Examination of tree water status of urban trees using thermal imaging

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Introduction

Identifying water status of urban trees is important not only because it's an indicator for tree drought tolerance but also useful to improve tree water use management (Jones, 2007). Water stress monitoring is essential for irrigation scheduling to improve water use efficiency (Jones, 2004b). There are various ways to monitor water status of plants including direct indicators such as leaf water potential, stem water potential, soil moisture and also indirect methods such as porometer, thermal imaging etc (Jones, 2007). Among these methods, thermal imaging is a promising low cost large scale measurement method.

Plant leaf temperature is an indicator of water availability. The first non-contact way to measure leaf temperature with the infrared thermometry dates back to 1960's (Jackson et al., 1981). Later, the method was widely validated and has a popular following (Idso et al., 1981; Jackson et al., 1981). The method (including the recent more advanced thermal imaging technique) has been applied in crops such as tomato, sunflower, cotton etc (Idso, 1982) , grapevines (Jones et al., 2002), and recently in tree crops such as pistachio (Testi et al., 2008) and almond (Gonzalez-Dugo et al., 2012). Thermal imaging has particular advantages for the quantitative analysis of spatial and dynamic physiological information. It is very useful, for example, in application in screening, such as in the selection of stomatal or hormonal mutants (Jones, 2004a), large spatial scale stomatal mapping (Berni et al., 2009) and heterogeneous evapotranspiration calculations (Moffett and Gorelick, 2012).

To convert the absolute leaf temperature to water stress index, the dry reference and wet reference temperatures are needed to represent the "most water stressed status" and "non water stressed status". There are three major ways for the conversion of leaf temperature to a water stress index. The first and also the most direct way is to create the wet reference and dry reference temperatures. For example, a fully irrigated plot is used to represent wet reference and infer the dry reference temperature from the leaf to air temperature –VPD curve (Idso et al., 1981). The second commonly used practice is to spray water on leaves to get the wet leaf temperature, and to apply vaseline to leaves (prevention of transpiration) for the dry reference temperature (Jones, 1999). The data analysis for both treatments is quite easy and straight forward but it is not practical to get continuous measurement over seasons or even days.

Another method which is still developing is to use intra-crown temperature variations as the water stress indicator. The method avoids the need to get the reference temperatures but has one difficulty that the variation of intra-crown temperature is not a monotonic function of water stress. Both the dry and wet end show much smaller variations in trees than those that are under mild water stress (Gonzalez-Dugo et al., 2012) are therefore not directly comparable over days.

Modelling dry and wet leaves provides a third way to normalize the leaf temperature but are only validated during short periods with certain environmental conditions such as clear days, low wind speed etc which are also the same requirements for the first direct method (Guilsard 2009).

Therefore, we targeted the development of a method that could obtain the water stress index for long-term measurements under different environmental conditions. The new method if successful will broaden the application of the thermal imaging in water stress detection. As mentioned previously, most of the studies were conducted in crops and few works were contributed to urban tree species. There is considerable concern about water sustainability in urban planning and the selection of trees for the urban landscape that are particularly drought tolerant. Thus the second aim of this study is to test the application of this method of monitoring on Australian native species in the natural environment. Two monitoring sites were selected at the Flinders University campus for this study. At the first site we set an experiment on a roof top to obtain the wet and dry reference temperature of artificial leaves and at the second site in the University grounds, we concurrently measured the leaf temperatures and the stem water potential of Acacia pycnantha.

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Methodology

We first set out to test a method for obtaining wet and dry reference temperatures continuously with a minimum of effort. We selected a material (wick) that could absorb water quickly and provide it continuously to the artificial leaves. The wick was supported by steel wires with one end connected to a bottle of water and the other end wrapped with leaf shaped cotton, filter paper, dry leaves taken from a tree, or no wrapping at all. The leaves were put in the bottles at different times, and the difference in degrees of wetness (water stress) was captured by the thermal imaging camera at the same instant (Figure 1). The filter paper leaf was saturated at the outset of the thermal imaging process and was thus used as the wet reference leaf. The dry leaf that was detached from a tree and could no longer transpire was used as the dry reference leaf. Figure 2 shows the experimental set up in the natural environment in the University grounds.

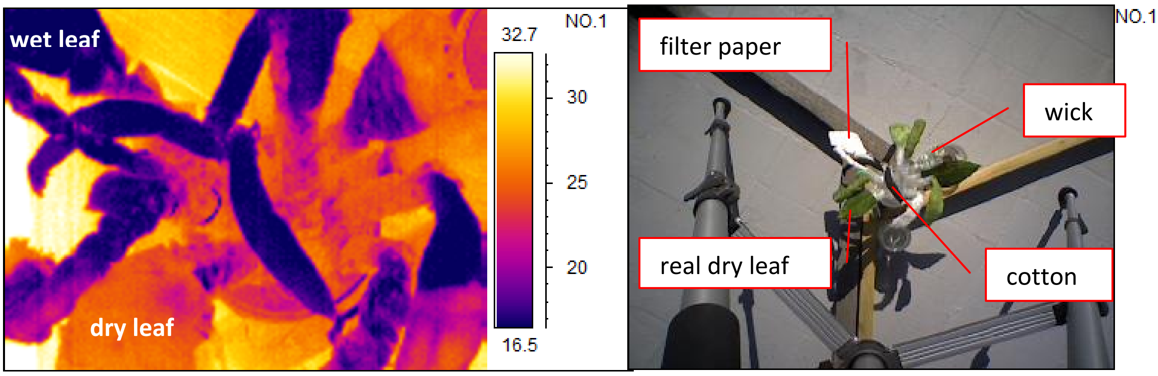

Figure 1: **Experimental setup in the laboratory for wet and dry leaf**

The water stress index (crop water stress index (CWSI) (IDSO et al., 1981)) was calculated as

$$CWSI = \frac{(T_c - T_a) - (T_{wet} - T_a)}{(T_{dry} - T_a) - (T_{wet} - T_a)} \quad (1)$$

where T_c is the absolute plant canopy temperature or leaf temperature, T_{wet} is the wet reference temperature when the plant is with fully water availability, T_{dry} is the leaf temperature when leaf was not transpiring, T_a is the air temperature which should be obtained surrounding the respective leaves but was usually assumed to be the same between the dry leaf site and wet leaf site. CWSI near to 0 indicates that the plant is under no water stress; while values near to 1 show that the plant is under water stress. Theoretically, based on energy balance and the Penman-Monteith equations, the dry and wet reference temperatures can be modelled (Jackson et al., 1981). The equations were used only to show the influencing factors on the leaf temperature such as net radiation R_n, vapour pressure deficit ($e_c^* - e_a$) and wind speed (influencing the aerodynamic resistance (r_a)) etc.

$$T_{dry} - T_a = \frac{r_a R_n}{\rho c_p} \quad (2)$$

$$T_{wet} - T_a = \frac{r_a R_n}{\rho c_p} \cdot \frac{\gamma^*}{\Delta + \gamma^*} - \frac{e_c^* - e_a}{\Delta + \gamma^*},\ \gamma^* = \gamma(1 + r_{cp} / r_a) \quad (3)$$

Where T_{dry}, T_{wet}, T_a have the same meaning as Equation 1. R_n is the net radiation on the leaf surface (W m^{-2} s^{-1}), ρ is the density of air (kg m^{-3}), c_p is the heat capacity of air (J kg^{-1} ∘C^{-1}), γ is the psychrometric constant (Pa ∘C^{-1}), Δ is the slope of the saturated vapour pressure-temperature (Pa ∘C^{-1}). e_c^* is the saturated vapour pressure at leaf temperature and e_a is the vapour pressure of the air (Pa), r_a is the aerodynamic resistance (s m^{-1}), and r_{cp} is the potential stomatal resistance of a well irrigated plant which is close to but not actually 0 (Jackson et al., 1981). We have assigned 0 by assuming that the evaporation on wet leaves is similar to that on a free water surface. That is confirmed to be reasonable because all the leaf temperatures converged to be almost the same when saturated (Figure 3). Therefore Equation 3 is reduced to

$$T_{wet} - T_a = \left[\frac{r_a R_n}{\rho c_p} \cdot \frac{\gamma}{\Delta + \gamma} - \frac{\Delta(T_c - T_a)}{\Delta + \gamma}\right] - \frac{1}{\Delta + \gamma} \cdot VPD \quad (4)$$

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When under a relatively stable environment, it can be seen from Equations 2 to 4 that the temperature difference between dry temperature and air temperature ($T_{dry} - T_a$) is roughly the same while the difference between wet leaf and air temperature ($T_{wet} - T_a$) becomes a linear function to air vapour pressure deficit (VPD) with a slope of $1/(\Delta + \gamma)$.

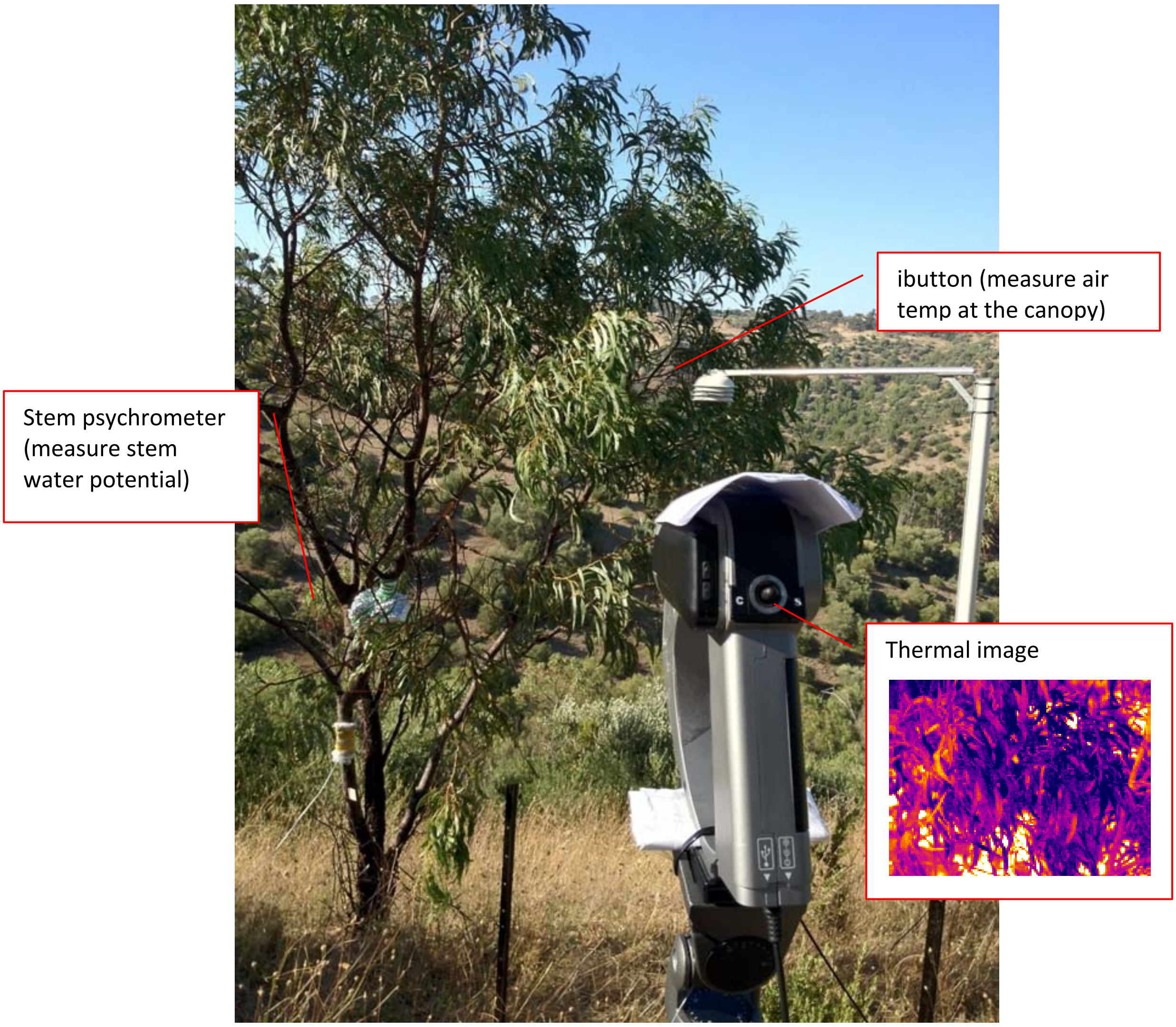


Figure 2: **field experiment on Acacia tree with thermal imaging and stem psychrometer**

Results and discussion

The artificial leaf data was collected on 17th Feb, 2012. One half hour of data (during 12:30 to 13:17) was missing because of a battery power down (Figure 3). The trend of wet and dry temperatures followed the diurnal mode because of radiation but dry reference temperatures showed a higher fluctuation than the wet reference leaf temperature. From 9 to 11 am, both the cotton leaf and wick leaf were close to saturated with CWSI near to 0, but after 2:30 pm as the water level in the bottle lowered and became disconnected from the wick leaf; the CWSI value approached 1. It was also demonstrated that the dry part of the artificial wick leaf reached higher temperatures than the genuine dry leaf while the wet parts of the leaf kept stable regardless of the leaf materials as long as they were fully wet. The results indicate that using wick leaf cannot represent the energy balance of the genuine leaves that are not transpiring, while, the wet leaf temperature (Figure 4) is reliable to use compared to Equation 4; the slope of the graph (0.0052) is near to the value of $1/(\Delta + \gamma)$ under average air temperature during the experiment.

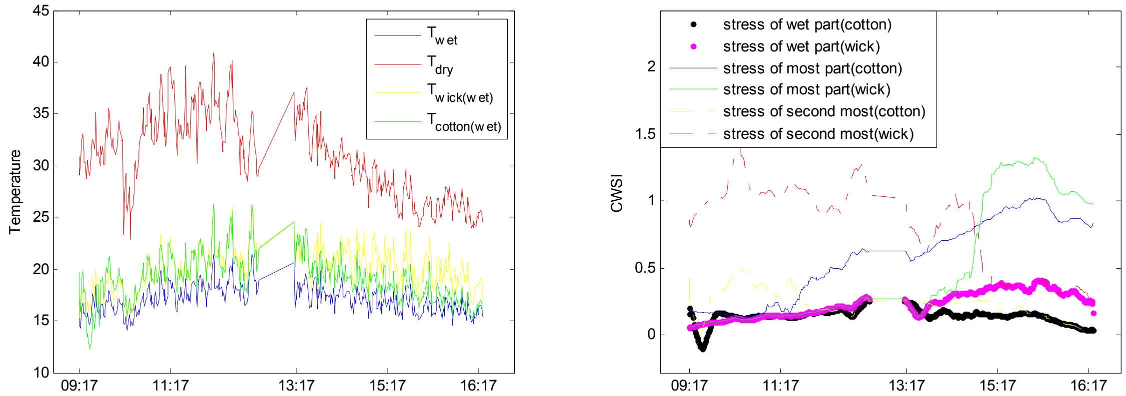


Figure 3. **Artificial leaf temperatures over the day (left), normalized thermal index -CWSI (right)**
note: the symbols of "wet", "dry", "wick", "cotton" correspond to the temperature of leaves referred to in figure 1. "most part" means the dominant temperature (most pixels) of the leaf, the second most is the second frequent temperature based on temperature histogram of pixels.

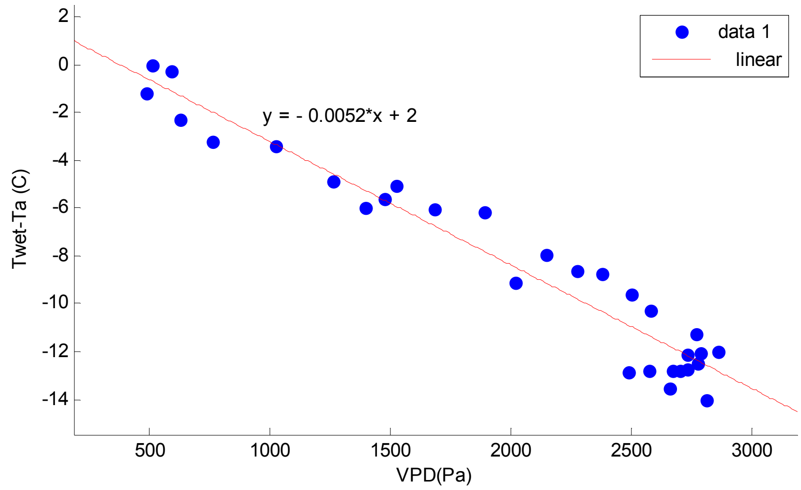
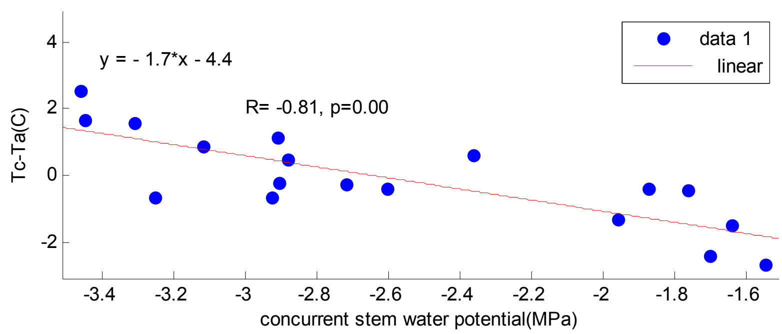


Figure 4. **Differences of wet reference temperature and air temperature versus the vapour pressure deficit**

Thermal images at leaf scale resolution were taken from 6th to 27th of Jan, 2012. Most of the days were clear or mostly clear. As we can see from figure 2 to 4, the leaf to air temperature difference can be influenced by environmental conditions. Thus it's practical to compare the temperature difference at the same time of the day when the radiation, wind speed etc were most likely similar. When compared to the direct water stress indicator-the stem water potential, it's quite easy to observe a good correlation with the stem water potential. The best correlation (R^2=0.8) of the day occurs between 14:30 to 15:00 pm. The reason could be that the air temperature or vapour pressure deficit reaches their maximum during the day in January when the plant is under largest water stress of the day. It's mentioned that the method is better performed in drier (higher VPD) conditions (Idso et al., 1981).



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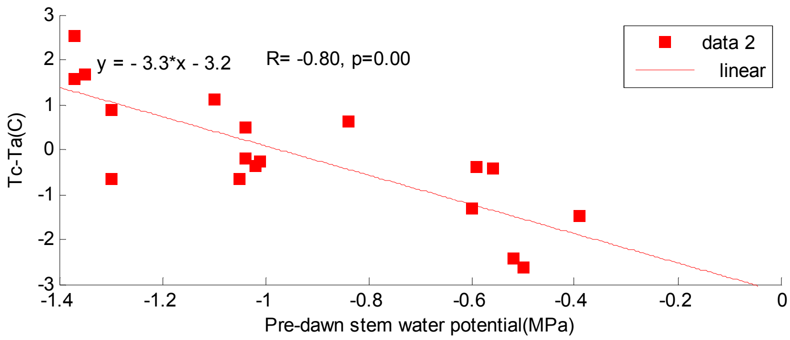

Figure 5. Leaf to air temperature difference versus the stem water potential during 14:30 to 15:00 of all sampling days in January

Conclusion

This method of obtaining easy-to-apply and continuous wet and dry reference temperatures is still under development. From the initial results of the artificial leaf experiment, it can be expected that the wet reference temperature can be realized using wicks in the field; this will be the next step to test. However, the method of obtaining a dry reference temperature needs to be improved. By directly comparing leaf to air temperature difference with the stem water potential, it is hoped to establish that leaf temperature can be a good indicator of water stress. The variation in correlation at different times of day demands further investigation. If the correlation can be quantified under various environmental conditions and a suitable algorithm is found to obtain reasonable thermal index on unfavourable conditions such as cloudy or windy days, it will widely broaden the application of thermal imaging technique in water stress detection.

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