1 cm), T_{wet} as the temperature of a black cotton wick of the same dimensions absorbing water from a small reservoir filled with water. At larger scale, Meron et al. (2003) presented the wet artificial reference surface (WARS) to derive T_{wet}, which has been used in a number of studies (Maes and Steppe, 2012; Agam et al., 2013, 2014; Rud et al., 2014). WARS is a water-absorbent cloth floating on a polystyrene foam board in a water-filled tray.

As pointed out by Prashar and Jones (2014), these two alternatives are not fully satisfactory. As to the evaporimeter, black surfaces may heat up many degrees above the temperatures of non-transpiring leaves. The energy balance of both the wet and the dry evaporimeter parts are unlikely to be representative of the energy balance of the leaves, because of the very different boundary layer conditions. Similarly, the energy balance of WARS is unlikely to correspond to that of the canopy (Maes and Steppe, 2012; Prashar and Jones, 2014). In addition, the large thermal mass of the WARS implies that it will also have a longer thermal time constant (larger thermal inertia) and might respond more slowly to environmental changes than the actual canopy (Prashar and Jones, 2014).

In this article, we present and evaluate a new type of wet reference target that remains wet, thus allowing automated canopy measurements, while having an energy balance as similar as possible to that of the canopy. This new reference target is evaluated on two orchard crops, grapevine (*Vitis vinifera* L.) and kiwifruit (*Actinidia chinensis*) in indoor greenhouse and outdoor orchard conditions, focusing on the relation between I_g and g_s. For the indoor greenhouse measurements, we also compare the new method with the standard manual wetting method. Finally, we propose an empirical method to estimate g_s with I_g.

2. Material and methods

2.1. Theoretical background and development of empirical model

The most practical way to create a wet reference target with properties similar to those of the leaves is to maintain the target wet on both sides. The temperature of a reference target wetted on both sides (T_{wet_2sides}) will be different from one that is wetted on one side (T_{wet_1side}). Consequently, I_g will be different when calculated with T_{wet_2sides} instead of T_{wet_1side} (see Eq. (1)). In Appendix A1, we evaluated the differences between T_{wet_1side} and T_{wet_2sides} and their influence on I_g using the leaf surface temperature model developed by Maes and Steppe (2012). This revealed that T_{wet_2sides} is always lower than T_{wet_1side} and therefore that I_{g_2sides} is smaller than I_{g_1side} (Fig. A1).

Differences in leaf properties (length, shape, spectral properties, orientation) between the reference targets and the actual leaves can be an important source of error in the estimation of I_g that can (Maes et al., 2011; Maes and Steppe, 2012). Although I_{g_2sides} is still influenced by differences in leaf properties between the reference target and the actual leaf, the model simulations indicate that this