Non-invasive water status detection in grapevine (*Vitis vinifera* L.) by thermography

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Abstract: Grapevines are preferentially grown under mild to moderate water stress conditions to achieve the best compromise between wine quality and quantity. Water status detection for advanced irrigation scheduling is frequently done by predawn leaf water potential (ΨPD) or leaf stomata conductance (gL) measurements. However, these measurements are time and labor consuming. Therefore, the use of infrared thermography (IRT) opens up the possibility to study large population of leaves and to give an overview on the stomatal variation and their dynamics. In the present study IRT was used to identify water stress of potted grapevines. In order to define the sensitivity of IRT measurements to water stress, the IRT-based water status information were compared with simultaneously measured ΨPD and gL data. Correlations between IRT-based CWSI data on the one hand and gL and ΨPD on the other showed the potential of IRT for water stress detection. However, the CWSI calculation procedure is laborious and the sensitivity of CWSI for water stress detection still needs to be improved. Therefore, further improvements are necessary in order to apply remote IRT-based systems for irrigation scheduling in the field.

Keywords: infrared thermography, leaf temperature, stomata conductance, leaf water potential, plant water stress and crop water stress index (CWSI)
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1 Introduction

Grapevine quality and yield is very sensitive to plant water status. Excessive water stress can impair photosynthesis and fruit sugar accumulation[1] as well as reduces fruitfulness of developing buds and thus reduces yield[2]. Excessive water supply results in high yield but minor quality. Therefore, precise irrigation regulation by

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maintaining slight to moderate water stress conditions in grapevine production is beneficial as it assures optimal quality without significantly affecting yield[3,4].

Water status detection for advanced irrigation scheduling is frequently done by predawn leaf water potential (Ψ_{PD}) or leaf stomata conductance to water vapour (gL) measurements. However, both measures are labor intensive, time consuming as leaf to leaf variations require much replication for reliable data and not yet possible to be automated.

It is well investigated that leaf temperature tends to increase with water stress[5,6]. Infrared thermography visualizes this increase in leaf temperature as a consequence of stomata closure when the plant is experiencing water stress due to decrease in energy dissipation. Water stress detection with infrared thermography is a non-contact method and thus very fast and practical. It is capable to estimate large leave populations simultaneously and provides an overview on gL variation and dynamics. Thermal images together with software analysis has overcome the problem of non-leaf material inclusion (soil & bark), and it is possible to study selected parts of the canopy.

Leaf temperature however depends not only on gL but also on other environmental factors like air temperature, radiation, humidity and wind speed, which may lead to inaccuracies in thermography-based water status detection. In order to overcome this shortcoming, the crop water stress index (CWSI) was defined[7,8]. For CWSI calculation leaf temperatures of maximum transpiration and non-transpiration conditions are needed. Attempts were made to obtain these information by spraying water on leaves and by covering the leaves with petroleum jelly, respectively[9-11]. Another alternative measure of crop stress is the use of wet artificial reference surface (WARS) and taking upper base line temperature, T_{dry} as (T_{air} + 5)℃ [12,13]. To include radiation and wind effects in the computation of the CWSI, efforts are also made to derive the CWSI from the energy balance equation[14].

Despite all these improvements in CWSI calculation the sensitivity of thermography in terms water status determination is not well investigated. Therefore, the objective of this study is to calculate CWSI for potted grapevines under different irrigation regimes and to determine the correlation between CWSI and well established water status measures like Ψ_{PD} and gL.

2 Material and Methods

The experiment was conducted in a greenhouse of Universität Hohenheim, Stuttgart (Germany) from September 19th till 28th, 2008 (day of experiment, DOE 1-10) on twelve potted six year old bacchus grapevines see Figure 1. Before the experiment was started, the grapevines were placed outdoor to obtain arbitrary soil water saturation during several successive rain events. Then all the twelve grapevine pots with clearly wet soils were brought to the greenhouse. Eight plants (1-8) were allowed to dry out without irrigation and the soil water content was measured with two-rod TDR-probe (Trime-IT, Imko Germany) in a ten-minute interval. The remaining four grapevines (9-12) served as references and were placed in a catchment tray to assure availability of sufficient water while, their water status (plants 9 &10) was controlled with TDR probes too. Finally, all twelve grapevine pots were covered with a tinfoil to prevent soil evaporation and soil heating.

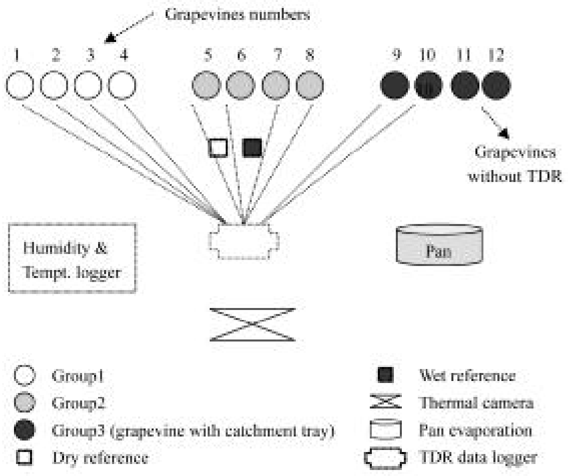

Figure 1 Experimental set-up

2.1 Thermal imaging

Infrared Vario CAM has been used to take the thermal and visible images (VIS) simultaneously. The VIS images are the images that have been recorded with the help of a visual camera of the thermography camera.

The IR-lens of the camera displays the object scenery on a micro-bolometer array with a resolution of 320×240 pixels. Irbis-professional-3 software allowed correction for object emissivity, object distance and temperature and relative humidity to analyse the pictures. The emissivity value of 0.98 was used for the grapevines. The distance between the camera and the plants was 1.7 m. And all the pictures were taken in the afternoon. A wet tensiometer cup filled with water was used as a wet reference (approximating maximum adiabatic cooling of the leaves) and black paper served as a dry reference (approximating maximum heating of the leaves) assumed to behave like a leaf with completely closed stomata.

The crop water stress index (CWSI) was calculated from the measured mean canopy temperature and wet and dry reference temperatures[14].

$$CWSI = (T_{canopy} - T_{wet})/ (T_{dry} - T_{wet})$$

Where, T_{canopy} is the actual canopy temperature obtained from the thermal image and T_{wet} and T_{dry} are the lower and upper boundary temperatures representing minimum (maximum transpiration) and maximum leaf heating (no transpiration) respectively. Note that T_{wet} and T_{dry} are equivalent to T_{base} and $T_{\max}$ in the original formulation of CWSI by Idso et al. in 1981[7].

2.2 Other measurements

Temperature and relative humidity data were logged in a one-minute interval (Hobo U12-011, Hobo USA). And vapour pressure deficit (VPD) was calculated according FAO guidelines. Due to the limited number of leaves per grapevines only one leaf per grapevine was used to determine predawn leaf water potential (Y_{PD}) with Scholander pressure chamber constructed by the Institute for Special Crop Cultivation and Crop Physiology of the University of Hohenheim. Leaf stomata conductance (gL) was measured with SC-1 porometer (Decagon devices USA) at noon and on a three days interval in the beginning and later on two days interval. The measurements were made on two preselected leaves on each grapevine with a minimum of three readings per leaf. In addition, daily pan evaporation (E_{pd}) from an open water surface (pan diameter = 21 cm) was determined gravimetrically.

3 Results

During the ten day experiment period three weather phases were identified (Figure 2). During DOE 1-3 the maximum temperature was around 22℃ and the relative humidity was 30%. From DOE 4 to DOE 6 the temperature dropped to 18℃ and the relative humidity increased to 80%. During DOE 7-9 the temperature increased again as in the beginning of the experiment and simultaneously the relative humidity decreased. According to the temperature and humidity trends, calculated averaged vapour pressure deficit (VPD) values were highest at the beginning and the end of the experiment and distinctly lower during the day 4-7 of the experiment.

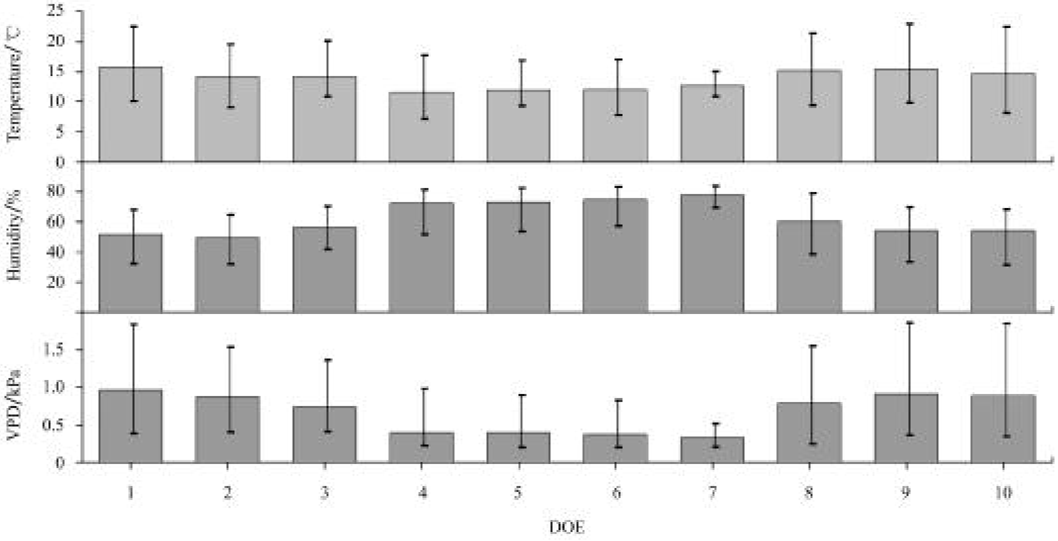

Figure 2 Mean, minimum and maximum humidity, temperature and vapour pressure deficit (VPD) during the experiment

At the start of the experiment the volumetric soil water contents (θ) of eight grapevines exposed to drying ranged from 21.9% to 31.6%. The grapevines were divided into three groups depending on their initial water content (group1= 30%, group 2 = 22% group 3 = 37%). At the end of the experiment, θ values of the eight grapevines were between 11.4% and 24.6% in which total change during the experiment was between 7.4% (Plant 2 & 3) and 11.1% (Plant 6). The average volumetric soil water content of all the three groups of grapevines is shown in Figure 3. Daily pan evaporation (E_{pd}) values showed a similar trend as VPD (Figure 4). At DOE 1 E_{pd} was 2.1 mm and decreased during the subsequent six days to 0.72 mm. During the last three days of experiment E_{pd} increased distinctly and reached values (DOE 9: E_{pd} = 2.08 mm) similar to that at DOE 1.

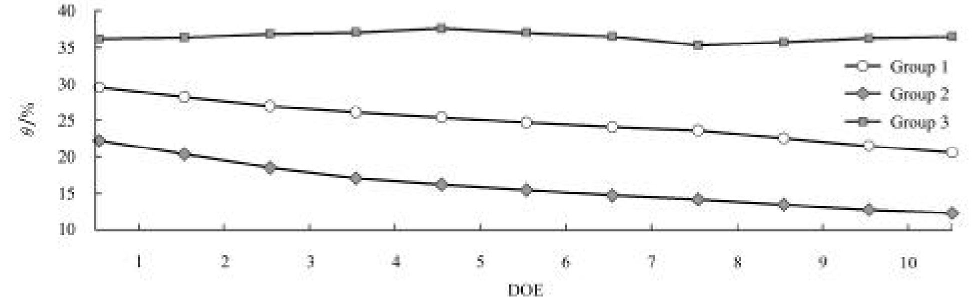

Figure 3 Average volumetric soil water content (θ) of all the three groups of grapevines during the experiment

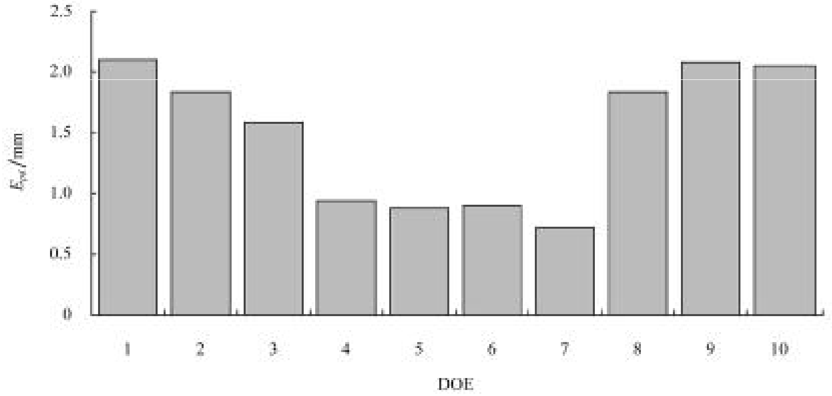

Figure 4 Daily pan evaporation (E_{pd}) measurement during the experiment

4 Thermal image analysis

In order to eliminate any incorporation of extraneous surfaces in the study of the leaf temperature such as fruit or bark and to identify the leaf area accurately, two methods were used.

In the first method the temperature frequency histograms were made to analyse the temperature of the dry and wet references and the leaves. For this the temperature of the wet and dry references are used as threshold and pixels which are outside of the dry-wet threshold range are excluded from analysis. In Figure 5 the dry reference is in the right, wet reference in the left and the experimental plant is in the middle. It can be seen that the wet reference is cooler than the experimental plant while the dry reference is warmer. It should be noted that the choice of dry-wet references may affect the value of the mean temperature, and the frequency distribution of temperatures obtained.

In the second method (Figure 6) the infrared image and the visible image were merged together. This helps to identify the leaf area especially when it is difficult to identify the leaves in the thermal image. The merging of two images facilitates the analysis of plant temperature accurately by calculating the temperature of each leaf. Results proved that both methods were similar with respect to the leaf temperatures obtained.

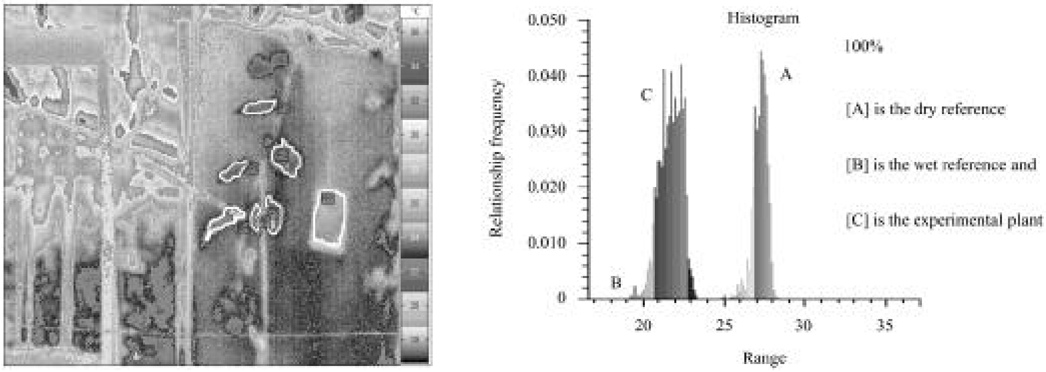

Figure 5 Temperature frequency distribution of the image after excluding the background surroundings of the grapevine canopy

Infrared image Visible image Merged image

Figure 6 Overlapping of visible and thermal images to identify accurately the plant leaves

5 Leaf temperature and CWSI measurements for identifying the water status

The temperature variation of non-irrigated grapevines (Figure 7) illustrate that not all the eight grapevines show the same increase in leaf temperature. It can be seen clearly that the average temperature of plants in group 3 at the start (23℃) and end (23.3℃) of the experiment was almost the same. Plants which show the highest increase in temperature are the plants in group 2 i.e. plants 7(6.6℃), 6 (5.4℃), and 8 (4.9℃). The different temperature trends are reflected in the calculated CWSI (Figure 8). Plants in group 3 had the lowest values at the experiment end, while CWSI in group 2 increased distinctly and showed highest values at DOE 10.

6 Relationship between leaf water potential, stomata conductance and CWSI

The predawn leaf water potential (Figure 9) of group 3 was always under 2 bar whereas group 2 plants showed continuous increase in Ψ_{PD} and continuous decrease in gL (Figure 10) and reaches its maximum at the end of experiment. This sharp decline in leaf water status and stomata conductance to water vapour indicates the necessity for water status monitoring for precise irrigation scheduling to prevent damage. Values of Ψ_{PD} in between 3-4 bar is mostly considered to be sign of water stress in grapevines. Generally, a good correlation with CWSI was found throughout the experiment except on the last day for group 1 when high Ψ_{PD} is not displayed by the high CWSI (Figure 9). Low Ψ_{PD} and high gL of group 3 is very well reflected in small CWSI value. A clear inverse relation can be seen in group 2 and 3 between gL and CWSI. It is interesting to note here that it is plants in group 2 which show very good correlation between CWSI and gL and between CWSI and Ψ_{PD}.

7 Discussion

The effective use of thermal sensing is to estimate plant temperature and to study plant water relations. This can be used further as an indicator of stomatal conductance because the leaf temperature is a function of

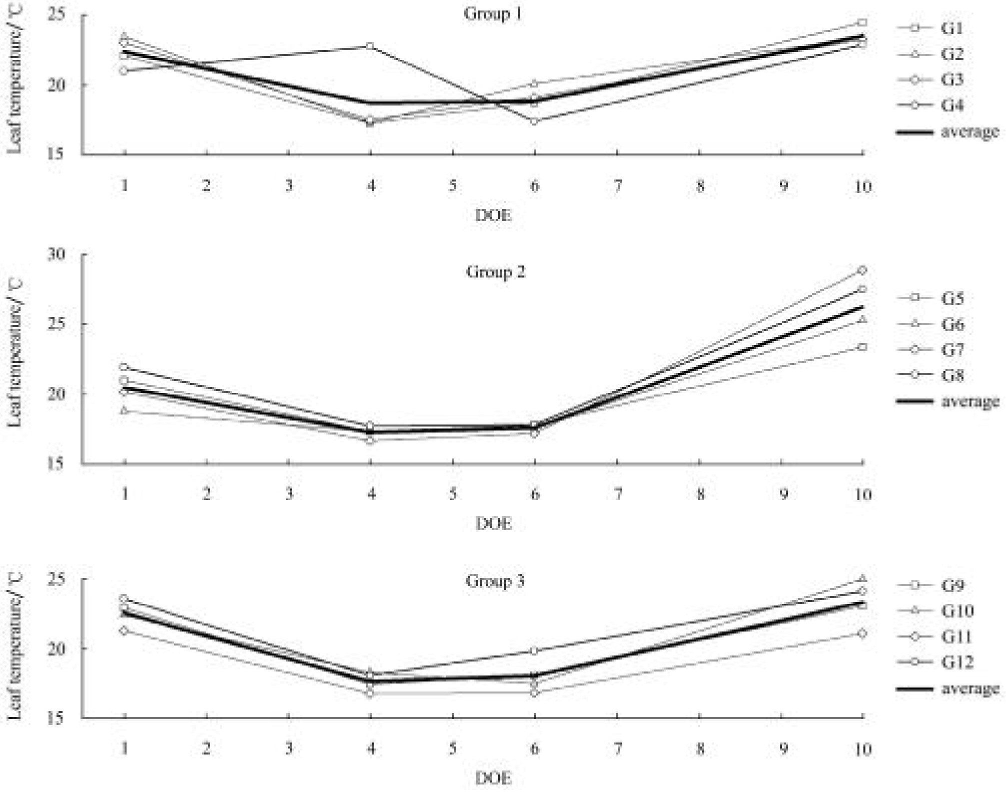

Figure 7 Leaf temperature variation of irrigated (group 3) and non- irrigated grapevines (group 1 and 2)

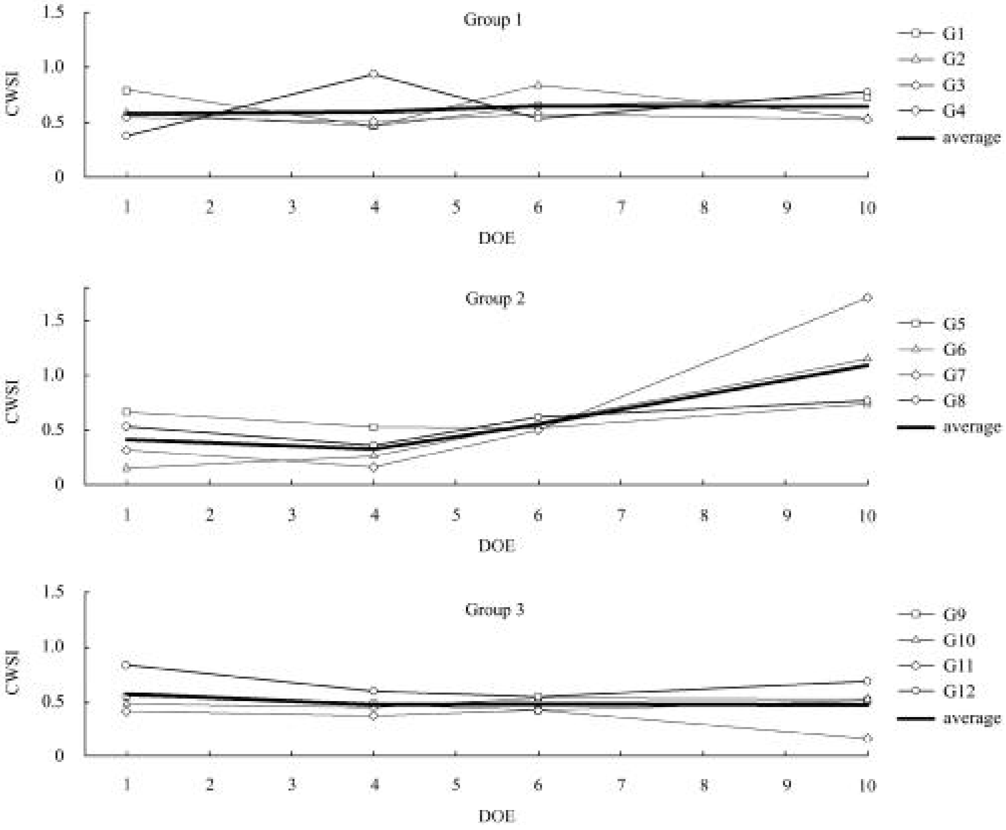

Figure 8 Crop water stress index (CWSI) measurements of irrigated (group 3) and non- irrigated grapevines (group 1 and 2)

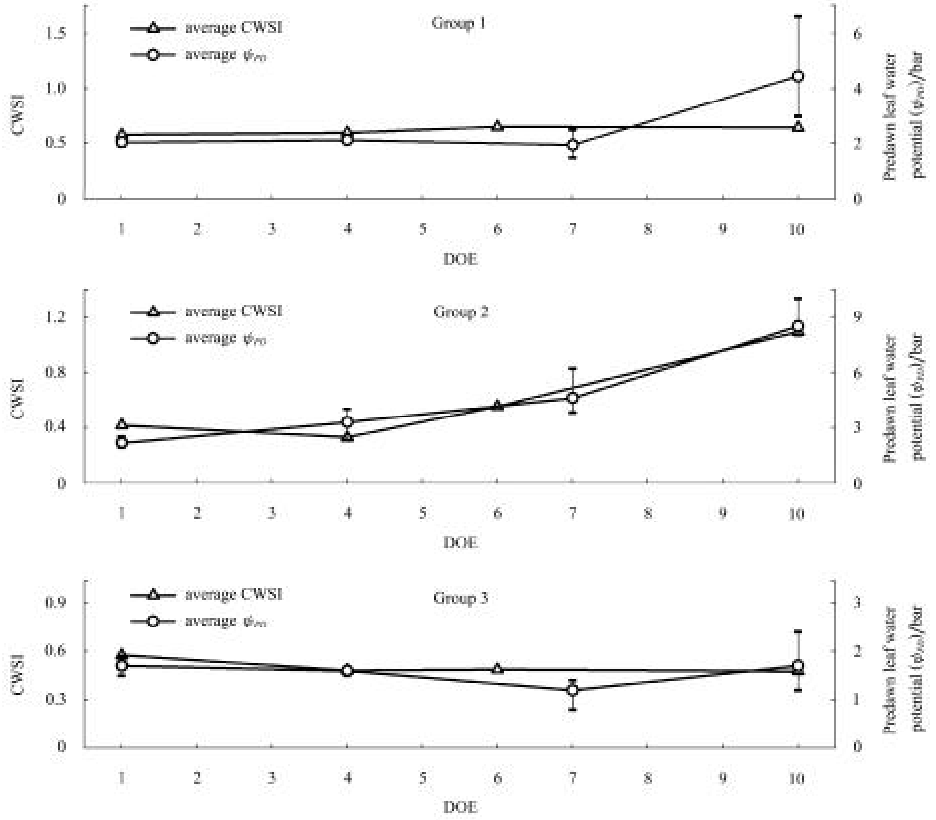

Figure 9 Crop water stress index (CWSI) vs. predawn leaf water potential (Ψ_{PD}) measurements

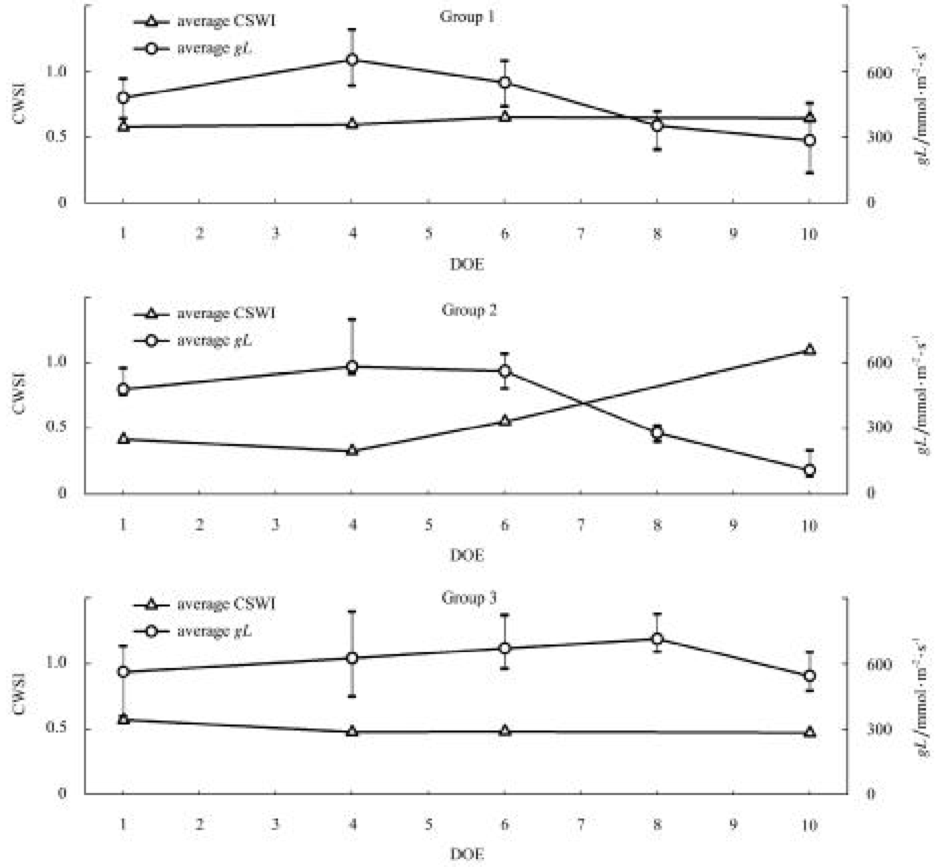

Figure 10 Stomata conductance to water vapour (gL) vs. crop water stress index (CWSI) measurements

evaporation rate and transpiration from the leaf. The leaf temperature affected by other physiological processes is very rare[15] for example it can be due to increase in respiration rate[16] but the heat generated is too small to have an effect on leaf temperature.

The use of different wet and dry reference surfaces to determine the limit of canopy temperature distribution has been used[9]. But the selection of the leaf area based on the references threshold may lead to the inclusion of non-leaf objects if the temperature of the leaf is close to either of the references. Even the time difference between spraying the leaves and taking the thermal image is not error free. Therefore, this will wrongly estimates the temperature difference between the stressed and non-stressed plants. It has been suggested to use the variation in temperatures within the canopy[17,18] to determine water stress but no evidence was found in our result to support this hypothesis as there was no large variation within the canopy to distinguish between stressed and non-stressed plants, which is in accordance with the findings of Grant et al., 2006[10].

The continuous measurements of the soil water status showed (Figure 3) that maximum change in θ at the end of the experiment was shown by Plants 6 and 7 in group 2 under severe water stress, while Plants 2 and 3 in group 1 revealed the lowest $\Delta\theta$ values and finally the least water stress. An explanation with different hydraulic properties or poorly installed TDR probes is unlikely since all grapevine soils showed similar water contents when being saturated after the experiment ($40\% < \theta s < 46\%$). Therefore, it is more obvious that the differences in θ between the grapevines resulted from different root water uptake and transpiration capabilities.

During the experiment it was found that the atmospheric evaporative demand in the beginning and the end of the experiment was similar (Figure 4). Thermal imaging has the potential to substitute direct leaf measurements and to provide a more robust signal of the crop water status. In the present study, it has been demonstrated that thermal images can be used as an alternative to direct gL and Ψ_{PD} measurements. The least increase of temperature in the reference plants in group 3 and the subsequent low CWSI, Ψ_{PD} and high gL values shows the potential of thermal imaging in distinguishing the two irrigation regime. There was a clear linear relationship between CWSI and Ψ_{PD} and inverse relationship between CWSI and gL. It is interesting to note that group, which showed the highest increase in temperature was the same group, which showed the maximum decline in gL and maximum increase in Ψ_{PD}.

8 Conclusions

In conclusion, it is evident from the data presented here that infrared thermography can be a useful method in irrigation scheduling but the use and selection of appropriate dry and wet reference threshold temperatures is important to avoid any inclusion of non-leaf objects in the image analysis. One of its major advantages when compared with leaf stomata conductance to water vapour measurement is the possibility to study large areas of canopy in less time. While an estimation of predawn leaf water potential and stomata conductance to water vapour requires meteorological data, the CWSI measurements are sufficient for detection of the plant water status and require no additional information. It is a more rapid and practical approach as it requires only thermal camera and no other special equipment. Further research should focus on the sensivity of thermal pictures with respect to the changing weather conditions for example change in wind speed, radiation and temperature, and the influence of leaf angle variation within the canopy.

Acknowledgments

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