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Thermostress. An automatic imaging process for assessing plant water status from thermal photographs

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Abstract. Leaf temperature can be used for monitoring plant water status. Nowadays, by means of thermography, canopy temperature can be remotely determined. In this sense, it is crucial to automatically process the images. In the present work, a methodology for the automatic analysis of frontal images taken on individual trees was developed. The camera used in this investigation took at the same time thermal and visible scenes, so it was not necessary to overlap the images. During the processing in batch no operator participated. This was done by means of a non supervised classification of the visible image from which the presence of sky and soil was detected. In case of existence, a mask was performed for the extraction of intermediated pixels to calculate canopy temperature by means of the thermal image. Sunlit and shady leaves could be detected and isolated. Thus, the procedure allowed to separately determine canopy temperature either of the more exposed part of the canopy or of the shaded portion. The methodology developed was validated using images taken in several regulated deficit irrigation trials in persimmon and two citrus trees cultivars (Clementina de Nules and Navel Lane-Late). Overall, results indicated that similar canopy temperatures were calculated either by means of the automatic process or the manual procedure. In addition, differences in midday stem water potential and stomatal conductance among irrigation treatments were associated with differences in canopy temperature in persimmon trees. The procedure here developed here allowed to drastically reduce the time amount used for image analysis also considering that no operator participation was required. Indeed, the tool here proposed will facilitate further investigations in course for assessing the feasibility of using thermography for detecting plant water status in woody perennial crops with discontinuous canopies

Keywords. Image analysis – Regulated deficit irrigation – Thermography – Water relations.

Thermostress. Un traitement automatique d'images pour évaluer l'état hydrique des plantes à partir de photographies thermiques

Résumé. *La température de la feuille peut être utilisée pour le suivi de l'état hydrique des plantes. De nos jours, à l'aide de la thermographie, la température du couvert végétal peut être déterminé par télédétection. Dans ce sens, le traitement automatique des images est crucial. Dans le présent travail, on a développé une méthodologie pour l'analyse automatique d'images frontales concernant les arbres pris individuellement. La caméra utilisée pour cette étude a pris en même temps des images dans les spectres thermique et visible, donc il n'était pas nécessaire de superposer les images. Le traitement en lots s'est fait sans opérateur. Ceci a été réalisé par classification non supervisée de l'image du visible à partir de laquelle on détectait la présence de ciel et de sol. S'il existait, un masque était appliqué pour l'extraction de pixels intermédiaires afin de calculer la température du couvert végétal à l'aide de l'image thermique. Les feuilles ensoleillées et ombragées pouvaient être détectées et isolées. Ainsi, la procédure permettait de déterminer séparément la température du couvert soit pour la partie la plus exposée de ce couvert, ou pour la partie ombragée. La méthodologie développée a été validée en utilisant des images prises lors de plusieurs essais d'irrigation déficitaire régulée sur plaqueminiers et sur deux cultivars d'agrumes (Clémentine de Nules et Navel Lane-Late). Dans l'ensemble, les résultats ont indiqué que l'on calculait des températures de couvert semblables soit par le traitement automatique ou par la procédure manuelle. En outre, des différences de potentiel hydrique des tiges à midi et de conductance stomatale parmi les traitements d'irrigation ont été associées à des différences de température du couvert chez les plaqueminiers. La procédure développée ici a permis de réduire drastiquement le temps pour analyser l'image et il convient également de considérer qu'aucun opérateur n'était requis. En fait, l'outil proposé ici facilitera les recherches en cours pour évaluer la faisabilité d'utiliser la thermographie pour détecter l'état hydrique des plantes chez des cultures arborées pérennes présentant un couvert discontinu.*

Mots-clés. *Analyse d'images – Irrigation déficitaire régulée – Thermographie – Relations hydriques.*

I – Introduction

Efficient irrigation scheduling procedures requires the analysis of plant water status. Leaf water potential measured with the pressure chamber, either at predawn or at midday, has long been used as a plant water stress indicator. However this measurement is quite time and labor consuming what often limits its use.

Transpiration is an endo-energetic thermodynamical process. When water is transpired by plants, the latent heat of evaporation is drawn from them, decreasing thereby their temperature.

Plants under soil water limitations often respond decreasing stomatal conductance (gs), reducing hence transpiration. This implies that canopy temperature should raise in plants grown under soil water limitations. Therefore infrared sensing of the canopy temperature can be used to estimate stomatal conductance and plant evapotranspiration (Merlot *et al.*, 2002; Jones *et al.*, 2002).

Infrared thermography is a powerful tool to estimate crop temperatures. Hand-operated cameras allow taking images of individual plants or even portions of them, achieving higher spatial resolution. For instance, images can capture different tree positions (shady, sunlit or zenithal position). Subsequently, images are processed, without the need of georeferentiation if crops are identified previously in the field and linked to their corresponding images. In order to make this technique more useful for assessing crop water status, the automation of the images analysis is required. This is particular important in the case of woody perennial crops that often have discontinuous canopies (i.e. ground cover is below 100%). In this case images can contain both canopy and soil portions that need to be separated. In this work, a methodology has been developed where vegetation temperature is calculated with the help of a color image. The camera used takes a color and infrared image at the same time, and therefore no alignment techniques are necessary. Objects in the scene are classified into classes using an unsupervised classification method of the color image. Classes are identified by means of its vector in the Red, Green and Blue model (RGB) and they are grouped according to their intensity. In this way, no operator participates in the analysis phase and images are processed in a sequential way. If sky or soil appear in the scene these classes are identified and removed from the analysis. Temperature can be calculated from the sunlit or shady leaves or from both together. The methodology has been implemented using ArcGIS 9.x (ESRI, Redlands, USA) a commercial software and its developing platform named ArcObjects. Examples of the validation of this procedure are reported and results obtained in different irrigation trials are also presented and briefly discussed.

II – Material and methods

1. Experimental orchards

The experiment was performed during 2009 in a commercial orchards of Persimmon (*Diospyros kaki* L.f.), located in Manises, (Valencia, Spain). The orchard was planted in 2001 with the cv 'Rojo Brillante' grafted on *Diospyros lotus* at 5.5 x 4 m. During the experimental period trees had, on average, a shaded area of 39%.The soil was sandy loam to sandy clay loam, calcareous; with an effective depth of 0.8 m. Trees were drip-irrigated with two laterals per row and 8 emitters (4 l/h) per tree. Two irrigation treatments were applied in this orchard: (i) Control, irrigated at 100% of the estimated crop evapotranspiration (ETc) defined by Allen *et al*. (1998); during the whole season with a total amount of water applied of 487 mm; and (ii) RDI, irrigated at 50% of ETc from July (DOY 185) to August (DOY 230) with a total amount of water applied of 429 mm. The statistical design was a complete randomized plot with three replicates plot per treatment and 6-7 sampling trees per replicate.

2. Plant water status determinations

Stem water potential (Ψs) was measured weekly at solar midday (14:00 h) using a pressure chamber (Model 600 Pressure Chamber Instrument, Albany, USA), following recommendations of Turner (1981) in three mature leaves of two trees per replicate plot. In the case of NLL and three trees per replicate plot, in the case of CN and Persimmon, were enclosed in plastic bags covered with silver foil at least two hours prior to the measurements. Mean values of Ψs for each tree were compared with the thermal image analysis.

Stomatal conductance (gs) was measured with a leaf porometer (SC 1 Porometer, Decagon, WA, USA) in the same trees where Ψs was determined. Gs of each tree was determined as the mean value of five measurements in five different fully exposed leaves. These mean values were used for comparison with the thermal image analysis.

Thermal images were taken with an infrared thermal camera TH9100 WR (NEC San-ei Instruments, Tokyo, Japan) with a precision of 2ºC or 2% of reading. The camera had a visible of 752 x 480 pixels and a 320 x 240 pixel microbolometer sensor, sensitive in the spectral range of 8 and 14 µm and a lens with an angular field of view of 42.0º x 32.1º. Emissivity used was 0.98, value that can be assumed for the healthy vegetation (Monteith and Unsworth 2008). Images were registered in a proprietary format denominated SIT where information is arranged in sections. Temperature is stored in a file of type "band sequential" (bsq) of 16 bits with temperature stored on 14 bits. Information referred to RGB format has a JPG format. Thermal images were taken at noon in both, sunlight and shaded sides of all the trees where Ψs and gs were measured.

II – Methodology developed

For the image analysis the ArcGIS 9.3 software (ESRI, Redlands, USA) was used. This software has an application called "Geoprocessing" which is a set of windows and dialog boxes used to manage and build models that execute a sequence of tools. These models can be customized and run by means of programming languages like Microsoft Visual Basic. In addition, it is possible to connect with a database (DB) to feed the processes developed in the ArcGIS environment and to store the results on the DB. The analysis process included the following steps (see algorithm in Fig. 1).

Images were catalogued and stored in the DB. Each image was clearly identified with the date and hour, treatment, replicate, tree and position (sunlit or shadow). Images were selected by means of a query to the DB. This allows to analyse all the images captured in a day or for a selected irrigation treatment.

The SIT image format was exported to a standard format compatible with the software used. For that purpose, pixels with thermal information image were exported to the bsq format (ESRI, 2007) and pixels with RGB information were exported to JPG format.

Thermal images were reclassified assigning to each pixel the corresponding temperature, in a binary code, according to the scale used by the camera. In this case, temperature range was -50ºC to 130ºC and pixel temperature was calculated by the equation: T (ºC) = 40 + (DN × 180)/16.384, where DN is the 14 bits value, 40 is the temperature value for DN = 0, 180 is the temperature range and 16,384 the possible values of a 14 bits pixel.

Non supervised pixel classification of the RGB image was performed (Lillesand *et al.*, 2004). The reason was to avoid the presence of an operator in the spectral signatures selection phase. Normally, up to six classes appeared in a scene: clear sky, clouds, shadows, soil, shady vegetation and sunlit vegetation. In a supervised process, the operator has to assign a representative area to the classes presented in the image. Successively, the operator should calculate, for each selected class, a spectral signature in RGB. This consists of a vector of three dimensions where

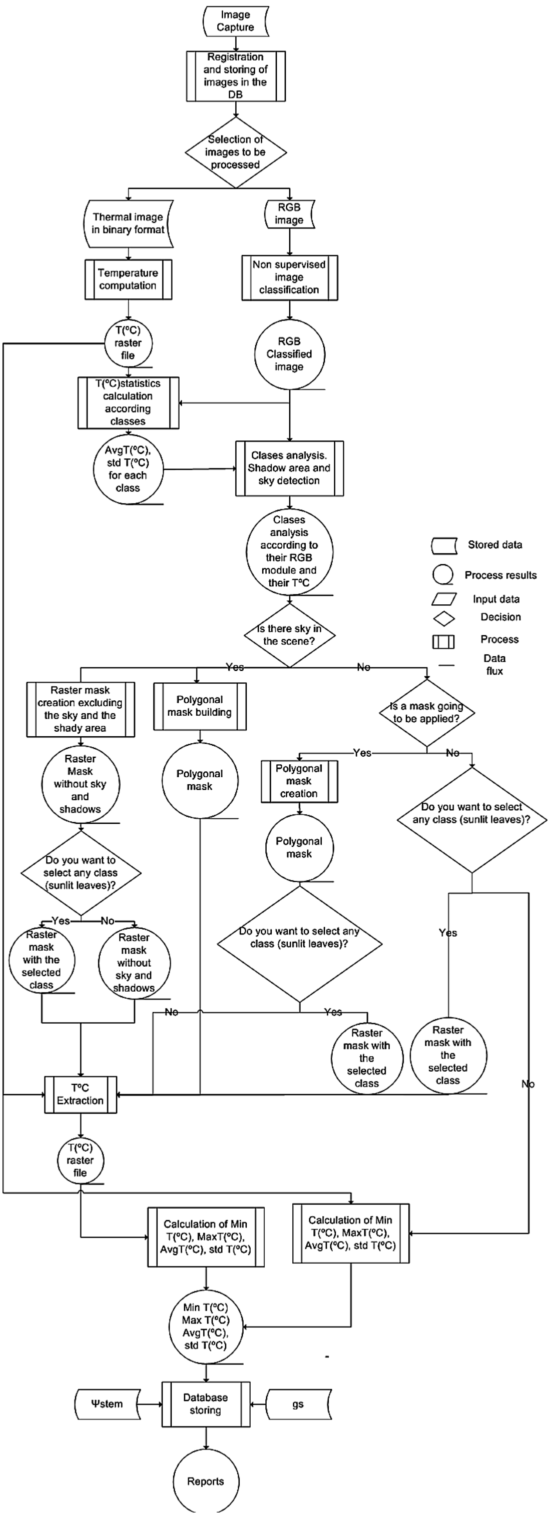

Fig. 1. Flux diagram of the whole automatic thermal image processing algorithm.

each component represents the red, blue and green bands. This process has to be repeated for each single image analysis considering that scene features might differ among days and even among scenes taken in a same day. The possible number of different classes in a scene was tested concluding that, for more than 7 classes, the algorithm did not find enough pixels to identify a new class. The above mentioned six classes were identified, assigning the extra class to pixels of vegetation. In the absence of clouds and when the sky had different levels of intensity, the extra class was assigned to sky. An example of this classification, is shown in Fig. 2 where a photograph taken in the Persimmon orchard has been included.

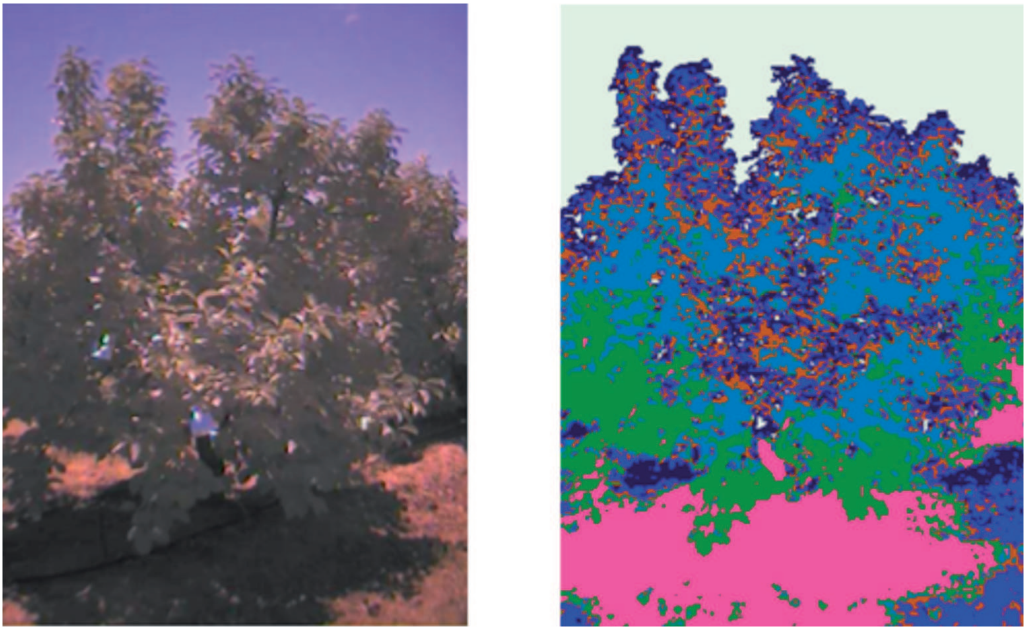

Fig. 2. Classification non supervised in seven classes of a RGB image of a persimmon tree.

Once the classes where set up, image was classified using a Maximum Likelihood Classification algorithm based on the Bayes theorem considering that each class is normally distributed in a multidimensional space (Lillesand *et al.*, 2004). The tool implemented in ArcGIS offered us the possibility of produce a raster file with 14 levels showing the interval of confidence of the pixel classification. For the images where neither sky nor soil were captured, captured, classes were assigned within the shady and sunlit vegetation, representing the intermediate classes vegetation with different illumination intensities.

For each class, the RGB vector module was calculated. Each coordinate vector was defined by the pixel value in the RGB bands. These classes are ordered according to their intensity. The darkest classes, usually represent shadows, have a lower value.

Due to the low sky emissivity in clear days (Wunderlich, 1972), pixels composing the sky classes show a lower average temperature and higher standard deviation than the other classes. In the case that sky would had been photographed, gravity centers of the darkest class and sky can be calculated and a polygonal can be created to overlap the intermediate pixels existing between both classes. The rest of pixels can then be excluded from the analysis to avoid possible errors in pixel classification (e.g., a sunlit soil zone could be misclassified as vegetation). The width of the mask was set taking into account the average distance from the camera to the tree and the camera field of view which determined the scale and the size of the photographed scene. This area must be lower than the canopy diameter, thus the target tree can be properly analysed (Fig. 4).

Fig. 3. Polygonal mask applied to a scene with sky and shadows.

When sky was not detected in the scene, masking was not applied, nevertheless, a mask can be forced to include only an image zone. In the case that the mask was applied, the shadiest class gravity center was calculated. The image orientation (vertical or horizontal) was determined and the midpoint of the opposite edge was chosen as reference to build the polygon mask.

When sunlit leaves were chosen for temperature calculation, pixels with highest RGB module were selected. In case all pixels need to be included the whole selectable classes can be easily taken into account. The minimum (Tmin, ºC), maximum (Tmax, ºC), average (Tc, ºC) and standard deviation (Tstd, ºC) of selected pixels were calculated. It is possible to exclude from the calculation those pixels not to be classified, for example those below a certain degree of confidence, making a mask with the confidence raster produced during the classification process. Output results were stored in the database together with Ψs and gs determined for each crop and date.

III – Results and discussion

1. Thermostress validation

The ANOVA results indicated that there were no statistically significant differences between canopy temperatures obtained either via automatic or manual procedures (P values of 0.427). The slopes of the linear regressions between pairs of Tc computed either manually or automatically were not different from 1 (Fig. 4).

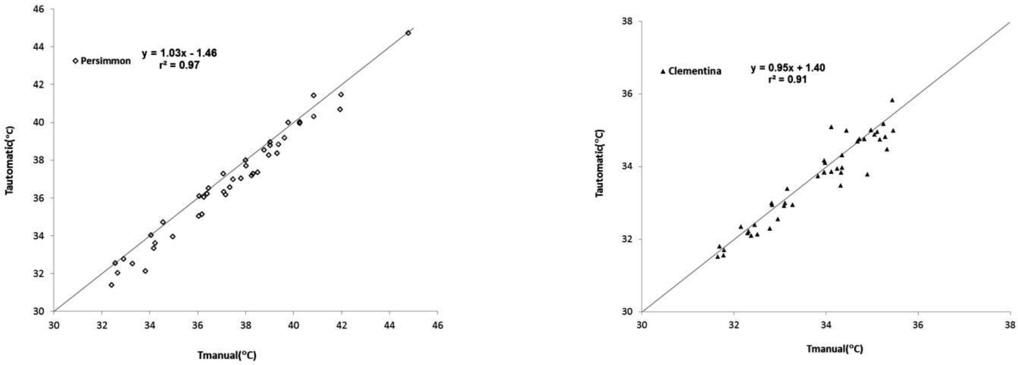

Fig. 4. Comparison of manual and automatic procedures of average canopy temperatures (Tc) calculation for a representative day in persimmon (DOY 204) and clementine (DOY 215). The solid line represents the 1:1 relationship.

However, the intercept ("a") was -1.46 indicating a general underestimation of the Tc when automatically calculated. This underestimation occurred in 36 images out of 44 that were taken to deliberately capture the whole tree. The reason for this underestimation is due to the fact that when the mask is created, some leaf pixels close to sky, together with some sky pixels misclassified as leaves, are included in the average Tc computation. Since the sky has a lower emissivity than the leaves, this lead to an underestimation of temperature calculated automatically. This fact can be seen in Fig. 5 where the T raster computed by means of a mask manually performed by an operator (Fig. 5A) and the T raster computed with a mask automatically created detecting the shadow and the sky (Fig. 5B) are shown. The darkest pixels represent the lower temperatures. They are located on the canopy outline with the sky as background. This issue could be overcome taking photographs with higher resolution, where sky and leaves could be more clearly separated.

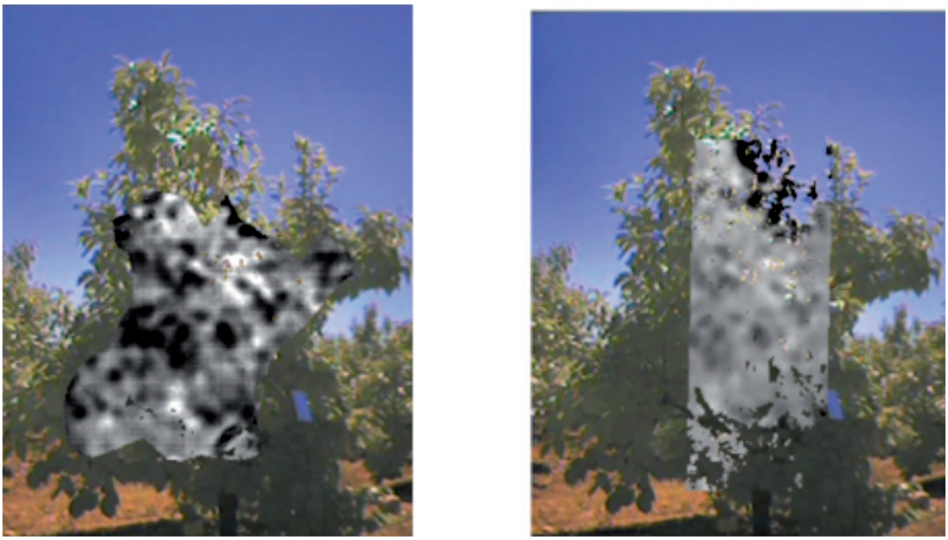

Fig. 5. Tc calculated by different types of masks in a persimmon tree. (A) The mask is manually created by an operator. The operator draws the mask following the tree outline avoiding sky pixels selection. (B) The mask is created automatically after sky and shadow detection. Pixels close to the tree outline are also selected.

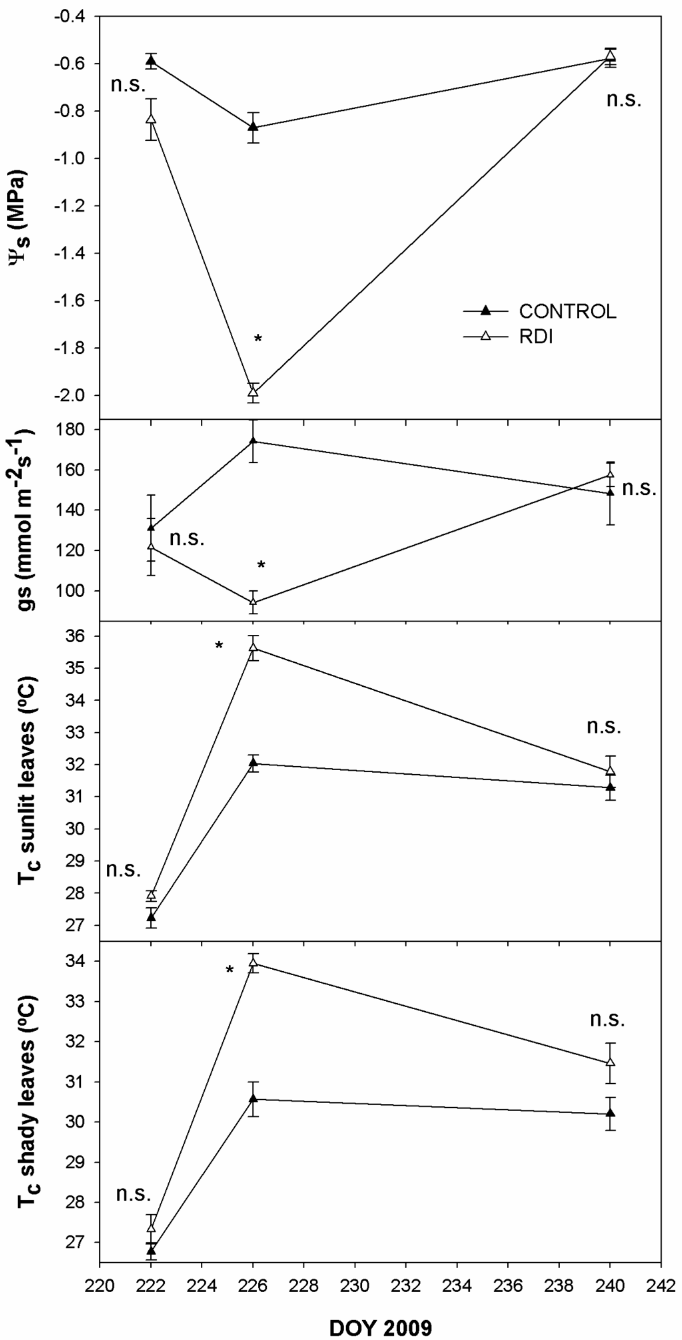

Fig. 6. Evolution of stem water potential (ψs), conductance (gs) and temperature from the sunlit and shady side of the canopy during the period of water restrictions in 2009. * and ns denote significant differences at P<0.05 and non significant differences, respectively, by Dunnett's test.

2. Thermostress application

The Thermostress procedure was applied to obtain canopy temperatures of kaki trees under different irrigation regimes (Fig. 6) During the period of water restrictions Control trees maintained ψs values around -0.70 MPa whilst RDI trees reached values of -1.99 MPa. Differences of 1.12 MPa on average between RDI and Control trees (DOY 226) resulted in a reduction of 46% for the gs in the water stressed treatment (174 mmol m^{-2} s^{-1} for the Control treatment and 94 mmol m^{-2} s^{-1} for the RDI trees). This gs reduction in the RDI trees was reflected in a high temperature of the canopy from these trees. Pictures from both sides of the trees (sunlit and shady side) detected the temperature increase. In pictures from the sunlit side, on average, Control trees had a temperature of 32ºC while RDI trees had a temperature 3.6ºC higher. The difference of temperature between treatments when pictures were taken from the shady side was similar, 3.4ºC, showing in this case Control trees temperatures of 30.6ºC. When water restrictions finished and irrigation was resumed to normal dose RDI trees returned to ψs, gs and canopy temperature values similar to Control trees (DOY 240).

IV – Conclusions

A routine for automatic canopy temperature extraction based on an unsupervised classification method of the color image has been developed and validated. This automatic process allows obtaining quickly canopy temperature data from experiments or commercial situations, drastically reducing the time consumed for images analysis eliminating in addition any subjectivity due to the operator analysis. Indeed, the procedure here developed might facilitate the adoption of the thermography for crop water stress detection and irrigation scheduling. At a commercial scale it is important to automate the information extraction process in order to be able to actuate on irrigation controllers. The routine proposed might serve as a first step in order to finally incorporate canopy temperature determinations by thermography in the irrigation scheduling automation.

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References

Lillesand T.S., Kiefer R.W., Chipman J.W., 2004. *Remote Sensing and Image Interpretation*, 5th ed. John Wiley and Sons Inc., New York.

Mazomenos B., Athanassiou C.G., Kavallieratos N., and Milonas P., 2004. Evaluation of the major female *Eurytoma amygdali* sex pheromone components, (Z,Z)-6,9- tricosadiene and (Z,Z)-6-9-pentacosadiene for male attraction in field tests. In: *Journal of Chemical Ecology,* 30, p. 1245-1255.

Merlot S., Mustilli A.C., Genty B., North H., Lefebvre V., Sotta B., Vavasseur A., Giraudat J., 2002. Use of infrared thermal imaging to isolate *Arabidopsis mutants* defective in stomatal regulation. In: *Plant Journal*, 30, p 601-609.

Monteith J.L., Unsworth M.H., 2008. *Principles of Environmental Physics*. Elsevier/Academic Press, p. 440.

Jones H.G., Stoll M., Santos T., de Sousa C., Chaves M.M., Grant O.M., 2002. Use of infrared thermography for monitoring stomatal closure in the field: application to grapevine. In: *Journal of Experimental Botany,* 53, p. 2249-2260.

Turner N., 1981. Techniques and experimental approaches for the measurement of plant water status. In: *Plant Soil,* 58, p. 339-366.

Wunderlich W.O. 1972. Heat and mass transfer between a water surface and the atmosphere. Lab. Report No. 14, Tennessee Valley Authority Engineering Laboratories, Norris, TN.