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METHODOLOGICAL IMPROVEMENTS WHEN USING THERMAL IMAGERY IN VITICULTURE

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Summary

Infrared thermography (IRT) is a promising technology in viticulture using absolute or relative techniques. Methodological inconsistencies exist in the literature. Standardisation of measurements must be provided to growers before accurate deficit irrigation scheduling is implemented. Four field experiments are reported. Ambient temperature and relative humidity were similar when measured within a vineyard block and at the end of a row, but not wind speed. Wet and dry reference leaves were thermally stable 30 s after wetting and for 60 (exposed) to 90 s (shaded). The computed thermal time constant were influenced by wind speed and ranged from 4 s to 14 s. 93% of triplicate thermographs of identical vine faces captured 2 min apart displayed a significant difference in mean temperature in all possible pairs. This confidence interval was however lower than the thermal camera accuracy. Thermographs of heterogeneous canopies were segmented using digital photographs and the temperature range of vertical reference leaves. Most thermographs had over 40% of misclassified pixels. Finally, measurement errors of the infrared thermometer were shown to induce large error when using leaf temperature to evaluate stomatal resistance. In Conclusion, absolute canopy temperature varies over short periods of time, particularly when wind speed increases. This and the accuracy error of thermographers induce errors when computing stomatal resistance. Wind speed measurements must be taken close to the target canopy. Thermographs of reference leaves should be taken 30s after wetting. Heterogeneous canopies cannot yet benefit from thermal imagery for irrigation scheduling.

INTRODUCTION

Canopy temperature as an indicator of plant water stress was proposed several decades ago, mostly using direct measures of leaf temperature. Most broad acre field studies usually compute the difference between leaf (T leaf) and the ambient temperature. They account for a range of environmental conditions by normalising for the vapour pressure deficit (Idso, 1982). The original definition of the Crop Water Stress Index was reported to vary as a function of soil drying (Payero and Irmak, 2006) and in regions displaying a variable climate over the growing season (Jones, 1992). Recently, Jones (1999a, 1999b) reformulated the widely accepted Crop Water Stress Index (CWSI) (Idso, 1982) by relating the canopy leaf temperature (T leaf) to the same canopy temperature in a wet and dry state (T wet and a dry T dry respectively). In this work, T wet and T dry represent practical approximations of the temperature of the canopy when fully transpiring and not transpiring respectively. Jones (1999a, 1999b) also proposed a second and more robust derivation. This rectangular hyperbola is extremely sensitive to small temperature changes close to the asymptotes, a situation unlikely to be encountered in the field. Relative thermal indices can be related to stomatal conductance, by measuring the environmental conditions of wind, ambient temperature, humidity and solar radiation (Jones, 1999a, Guilioni et al., 2008). The value of these indices is to describe stomatal behavior without the need for further measurements. Absolute leaf temperature (T leaf) in the absence of threshold temperatures (T wet and T dry) or knowledge of environmental conditions therefore seems to offer limited value in physiological and applied studies. Application to viticulture have overwhelmingly focused on irrigation scheduling (Jones, 1999a, Jones et al., 2002, Cohen et al., 2005, Leinonen et al., 2006, Moller et al., 2007), pathogen detection (Stoll and Jones, 2005, Stoll et al., 2008) and was suggested as a methodology for berry quality assessment (Stoll and Jones, 2005). Some experimental inconsistencies exist in the literature and need addressing. An analysis by Guilioni et al. (2008) has addressed the confusion surrounding IRT for amphi and hypo stomatal plants as well as single and two sided wetting of reference leaves.

This observatory study was designed to improve field data capture by assessing: a) the time period between spraying of the wet reference and acquisition of the thermograph.; b) the impact of the thermal time constant of leaf and reference tissue on the accuracy of computed relative thermal indices and the assumed steady state of canopy leaves; c) the impact of using planar reference leaves in association with canopies displaying non planar leaf angle distribution; d) the impact of self sheltering and shading in sprawling vineyards when capturing environmental conditions at point scale; e) the impact of instrumental errors in absolute and relative thermal studies.

MATERIAL AND METHODS

Experimental site. The site used was the Charles Sturt University vineyard, Wagga Wagga, NSW, Australia (35.05°S, 147.35°E), with an elevation of 219 m above sea level. Mean January Temperature (MJT) is 24.05°C (www.bom.gov.au). Vines were planted in a North-South direction to the red cultivar Cabernet Sauvignon and trained to a bilateral permanent cordon.

Data capture: Thermal images, visible images and environmental data. The thermal images were captured using an IR SnapShot 525 (Infrared Solutions Inc., Plymouth, USA). Instrumental errors for this device include the Noise Equivalent Temperature Difference (NETD, specified as <0.4°C at 30°C), the necessity to manually focus the thermographer and the use of the appropriate emissivity coefficient, set in this study to 0.97 (Jones, 1992). The overall instrumental error stated by the
manufacturer is \( \pm 2^\circ\text{C} \) or \( \pm 2\% \) of the temperature range of a thermograph, whichever is greater. The total accuracy error of this model of thermal camera was however found to be below \( 1^\circ\text{C} \) in a previous study by Leinonen et al., (2006), and to correlate within \( 0.5^\circ\text{C} \) with fine wire thermocouple measurements (Jones, 1999a). Visible images were acquired using a digital Cyber-shot DSC–P73 camera (Sony Corporation, New York, USA). In all cases, the thermal camera was placed on a tripod. When quasi simultaneous visible and thermal images were captured, the visible camera was placed upon the body of the thermal camera.

Environmental data capture. Ambient temperature, relative humidity and wind speed were measured using two sets of instruments between the 6th and 14th December 2006 (\( n = 11923 \) data points). A field weather station (WeatherMaster 2000, Envirodata Pty Ltd, Warwick, Australia) and field data loggers (Gemini Data Loggers (UK) Pty Ltd, West Sussex, United Kingdom) were placed outside and within the vineyard row respectively. The internal clock of each instrument as well as the logging frequency of the sensors (1 min) were synchronized and recorded at each field measurement of thermal images.

Time between wetting and thermal measures. A dataset of thermal images was collected on the 9th January 2006 (cloudless conditions) at approximately 8:50 am. The thermal camera was facing a pair of sun exposed wet and dry reference leaves. The wet reference leaf was sprayed with soapy water (time = 0) and thermographs were taken as often as the thermal camera permitted (every 15-20 seconds) until water had completely evaporated. This operation was then repeated on the shaded face of the canopy.

The thermal time constant of reference leaves. The thermal images described in the previous section were imported in ENVI 4.2 (Research Systems Inc., Boulder, USA). A class image of Regions of Interests (ROIs) defined around the wet and dry reference leaves was used to extract the mean and standard deviations. Environmental data for computation was measured close to the leaves. The thermal time constant for reference leaves \( \tau_s \) (s) was computed using (Jones, 1992, Eqn 9.11).

\[ \tau_s (s) = \frac{1}{2\pi f} \]

The steady state of canopy leaves. On the 6th of January 2006 (a cloudless day), 177 thermographs of the exposed or shaded canopy faces of 59 grapevines were taken throughout the day from 7:30 am to 5:30 pm. Triplicates of each measure were captured at \( t = 0 \), \( t = 2 \) min and \( t = 4 \) min to investigate the possible short term variability of canopy temperature. Matched paired \( t \) tests were performed on the three possible pairs of images within each triplicate. Due to the risk of Type 1 errors in multiple \( t \) tests, a confidence level of 99\% was used in this analysis. All tests were carried out using SPLUS 7.0 (Insightful Corporation, Seattle, USA).

Vertical reference leaves used with non vertical canopies. Thirty two thermographs of grapevine canopies (including a wet and a dry reference leaf) were captured between the 13th and 16th of February 2006 at the Charles Sturt University vineyard. For every thermal image, a visible image was also taken. The temperature of the wet and dry reference leaves was extracted using Snapview 2.1 (Infrared Solutions Inc., Everett, Australia). The visible and thermal images were classified as “exposed”, “shaded”, “unclassified” or “masked” and subsequently warped in ENVI 4.2 using the methodology defined by Guisard et al. (2009). All pixels having a temperature larger than the dry reference leaf plus twice the standard deviation of the dry reference leaf or lower than the wet reference leaf minus twice the standard deviation of the wet reference leaf were attributed to this thermal mask. This procedure is less restrictive but in accordance with that used by Jones et al., (2002). Extending the temperature range by using standard deviations of the reference leaves was used to include slightly non vertical leaves within the canopy to be included in the analysis. Physiologically meaningful upper and lower leaf temperature thresholds (\( U_T \) and \( L_T \) respectively) were computed by solving the relationship given by Leinonen et al. (2006, Eqn 6) for \( T_{leaf} \) for hypostomatous leaves. Values of \( r_{lw} \) = 50 and 800 s.m\(^{-1}\) for \( L_T \) and \( U_T \) were used respectively. The percentage of pixels belonging to the “exposed” class but excluded from the physiologically meaningful range (\( L_T - U_T \)) was computed.

Sensitivity analysis of measurement errors inherent to the infrared thermographer. A theoretical analysis was carried out to assess the significance of measurement errors on computed stomatal resistance when using absolute thermal imagery. Stomatal resistance was computed by reverting the energy balance of amphistomatous leaves (Leinonen et al., 2006, Eqn 1). Ambient temperature was set to 25°C, net isothermal radiation to 300 W.m\(^{-2}\) and relative humidity to 30\%. These conditions yielded a theoretical leaf to air temperature differential of 4.3 and 2.6°C for wind speeds of 1 and 4 m.s\(^{-1}\) respectively when \( r_{lw} \) was arbitrarily set to 400 s.m\(^{-1}\). The accuracy error range for the thermal camera stated by the manufacturer (\( \pm 2^\circ\text{C} \)) was used to compare the theoretical \( r_{lw} \) (400 s.m\(^{-1}\)) against that computed from the energy balance (\( r_{lw} \) corrected), should the thermograph over or underestimate \( T_{leaf} \), using (%error = \( (r_{lw(corrected)} - 400)/400 \times 100 \).

Statistical analysis. This study is observatory and is therefore valid for the conditions encountered at the time of data capture. It includes as many replicates as physically possible. The results presented here therefore focus on methodological analysis rather than absolute guidelines.

RESULTS AND DISCUSSION

Environmental data capture. Relative humidity measurements at the canopy face were well correlated to those measured at the end of the row albeit consistently smaller. Ambient temperature measured at the canopy face also displayed a good correlation with that measured at the end of the row (approximately 100m). The underestimation of relative humidity or overestimation of ambient temperature by field instruments placed away from the target canopy is unlikely to significantly affect the computation of stomatal resistance. The relationship between wind speed measured at the canopy face and that measured at the end of the row displayed a large scatter of data. The wind speed at the canopy face was consistently smaller than at the end of the row partly due to a sheltering effect of the canopy. This is likely to have a strong impact on atmospheric resistances to heat and vapor exchange between the leaf and the atmosphere (\( r_{inR} \) and \( r_{inH} \); Jones, 1992), particularly at low wind speeds (\( < 2 \text{ m.s}^{-1} \)). Location of the wind speed sensor relative to the target vines has a
stronger impact on the computed stomatal resistance than the accuracy error of the anemometer (Leinonen et al., 2006) when using field thermography.

**Time between wetting and thermal measures.** The temperature range of the dry reference leaves (2.71°C and 0.98°C for sun exposed and shaded leaves respectively) was much smaller than that of the wet reference leaf (4.78°C and 2.72°C for sun exposed and shaded leaves respectively) (Figure 1).

A period of lower temperature was observed between \( t = 30 \) s and \( t = 100 \) s and between \( t = 30 \) s and \( t = 120 \) s for the exposed and shaded wet reference leaves respectively. Wet references returned to a temperature similar to that at \( t = 0 \) s after 180 s and 250 s for exposed and shaded leaves respectively. The period between spraying the wet reference leaf and thermal measurements reported in the literature varies between 20 s and 1 min (Moller et al., 2007, Jones et al., 2002). For this study, a period of 20 s after wetting would have been too short to reach a representative wet temperature. A small field experiment or a simple energy balance of theoretical wet and dry reference leaves using likely environmental conditions is therefore required prior to field measures.

The thermal time constant of reference leaves (Exposed canopies). Wind speed ranged from 0.6 m.s\(^{-1}\) to 1.1 m.s\(^{-1}\) and ambient temperature ranged between 26.1°C and 26.5°C for the duration of the 20 thermal measurements (230 seconds) (Figure 2). The small decrease in wind speed at \( t = 30 \) s resulted in an increase in the wet reference leaf temperature approximately 5 s later as shown in Figure 1. Conversely, a small increase in wind speed at \( t = 180 \) s resulted in a decrease in the wet reference leaf temperature approximately 4 s later.

The thermal time constant of reference leaves (Shaded canopies). Wind speed ranged from 0.4 m.s\(^{-1}\) to 1.0 m.s\(^{-1}\) and ambient temperature ranged between 26.1°C and 26.9°C for the duration of the 31 thermal measurements (345 seconds). Both measures were thus similar to the measures carried out on the exposed reference leaves. The thermal time constant of the wet reference leaf was relatively stable, ranging from 4 to 6 s. The thermal time of the dry reference leaf was mainly influenced by a reduction in wind speed at \( t = 60 \) s, with \( t \) increasing from 12 to 14 s. It is acknowledged here that errors in thermal time computations can be induced by the water and Vaseline™ layers on the reference leaves. Furthermore the relationship between tissue temperature and environmental conditions is asynchronous in situations of continuous change (Jones, 1992). In practical terms, thermographs should therefore be captured in “average” conditions. This would be difficult to achieve in most studies. As the thermal time constant of reference leaves are not equal, the are imperfect physiological thresholds. It is however the best approximation available to date. It is in fact a better approximation than that used in other studies where \( T_{Dry} \) has been estimated using a simplified method such as \( T_{Dry} = T_{Ambient} + \alpha \)°C (Cohen et al., 2005, Ehrler et al., 1978, Irmak et al., 2000). A dry reference leaf energy balance yields \( \alpha = \frac{(t_{max}R_m)/(p_c)}{\alpha} \) (Jones, 1999a). When thermal measurements are carried out at a consistent time of day over the duration of an experiment, \( R_m \) may be considered stable if cloud cover is consistent, so that \( \alpha \) is mostly influenced by wind speed and to a lesser extent by the ambient temperature (\( T_{Ambient} \)). The proposed fixed value of \( \alpha = 5°C \) (Cohen et al., 2005, Ehrler et al., 1978, Irmak et al., 2000) is therefore acceptable but only applicable to specific environmental conditions. In this study, observed values of \( \alpha \) varied between 5.1 and 7.4°C over 230 s for the sun exposed side of canopies, but \( T_{Ambient} \) varied by 0.5°C over the same period. The use of a fixed \( T_{Dry} \) value would have therefore induced an error in the computation of relative thermal indices.

The steady state of canopy leaves. Ninety seven percent of the paired comparisons within triplicates displayed a significant difference in mean temperature at the 1% significance level. Similarly, 93% of triplicates displayed a significant difference in mean temperature in all possible pairs. The mean of the absolute value of the paired differences ranged between 0 and 7.7°C (mean= 1.04°C; SD= 1.77°C). The confidence intervals (CI = \( z^\*\sigma/n^{1/2} = 0.04°C \) using the averaged data) of the paired comparisons are well below the thermal camera accuracy error. The large number of thermographs displaying a significant mean temperature difference is influenced by the large number of
pixels considered in the t tests. However, 36 % of the thermographs pairs had a mean temperature differences greater than 1°C (approximately reflecting the accuracy error of the thermal camera). This practical difference is more useful than the statistical difference, and strongly suggests that absolute temperatures lack temporal robustness for plant studies, even over short periods of time.

**Vertical reference leaves used with non vertical canopies.** A visual observation of the segmented dataset identified regions belonging to the grapevine canopy, yet excluded from the $L_T - U_T$ or $T_{Wet} - T_{Dry}$ ranges. The number of such pixels ranged from 22 to 100% over the dataset, most thermographs having more than 40% of misclassified pixels. The relationship between relative thermal indices and stomatal resistance rests upon the assumption that the reference leaves should be optically and energetically similar to the canopy. Application to precise irrigation strategies such as Regulated Deficit Irrigation or Partial Rootzone Drying is therefore inappropriate.

**Sensitivity analysis of measurement error inherent to the infrared thermographer.** The computed stomatal resistance errors ranged between -59 and +395% and -69 and 737% at wind speeds of 1 and 4 m.s$^{-1}$ respectively (Figure 3).

![Figure 3. Percentage errors in computed stomatal resistance. All computations using ambient temperature = 25°C, relative humidity = 30%, net isothermal radiation = 300 W.m$^{-2}$, stomatal resistance = 400 s.m$^{-1}$, wind speed = 0.1 m.s$^{-1}$ (diamonds) and wind speed = 4 m.s$^{-1}$ (circles). Insert shows the relationship within a reduced accuracy error range of the thermographer.](image)

Accuracy errors of the thermograph larger than 1.2°C were associated with complete closure of the stomata ($f_{W}$ > 800 s.m$^{-1}$, data not shown) for the conditions used in Figure 3. The insert in Figure 3 demonstrates that even with an accuracy error range of ±0.5°C reported by Jones (1999a), the computed stomatal resistance error ranges between -22 and +31 % and -30 and +60% for wind speeds of 1 and 4 m.s$^{-1}$ respectively. Small leaf temperature errors such as ±0.5°C were shown to induce large stomatal resistance computation errors. These results are in accordance with Leinonen et al., (2006). Relative thermal indices are less affected by the instrumental error when the reference leaves are placed together with the grapevine canopy in a thermograph.

In conclusion, direct measurement of leaf temperature to estimate stomatal resistance was found to be less precise than relative thermal indices. Furthermore, relative thermal indices reduce the impact of instrumental errors. In absolute studies, wind speed data should be captured as close as possible to the target canopy. Researchers can now focus on the major challenge of evaluating the reference temperature of leaves placed in non planar canopies. Thermal models of three dimensional grapevines provide an opportunity to address these challenges.

**LITERATURE**


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