Crop temperature measurements for crop water status identification in greenhouses

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Abstract

Proper irrigation management in hydroponics through efficient use of water and fertilizers is crucial to the production of high quality products. Low water supply rates may lead to crop water stress and reduction of production. The temperature of the plant has been identified as a good indication of plant water status and has been included in several crop water status related indices. However, measuring crop temperature is a complex task, as contact sensors must be small and can lose contact with the plant. Recently, remote sensing methods have offered a promising alternative for crop temperature measurements. This work was to assess the reliability of crop temperature measurements obtained by different infrared thermometers, either as single sensors (infrared thermograph and infrared thermocamera) or infrared thermometers connected to a wireless sensor network (WSN), and this work was to compare and evaluate different crop water status indices which are based on crop temperature. Experiments were conducted in a hydroponic cultivation system with tomato crops. The crop water status indexes used were: stress degree day (SDD), temperature stress day (TSD) and crop water stress index (CWSI). The indices were evaluated using plant physiological characteristics like crop transpiration, sap flow and crop photosynthesis, and were able to early detect crop water stress. The goal was to study the effective performance of the thermal indicators in detecting crop water stress on greenhouse conditions, in which, air temperature, humidity, vapor pressure deficit and solar radiation vary greatly. Measurements from all single sensors and the WSN were used for that purpose. It was concluded that crop temperature may be a proper indicator to detect water stress on a daily basis. On an hourly basis, different forms of stress cause an increase of crop temperature, therefore further analysis is required.

Keywords: irrigation control, crop temperature, thermal indices, thermography

INTRODUCTION

In the framework of "*speaking plant approach*" methods, different physiological information could provide important supplementary data for crop water stress detection in greenhouse conditions, especially if integrated into control systems or computer models. On-demand irrigation is based on precise plant needs, thus canopy needs must be identified and assessed based on speaking plant approach methods. For this purpose, different plant-based physiological indicators are developed to detect crop water stress. The most popular methods to measure crop water variation are based on foliage reflectance and temperature evaluation according to remote reflectance and temperature sensors. Crop temperature has been identified as a good indicator for crop water status and has been included in several crop water status-related indices. Usually, in crop water stress conditions, the crop

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temperature varies due to transpiration and stomatal conductance fluctuation, as the plants manifest self-protection mechanisms (closure of stomata and modification of transpiration rate) to prevent irreparable physiological damages but to result in the increase of crop temperature (González-Dugo et al., 2005; Prenger et al., 2005; Sepulcre-Cantó et al., 2006; Maes and Steppe, 2012).The most popular thermal indices based on crop temperatures at plant and canopy levels are the "stress degree day" (SDD), the "temperature stress day" (TSD) and the "crop water stress index" (CWSI).

The stress degree index (SDD) was proposed by Idso et al.(1977) and Jackson et al. (1977) and calculates the difference between crop and air temperature (T_c–T_a) at solar noon period at day *i* during an *n*-day period. SDD are negative values in good plant irrigation conditions and become positive in water stressed conditions (Wanjura et al., 2006; Sepulcre-Cantó et al., 2006; Maes & Steppe, 2012). SDD is influenced from different environmental conditions such as vapour pressure deficit (VPD) and solar radiation intensity, and it is not applicable for use with short duration irrigation frequency periods (Sepulcre-Cantó et al, 2006; Maes & Steppe, 2012). However, TSD calculates the crop temperature difference between unknown water stressed and healthy plants (T_s-T_c), at the same time period under similar environmental conditions, to detect different water stress levels. TSD index is divided into: a) TSD_{cal} index in which crop temperature of non-stressed and stressed treatment is calculated based on the Penman-Monteith equation, b) TSD_{meas} index in which the crop temperature of unknown level of water stress plants is measured while the potential crop temperature of non-stressed plants is calculated through the Penman-Monteith equation and c) TSD_{field} in which the temperature of non-stressed plants and of plants with unknown water content is measured. In the case of TSD_{field} index definition, sufficiently watered plants should exist in order to measure the minimum temperature in certain environmental conditions. Finally, CWSI varies from 0 (healthy plants) to 1 (fully water stressed plants), by combining information from crop temperature, VPD and other environmental conditions (Katsoulas et al., 2002, 2011).

In this work, remote sensing based on crop temperature was used to estimate crop temperature and its correlation with crop water status was studied to determine the most effective thermal indices in water stress detection.

MATERIAL AND METHODS

Greenhouse facilities and plant material

The experiments were conducted in the greenhouse facilities of the University of Thessaly, in Velestino, Greece (39° 44' N, 22° 79' E). The greenhouse was a 160 m^2 single-span with single layer polyethylene film cover. Tomato plants (*Lycopersiconesculentum*, cv. Zizel) were grown in a hydroponic system with perlite substrate slabs, at a density of 2.4 plants per m^2. Fertigation was automatically controlled with set points for electrical conductivity of 2.4dS m^{-1} and pH of 5.6. The two treatments were plants that were sufficiently watered, and plants that were water stressed. The first day of the experiment both treatments were watered ("control day"), while at the second day, one group of plants received the water stress treatment, implemented by withholding water by removal of the irrigation emitters from the slab. The stressed plants remained without water for the next three days. The fifth day of the experiment, the emitters were placed back on to the slab, while at the same time 10 l of nutrient solution were added directly to the slab. The daily irrigation water amounts were from 2.4 to 3.1 l per plant, while 30% of that amount was drainage.

Measurements

Greenhouse air temperature and relative humidity were measured using temperature and humidity sensors (HD9009TR Hygrotransmitter, Delta OHM S.r.L., Padova, Italy).Incoming solar radiation was monitored using a pyranometer (CM-6, Kipp&Zonen B.V., Delft, The Netherlands). Plant temperature was measured using an infrared thermograph (OS5551A, series Range 2, 20-122cm, Omega Engineering Inc., USA). To assess the physiological status of the crop, measurements of substrate moisture (Grodan, WCM control, Netherlands) and crop photosynthesis (LCpro+, ADC BioScientific Ltd., UK) were carried out completed. Finally, the sap flow in the stems of the plants was measured using sap flow sensors (SF-SP 5 PR, Phytech, Israel). Data were recorded every 10 minutes by a data logger (ZENO®-3200, Coastal Env. Systems, Inc., Seattle, WA, USA).

Calculations

Based on crop temperature, the thermal indices SDD, TSD_{meas}, TSD_{field} and CWSI were calculated. SDD calculates the difference between crop and air temperature (T_c-T_a) and TSD (TSD_{field} and TSD_{meas}) calculates the temperature difference between plants with unknown level of water stress and well-watered plants (T_s-T_c). In the case of TSD_{meas}, the crop temperature of water stressed plants was measured, while the crop temperature of well watered plants was calculated through equation (2). In the case of TSD_{field}, the temperature of non-stressed and unknown water content was measured. CWSI (eq. 3) combines information from crop temperatures (of non-stressed plants, plants with unknown level of water stress and fully stressed plants) with VPD and other environmental conditions based on equations (1) and (2):

$$T_M = T_a + \frac{R_S}{\rho g_a C_\rho} \tag{1}$$

$$T_m = T_a + \frac{\left(\frac{1}{g_a}+\frac{1}{g_M}\right)\frac{R_S}{\rho C_\rho}-\frac{VPD}{\gamma}}{1+\frac{\Delta}{\gamma}+\frac{g_a}{g_M}} \tag{2}$$

$$\mathrm{CWSI} = \frac{T_c-T_m}{T_M-T_m} \tag{3}$$

where, T_a is the air temperature (°C), g_a is the aerodynamic conductivity (m s^{-1}), g_M is the maximum stomata conductivity (m s^{-1}), ρ and C_p are the density (kg m^{-3}) and the specific heat capacity of the air (J kg^{-1} K^{-1}) respectively, R_s is the radiation intensity (W m^{-2}) inside the greenhouse, Δ is the slope of the air saturation curve (Pa K^{-1}), VPD (kPa) is the vapor pressure deficit and γ is the psychometric constant (kPa).

RESULTS AND DISCUSSION

The values of air temperature and healthy and stressed crop temperatures during the days of the experiment are presented in Figure 1.The intense variation of the environmental conditions can be observed, as the highest value of air temperature at noon was approximately 35°C while the average daily temperature was 25.5°C. Solar radiation intensity inside the greenhouse was 560 Wm^{-2} at midday and the average relative humidity was 65%. It was observed that the mean crop temperature of stressed plants varied depending on the water stress progress. For instance, on the 1st Day (in which the crop of both treatments were irrigated according to conventional time irrigation schedule), the mean and the maximum crop temperature of the plants were 21.7°C (control plants) and 21.5°C (stress treatment), and 32.1°C (control treatment) and 33.0°C (stress treatment), respectively. These values indicate good water status of all plants. On the 2nd Day (1stDay of withholding irrigation in stress plants), an increase in both mean crop temperature of control and stressed treatments is observed 22.5°C and 22.4°C, respectively. The temperature difference between the control and stressed plants was more than 0.6°C on the 3rd Day of the experiment (2nd Day of irrigation holding for stressed plants) and more than 1.4°C on the 4th Day (3rd Day of irrigation holding). On the last Day of the experiment (5th Day) in which the emitters were replaced onto the slab of the stressed plants, the mean crop temperature difference decreased at 0.8°C.

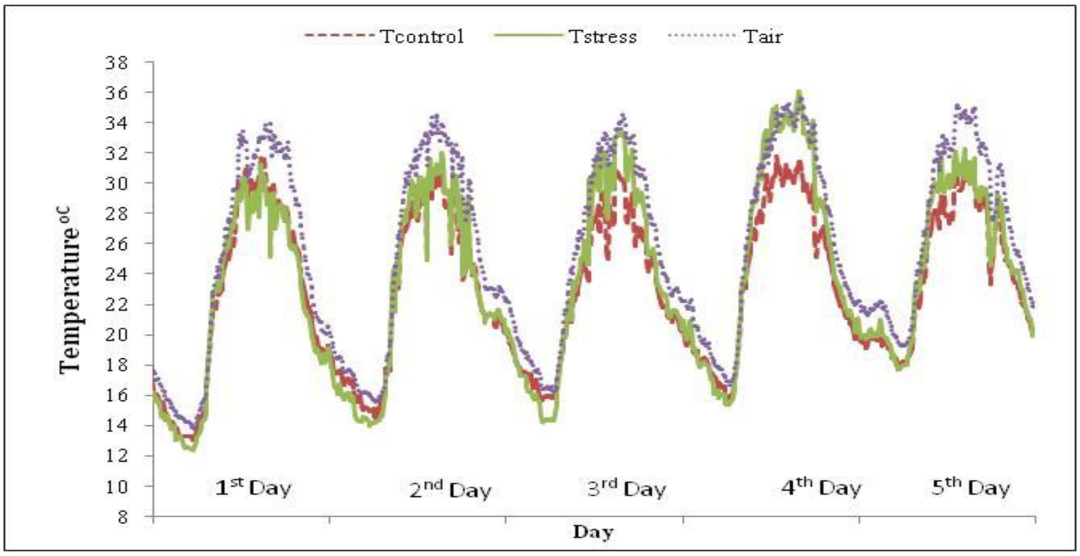

Figure 1. Daily progress of air (Tair), healthy (Tcontrol) and stressed crop (Tstress) temperature variation the1st day (well irrigated plants), 2nd, 3rd, 4th day (water stressed plants) and 5th day (re-irrigated plants) of the experiment.

Based on the data from Figure 1 and the measurements of environmental conditions, the stress indices, such as SDD (according to continuously temperature of the crop and air (Tc-Ta) difference), $TSD_{meas.}$, TSD_{field} and CWSI, were calculated. The maximum value of SDD for the well watered and healthy plants was less than 0.6°C during noon (Table 1). The water stressed plants presented positive values, greater than 0.6°C from the first day of irrigation holding, as the maximum values of the index reached almost the value of 1. In Table 1, the SDD variation based on stressed plants is shown and is compared to the index values of healthy plants, during the days of the experiment. During the next two days, the maximum canopy to air temperature difference of the water stressed plants was higher than 2°C during midday.

Table 1. Daily mean (μ), standard deviation (σ) & maximum (max) value of SDD according to treatment (healthy and stressed plant) during the days of the experiment (1st Day: control day, 2nd, 3rd, 4th Day: irrigation holding for the 2nd treatment, 5th Day: re-irrigation for the 2nd treatment).

	(Tc-Ta) °C			
	Control		**Stress**	
Days of the experiment	**(μ±σ)**	**max**	**(μ±σ)**	**max**
1st Day	1.91±1.05	0.12	2.16±1.18	0.26
2nd Day	2.19±1.48	0.52	2.32±1.25	0.95
3r Day	2.54±1.55	0.6	1.89±1.09	2.28

4th Day	2.45±1.25	-0.26	1.01±1.02	1.72
5th Day	1.72±1.14	-0.66	1.99±1.31	0.312

In Table 2, the mean, min and max values of TSD_{field} and TSD_{meas} are presented. TSD_{field} was equal to -0.29 during the 1st Day of the experiment (well watered plants in both treatments). On the 2nd Day of the experiment (1st Day of irrigation holding), the index became positive from the first hours of the day, as the average index value increased by more than 1. During noon, as the irrigation needs were maximized, the index value increased by at least 2 degrees. TSD_{field} seems to be a suitable thermal index for early water stress detection. However, the existence of well irrigated plants as a reference point during the measurements is required. TSD_{meas} could detect crop water stress without measuring the temperature of well watered plants (using a sensor), because the minimum temperature was calculated based on the Penman-Monteith equation. Despite that TSD_{meas} values were higher than TSD_{field}, they followed a similar variation with TSD_{field} as the crop water stress was developing. More specifically, on the 1st Day of the experiment, TSD_{meas} was equal to 3.95, while on the 2nd Day of the experiment TSD_{meas} increased by more than 1and by 1.5 during the 3rd and the 4th Day of the experiment, respectively, due to increasing water stress. TSD_{meas}, similar to SDD index, was affected by the environmental conditions variation. TSD_{meas} varied according to VPD fluctuation, while it seems that only TSD_{meas} (and not TSD_{field}) was influenced by that parameter, with a correlation coefficient greater than 0.8 (see Figure 2). TSD_{field} gave a low correlation coefficient with VPD variation (R^2=0.03).

Further normalization by dividing the index with the maximum crop temperature in specific conditions, could eliminate the influence of the environmental conditions. This normalization method transforms TSD_{meas} to CWSI. In Table 3, the daily average and standard deviation of CWSI values of the sample during the days of the experiment are presented. Katsoulas et al. (2002) noted that the high values of CWSI observed during dusk, were caused by low light radiation and should not be considered. The mean daily value of CWSI for the well watered plants varied from 0.43 to 0.48, while the respective values for the water stressed plants increased from 0.42 to 0.71 as the water stress was developing. The maximum index value (0.71) was observed during the 4th Day of the experiment, in which water stress was maximum. During the final day, in which the emitters were replaced into the hydroponic bag, CWSI decreased, reaching values equal to 0.53. Comparing CWSI with VPD fluctuation, it was observed that CWSI was a stable thermal index that detected crop water stress without the influence of VPD variation.

Table 2. Daily mean (μ), maximum (max), minimum (min) value of TSD_{field} and TSD_{meas} of the canopy and standard deviation (σ) of the sample, during the days of the experiment (1st Day: control day, 2nd, 3rd, 4th Day: irrigation holding for the 2nd treatment, 5th Day: re-irrigation for the 2nd treatment).

	1st Day	**2nd Day**	**3rd Day**	**4th Day**	**5th Day**
			TSD_{field}		
μ±σ	-0.29±0.99	0.99±0.62	2.17±1	3.33±0.89	1.20±0.86
max	1.46	2.05	3.90	4.64	3.00
min	-2.15	-1.12	0.35	1.23	-0.97
			TSD_{meas}		
μ±σ	3.95±1.7	4.08±2.08	5.58±2.8	7.03±2.61	4.41±1.56
max	6.88	7.58	9.53	10.86	7.28
min	-1.31	-1.98	-1.98	-1.51	-0.84

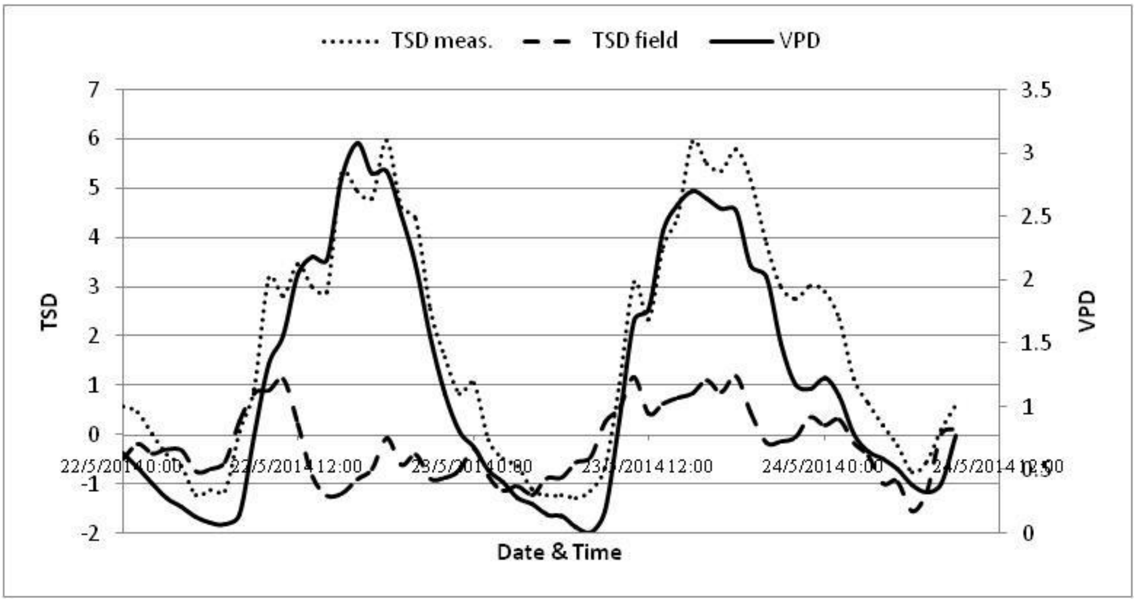

Figure 2. TSD_{field} and TSD_{meas} variation based on VPD fluctuation.

By comparing the thermal indices with variation of photosynthetic rate, it was concluded that the thermal indicators could detect tomato water stress one day before it could be detected by the decrease in the rate of photosynthesis. On the second day of no irrigation, the photosynthetic rate of water stressed plants was lower (2%) than the photosynthesis of well-watered plants, while on the third day, the photosynthesis decreased by more than 25%. During the final day of the experiment, photosynthesis of the water stressed plants approached the values of the non-stressed plants, due to resumption of irrigation.

Table 3. Daily mean (μ) and standard deviation (σ) of CWSI values of the sample according to treatment (healthy=Control and stressed plant=Stress) during the days of the experiment (1st Day: control day, 2nd, 3rd, 4th Day: irrigation holding for the 2nd treatment, 5th Day: re-irrigation for the 2nd treatment).

	CWSI (μ ± σ)				
	22/5/2014	**23/5/2014**	**24/5/2014**	**25/5/2014**	**26/5/2014**
Control	0.48±0.05	0.45±0.1	0.46±0.063	0.43±0.08	0.43±0.11
Stress	0.42±0.1	0.51±0.13	0.64±0.06	0.71±0.08	0.53±0.12

CONCLUSIONS

The following conclusions can be drawn from the study:

– The crop temperature and the thermal indices SDD, TSD_{field}, TSD_{meas} and CWSI could be appropriate indicators for water stress detection on a dailytime-scale. However, on an hourly time-scale, different types of stress lead to crop temperature increase and severe index variations, as previously demonstrated. For this reason, further emphasis should be given to environmental conditions during the measurements inside the greenhouse, while the proper correlation of thermal indices with other plant characteristics becomes absolutely necessary.Through this research, it was concluded that TSD_{field} was a quite stable thermal index relative to environmental conditions variation, as it detected crop water stress from the first day of withholding irrigation. However, the existence of well-irrigated plants is necessary, as a reference, something that is not always feasible in greenhouse conditions. TSD_{meas} could detect crop water stress from the 1st Day of withholding irrigation without the need of well-watered plants, as the minimum temperature was calculated through the Penman-Monteith equation. However, TSD_{meas} is quite influenced by the VPD fluctuations.

– CWSI did not seem to be affected by the environmental conditions and it was able to detect crop water stress from the very first day of withholding irrigation. SDD was another indicator that detected water stress from the first day.

– The thermal indicators could detect tomato water stress one day before it could be detected by the decrease in photosynthesis rate. The crop temperature variation relative to different plant water levels during the day was too limited and difficult to be studied, mainly due to the large variation of greenhouse environmental conditions. Further study of the thermal indices based on hourly variationin different environmental conditions and substrate moisture concentrations could lead to more satisfactory results. Moreover, further statistical analysis of the data could contribute to the formation of other novel thermal indicators.

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