INFRA-RED THERMAL IMAGE ANALYSIS FOR GRAPEVINES

ANALYSE D'IMAGE THERMIQUE INFRAROUGE POUR VIGNES

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SUMMARY

Infrared thermal images (IRTI) have been used for grapevine research since the early 90's. Even though its promising results in the assessment of canopy stomatal conductance and plant water status, from the beginning and recent research publications, it has not been fully applied on a commercial scale yet. It is believed that the bottleneck for this technology is the lack of reliable automation tools for IRTI analysis. Accurate and reliable automation techniques will allow the use of this technique to assess the spatial variability of physiological processes within the canopy using infrared cameras mounted on moving vehicles, drones, octocopters or robots. Automated analysis systems are requirement of The Vineyard of The Future initiative, which is an international effort to establish fully monitored vineyards in the most prominent viticultural and winemaking areas in the world. In this work, a semi-automated IRTI analyses performed using a code written in MATLAB® for estimate dry and wet references excluding non-leaf temperatures was compared with evaporimeter (EvapoSensor, Skye Instruments Ltd, Powys, UK) measurements used to provide dry and wet references from IRTIs. Results obtained from this research (grapevines cv. Tempranillo) showed good and statistically significant correlations between temperature references obtained from IRTI analysis and measured values. This work constitutes one additional step forward to the implementation of thermal imaging as an automated routine technique for physiological vineyard assessment from proximal sensing and unmanned aerial vehicles (UAV) platforms.

Keywords: Image analysis, MATLAB® programming, remote sensing, Climate change.

INTRODUCTION

Under water stress conditions, grapevines (isohydric and near-isohydric cultivars) can control their level of transpiration by closing stomata (Schultz, 2003; Chaves *et al.,* 2010), which results in a reduction of energy dissipation and an increase of canopy temperature compared to non-stressed plants (Idso *et al.,* 1981). Therefore, the use of infrared thermal images (IRTI) allows the visualization of differences in surface temperature between stressed and non-stressed plants of large groups of leaves simultaneously.

IRTI have been used for grapevine research since the early 90's with good results in the estimation of canopy stomatal conductance and plant water status. Several studies has been done in grapevines to obtain crop water stress index (CWSI) calculated from IRTI. CWSI was elaborated by Idso *et al.,* (1981) and involves the normalization of both, the effects of atmospheric humidity and the expected temperature of a well-watered crop. This index have been compared with conventional plant water stress measurements, such as stomatal conductance and leaf or stem water potential with good results (e.g. Ferrini *et al.,* 1995; Jones 1999a; b; Jones *et al.,* 2002; Möller *et al.,* 2007; Grant *et al.,* 2007; Guilioni *et al.,* 2008; Wang et al. 2010). Recent studies propose the use of an empirical CWSI calculated as function of canopy temperature (T_c), wet reference temperature (T_{wet}) and dry reference temperature (T_{dry}). The main advantage of this approach in comparison with base line temperature approach proposed by Idso (1982) is that allows an appropriate scaling of the leaf or canopy temperature measurements for the current environmental conditions (Jones *et al.,* 2002). T_c, T_{wet} and T_{dry} values can be obtained using different approaches. T_c can be obtained as an average of the leaves within a polygon drawn on an IRTI (Möller *et al.,* 2007). Computers programs from the IR camera providers such as FLIR QuickReport® offer basic computations of mean, maximum and minimum temperature from regions of interest (ROI) obtained by drawing ROIs in the image. This technique is time consuming considering that a considerable number of thermal images are required to have a representative assessment of the spatial variability of plant water status of an irrigation block or a complete vineyard (Fuentes *et al.,* 2012). Also, the use of polygons or ROIs considers only part of the total information of the IRTI. In general the top part of the canopy is not considered, due to influence of wind. Another alternative to obtain T_c is the use of visible images to filter non-vegetation temperatures by pre-analyzing the visible red, blue and green (RGB) components of each image to separate leaf and non-leaf material by color discrimination (Leinonen and Jones 2004; Wang *et al.,* 2010). However, this method requires further steps in the analysis and an extra threefold data volume to be analyzed, considering visible (RGB) and infrared data per canopy (Fuentes *et al.,* 2012). T_{wet} can be obtained as an average temperature of wetted surface (natural or artificial). One alternative is to use a leaf sprayed on both sides with water containing a small quantity of detergent as a wetting agent approximately two minutes before the imaging (Jones *et al.,* 2002). T_{dry} can be obtained using meteorological values (dry buld and air temperature) or using a dry surface reference for example a leaf covered in petroleum jelly on both sides (Jones *et al.,* 2002). Finally, one alternative method to obtain T_{wet} and T_{dry} is the use of EvapoSensor, which is fitted with two temperature sensors, built into two flat, black arms to simulate leaf surfaces. One artificial leaf is kept wet by means of a water reservoir within the sensor housing, whilst the second artificial leaf remains dry. These artificial leaves are affected by their local microenvironment. Thermography analysis has not been fully applied on a commercial scale yet. It is believed that the bottleneck for this technology is the lack of reliable automation tools for IRTI analysis.

Accurate and reliable automation analyses will allow the rapid use of this technique to assess spatial variability of canopy physiological processes using infrared cameras mounted on moving vehicles, drones, octocopters or robots. Automated analysis systems are the requirement of The Vineyard of The Future initiative, which is an international effort to establish fully monitored vineyards in the most prominent viticultural and winemaking areas in the world. For this reason, in this study a semi-automated IRTI analyses was performed using a code written in MATLAB® to estimate dry and wet references (T_{dry} and T_{wet}) excluding non-leaf material. T_{dry} and T_{wet} estimated from image data was compared with measured values of an evaporimeter (EvapoSensor, Skye Instruments Ltd, Powys, UK) used to provide dry and wet references in the field.

MATERIAL AND METHODS

Study site

For this study, IRTIs were obtained from a commercial vineyard cv. Tempranillo, located in Tudelilla, La Rioja, Spain. Vines were planted in NE-SW rows orientation at 2.6 m apart and 1.2 m within-row spacing (plant density of 3205 plants ha^{-1}) and trained on a vertical shoot-positioned system (VSP) with the main wire 1 m above the soil surface. Shoot trimming was performed once in June. The climate is a Mediterranean semiarid, with hot summers and average annual rainfall of 400 mm, with very scarce precipitation during the summer. The vineyard was irrigated using 2 L h^{-1} drippers spaced at equal intervals of 0.8 m in the vine rows. Four different irrigation regimes were applied to develop a large range of water status in the vineyard: Rain-fed (non-irrigated) (RF), standard irrigation (SI), moderate irrigation (MI) and full irrigation (FI). Irrigation was applied every day from the 1st July until 15th September with frequency varying from 1, 2 and 3 hours per day for standard irrigation, moderate irrigated and full irrigation, respectively.

Thermal imaging

IRTI were taken with a handheld infrared camera (ThermaCAM P640, FLIR Systems, Sweden). This camera includes a high-definition (640x480 pixels) infrared detector in the spectral range from 7.5 to 13 µm and provided also digital color images (RGB). Images were taken in lateral position from the sun-exposed side of the canopies at 1.5 m from the canopies in the morning (10:00 h) and in the afternoon (16:30 h). IRTI were filtered using an interactive filtering process to exclude non-leaf material. This filtering process was carried out using a code written in MATLAB® 2009a (The Mathworks Inc., Natick, MA, USA) (Figure 2). The use of the semi-automated code requires that all thermal images are saved in a Microsoft Excel file, in which each image is stored as a separate worksheet (Fuentes *et al.,* 2012). To change the file format, thermal images were loaded using the FLIR QuickReport software (FLIR Systems, Portland USA) and exported to Excel file. Thermal images were imported and stored in matrix variables automatically, which can be treated in MATLAB as 8-bit indexed images.

Determination of wet and dry references temperatures

Wet and dry references temperatures are used for the derivation of stress indices, such as CWSI. In this study an evaporimeter (EvapoSensor, Skye Instruments Ltd, Powys, UK) was used to provide simulation of artificial leaves which act as wet and dry references (Figure 1). Wet and dry references were used to simulate leaves with open and fully closed stomata, respectively. The artificial leaves were composed of black metal (platinum), 5 cm long × 1 cm wide and 0.5 cm thick. The wet artificial leaf was maintained wet by means of a wick of black cotton which continuously absorbs water from a small reservoir, which was filled with distilled water. The evaporimeter was placed on handmade holders with the artificial leaves facing the same direction as the canopy of interest to obtain the temperatures of these references (T_{dry_e} and T_{wet_e}).

Statistical analyses

The comparison between T_{dry} and T_{wet} obtained from the infra-red thermal image analysis versus

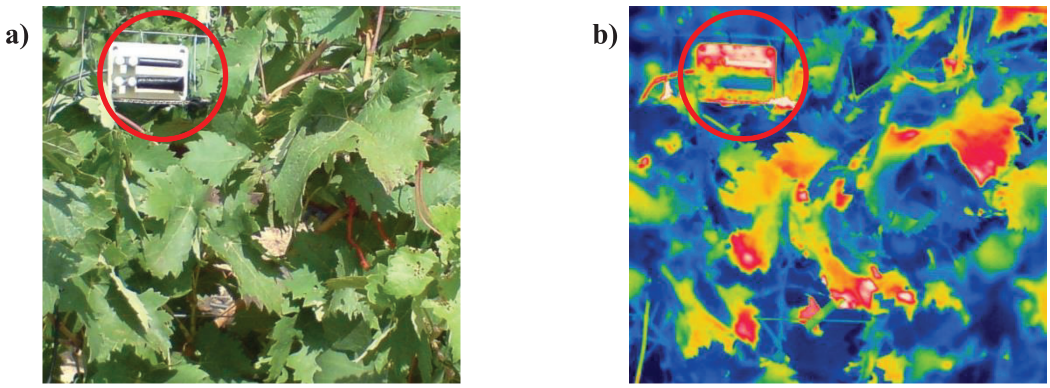

Figure 1. Illustrations of typical plant canopy a) Original optical image. b) Infra-red thermal image. Inside the red circle, the evaposensor.

Illustrations de couvert végétal typique a) Image optique originale. b) Image thermique infrarouge. A l'intérieur du cercle rouge, l'evaposensor

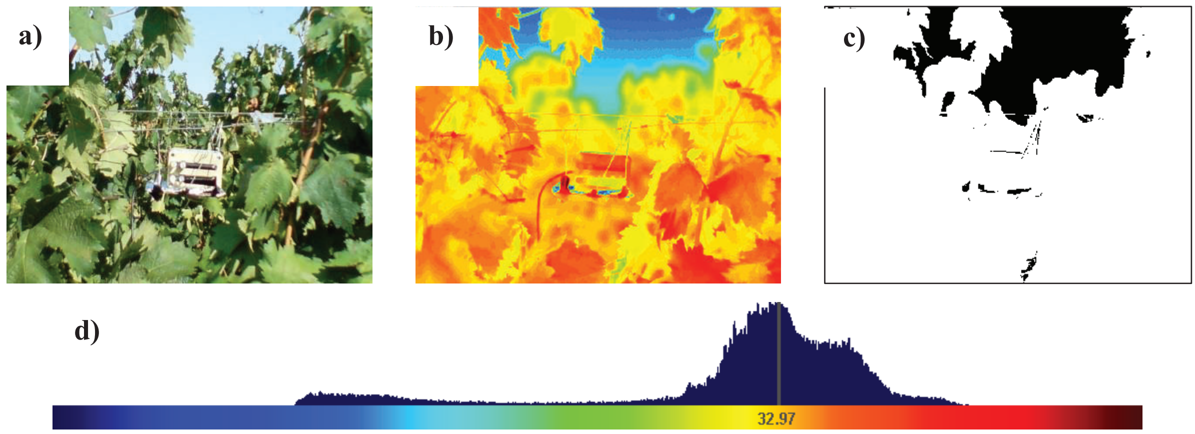

Figure 2. Example of infra-red thermal image analysis: a) Original optical image; b) Infra-red thermal image; c) filtered image.

Exemple de analyse d'image thermique d'infra-rouge: a) Image optique originale; b) Image thermique infrarouge; c) Image filtrée.

references temperatures values obtained from evaposensor were carried out using a linear regression analysis determining the determination coefficient (r^2), intercept (a), slope (b), mean absolute error (MAE) and root mean square error (RMSE).

RESULTS AND DISCUSION

The T_{dry_e} and T_{wet_e} values obtained from image analysis of evaporimeter (Figure 1) are presented in Table 1.This table show that, as expected, the images taken in the morning were cooler than the images taken in the afternoon. T_{dry_e} values registered from the morning IRTI ranged from 26.3 to 35.3°C, while the T_{dry_e} values registered from the afternoon images ranged from 34.6 to 41.6 °C. Similarly, T_{wet_e} values registered in the morning were cooler than the values registered in the afternoon. T_{wet_e} values ranged from 19.3 to 25.9 °C and 25.9 to 30.4 °C during the morning and afternoon, respectively. When evaporimeter temperature references are used in the calculation of CWSI, strong correlations between CWSI versus stomatal conductance and stem water potential were observed by Ochagavia *et al.,* (2011) and Diago *et al.,* (2012).

The main problem when using IRTI directly is the extraction non-leaf material and background. Different approaches to the elimination of background temperatures have been explored. Giuliani and Flore (2000) used a program based on thermal histograms to process the digital images and exclude background temperatures. Jones *et al.*, (2002) discussed the use of reference surfaces (dry and wet) as limits to remove non-leaf material from histograms. Other approaches required the analysis of visible and thermal images of each image to separate leaf and non-leaf material by color discrimination (Leinonen and Jones 2004; Möller *et al.,* 2007; Alchanatis *et al.,* 2010; Meron *et al.,* 2010). However, this method requires additional steps in the IRTI analysis, considering visible (RGB) and infrared data (Fuentes *et al.,* 2012). In

TABLE I

Descriptive statistical analysis of observed and estimated reference temperatures (T_{dry} and T_{wet}).

Analyse statistique descriptive des températures de référence observées et estimées (T_{sec} et T_{humide}).

Variable	Avg.	Min.	Max.	Range	S. D.	C.V. (%)
			Morning infra-red thermal images			
T_{dry_e}	31.0	26.3	35.3	9	2.1	6.7
T_{dry_image}	30.3	24.6	35.5	10.9	2.7	8.9
T_{wet_e}	22.2	19.3	25.9	6.6	1.4	6.4
T_{wet_image}	20.9	17.2	25.2	8	2.0	9.7
			Afternoon infrared thermal images			
T_{dry_e}	38.9	34.6	41.6	7	1.8	4.6
T_{dry_image}	39.2	34.9	41.1	6.2	1.6	4.0
T_{wet_e}	28.0	25.9	30.4	4.5	1.2	4.3
T_{wet_image}	27.8	23.5	31	7.5	2.0	7.2

S.D. is the standard deviation (°C), C.V. is the coefficient of variation (%), Min. is the minimum (°C), Max. is the maximum (°C) and Avg. is the average values (°C).

S.D. est l'écart type (°C), C.V. est le coefficient de variation (%), Min. est le minimum (°C), Max. est le maximum (°C) et Avg. sont les valeurs moyennes (°C).

this regard Fuchs (1990) and Jones (2004) suggested the use of the variation in temperatures within the canopy to determine water stress.

The resolution obtained using the infrared camera ThermaCAM P640 (640x480 pixels) used in this study permitted differentiating between leaves and sky temperatures (Figure 2). Therefore, the filtering process allowed obtaining values of T_{dry} and T_{wet} directly from IRTI ($T_{dry:image}$ and T_{wet_image}). These values were similar to those registered with evaposensor. Values calculated with the morning images presented more variability with coefficient of variation (CV) around 9%. In the afternoon, CV values were lower with values of 4.0 and 7.2 % for $T_{dry:image}$ and T_{wet_image}, respectively (Table 1). Jones *et al.,* (2002) proposed the use of vine leaves as reference since leaves have similar radiometric and aerodynamic properties to the canopy. However, Grant *et al.,* (2007) showed that the use of individual wet and dry leaves as references to calculate stress indices might not be suitable for whole canopies and differences of time between spraying the wet leaves and taking the image may cause errors.

The linear regression analysis between T_{dry_e} and T_{dry_image} for whole data set (morning and afternoon IRTI) was highly significant with a determination coefficient (r^2) of 0.89, an intercept (a) of 6.1 °C and slope (b) of 0.83 (Table 2). Figure 3a, displays the linear comparison between T_{dry_e} and T_{dry_image}, this figure shows that the points were very close to the 1:1 line. Also, MAE and RMSE values were 1.15 and 1.41°C for the comparisons between T_{dry_e} versus T_{dry_image} and T_{wet_e} versus T_{wet_image} , respectively. Likewise, the linear regression analysis between T_{wet_e} and T_{wet_image} was highly significant with r^2 =0.87, a= 6.9 °C and b= 0.74 (Table 2). Finally, the comparisons between T_{dry_e} versus T_{dry_image} and T_{wet_e} versus T_{wet_image} presented values of MAE and RMSE equal to 0.91 and 1.12 °C, respectively.

CONCLUSIONS

In this study, a semi-automated infra-red thermal image analysis to obtain dry and wet references

TABLE II

Statistical comparison between observed and estimated reference temperatures.

Comparaison statistique entre les températures de référence observées et estimées.

Comparison	a	b	r^2	MAE	RMSE
T_{dry_e} versus T_{dry_image}	6.1	0.83	0.89	1.15	1.41
T_{wet_e} versus T_{wet_image}	6.9	0.74	0.87	0.91	1.12

a is the intercept (°C); b is the slope (dimensionless); r^2 is the coefficient of determination (dimensionless); MAE is the mean absolute error (°C); RMSE is the root mean square error (°C).

a est l'ordonnée à l'origine (°C), b est la pente (sans dimension); r^2 est le coefficient de détermination (sans dimension); MAE est l'erreur absolue moyenne (°C); RMSE est l'erreur quadratique moyenne (°C).

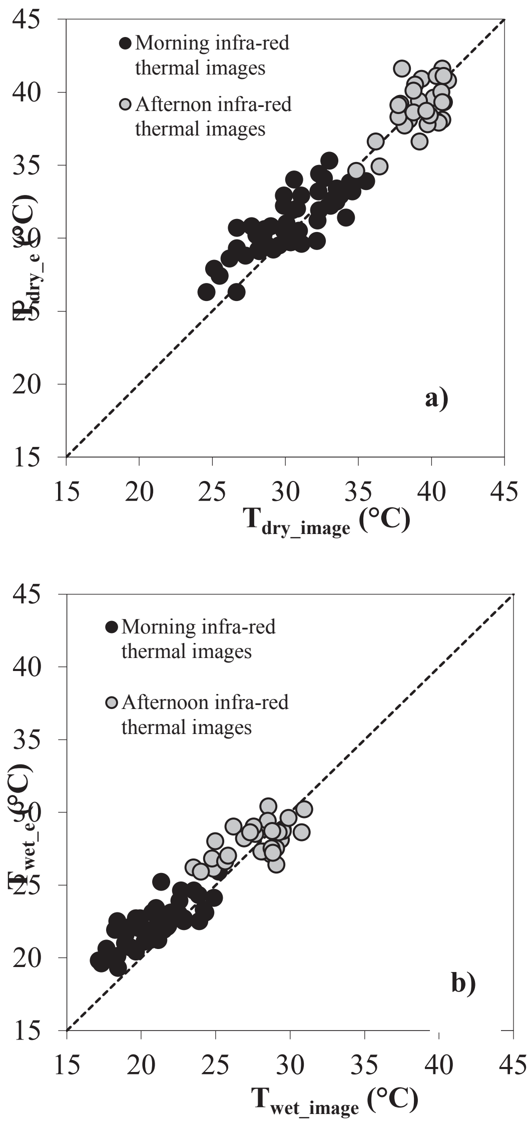

Figure 3. Comparison between measured and estimated dry (a) and wet (b) temperature references calculated using images taken in the morning (grey circles) and in the afternoon (black circles).

Comparaison entre les références de température mesurés et évalués au sec (a) et humide (b) calculés en utilisant des images prises dans la matinée (cercles gris) et dans l'après-midi (cercles noirs).

temperatures was evaluated by the comparison with

reference values obtained from an evaporimeter with two artificial leaves which act as wet and dry references. The results showed that there were significant correlations between dry and wet temperature references obtained from IRTI analysis and measures values with r^2 equal to 0.89 and 0.87, respectively. Further studies will be conducted to automate the data acquisition and analysis for real-time assessment. However, further investigations are required to improve and automate the analysis of infra-red images for implementing these techniques in the evaluation of physiological vineyard aspects from proximal sensing and unmanned aerial vehicles (UAV).

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