Remote sensing for crop water stress detection in greenhouses

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Abstract

Irrigation management is considered as one of the most important cultivation techniques which can lead to production of high quality products through efficient use of water and nutrients. The temperature of the crop has been identified as a good indicator of plant water status and has been included in several crop water status related indices. During recent years, remote sensing methods have offered a promising alternative for crop temperature measurements. Furthermore, another advantage of remote sensing is that can be easily implemented for evaluation of spatial distribution of the measured parameter. The aim of this work was to evaluate different thermal indices, such as the stress degree day (SDD), the temperature stress day (TSD) and the crop water stress index (CWSI), on their performance for plant water stress detection in greenhouses based on remote infrared thermograph measurements and on their potential use for irrigation scheduling.

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

Introduction

Crop temperature has been identified as a good indicator for plant water status and has been included in several crop water status-related indices. It has been also correlated with plant transpiration and stomatal conductance (Prenger et al, 2005). When plants are under water stress, it manifest self-protection mechanisms (closure of stomata and adaptation of transpiration rate) in order to be protected from various irreparable physiological damages having as a result the increase of leaf temperature (González-Dugo et al, 2005; Sepulcre-Canto et al, 2006; Maes & Steppe, 2012). Jackson et al (1981) were the first to use methods based on leaf temperature to detect plant water stress. Since then, different thermal indices have been developed, based on leaf temperatures at plant and canopy levels, such as the “stress degree day” (SDD), the “temperature stress day” (TSD) and the “crop water stress index” (CWSI).

SDD calculates the difference between crop and air temperature (T_c–T_a) in order to detect plant water stress during the day (Sepulcre-Canto et al, 2006; Maes & Steppe, 2012). When SDD values become positive, plants need further watering and irrigation should be initiated (Wanjura et al, 2006). However, SDD is characterized as unstable index due to effects from environmental conditions, such as vapour pressure deficit (VPD) and solar radiation intensity (Sepulcre-Canto et al, 2006), and thus it is not applicable in short-time irrigation frequency periods (Maes & Steppe, 2012). According to Maes and Steppe (2012), the replacement of air temperature by healthy plant temperature in certain environmental conditions could detect plant water stress during different time periods of the day. TSD is that thermal index that calculates the temperature difference between unknown water stressed and healthy plants (T_s-T_c), at the same time period under similar environmental conditions, in order to detect different water stress levels. Clawson et al (1989) separated TSD index in: a) TSD_{cal} index in which leaf temperature of non-stressed and stressed plants is calculated based on Penman-Monteith equation, b) TSD_{meas} index in which the leaf temperature of plants with unknown level of water stress is measured while the potential leaf 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 leaf water content is measured. In the case of TSD_{field} index definition, well watered plants should exist in order to measure the minimum temperature in certain environmental conditions.

CWSI combines information from leaf temperature, VPD and other environmental conditions (Katsoulas et al, 2002, 2011). It varies from 0 (healthy plants) to 1 (fully water stressed plants), while the daily crop temperature variation of water stressed plants is expected to change from 1ºC to 3ºC.

Most of researchers in greenhouse environment consider the climate inside a greenhouse as uniform (Kittas & Bartzanas, 2007). The assumption of complete homogeneity of greenhouse microclimate is not valid in a typical modern greenhouse since greenhouse size has greatly increased over recent decades. In larger greenhouses, temperature and humidity distributions are highly heterogeneous both horizontally and vertically. This increases energy, water, fertilisers and pesticides (about 15% in each category) consumption.

Bojacá et al (2009) used 25 temperature sensors to monitor the air temperature in 1 ha greenhouse and produced the temperature distribution maps. Then, they used a crop growth model to model the growth performance of a tomato crop and produced the final fruit weight maps. They observed average temperature differences of 1ºC were at radiation intensities below 170Wm^{-2}, but when the global radiation reached levels above 750 W m^{-2}, average temperature variations were as high as 2.2ºC. The temperature differences between extreme locations, although only 1ºC higher during the day, can determine differential behaviours on plant growth and development. However, measuring crop temperature by conventional sensors is a difficult task, since contact sensors must be very small and usually loose contact with the plant. Furthermore, using conventional wired sensors in not easy to monitor several positions. During recent years, remote sensing offers a promising alternative for temperature measurements.

In this work, remote sensing is used to measure leaf temperature and its correlation with plant water status is studied. In addition, the most effective thermal indices in water stress detection were analyzed.

Materials and methods

Greenhouse facilities and plant material

The experiments were conducted in the greenhouse facilities of the University of Thessaly, in Velestino, Greece (39º 44' N, 22º 79' E). The greenhouse was a single-span one, with polyethylene film cover and had an area of 160 m^2. During the experiments, tomato plants (*Lycopersicon esculentum*, cv. Zizel) were grown in a hydroponic system with perlite substrate at a density of 2.4 plants per m^{-2}. Fertigation was automatically controlled by a computer with set points for electrical conductivity of 2.4dS m^{-1} and pH of 5.6. Plants were pruned to one stem. Two treatments took place. The first treatment concerned well watered plants, while the second one concerned water stressed plants.

The first day of the experiment was the "control day" for both treatments, while at the second day, the plants of the 2nd treatment were introduced to water stress by withholding water through drippers removal from the slab. The stressed plants remained without water for the next three days. The fifth day of the experiment, drippers were placed back to the slab, while at the same time 10 l of nutrient solution were added to the hydroponic 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 by means of 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). Furthermore, in order to assess the physiological status of the crop, measurements of substrate moisture (Grodan, WCM control Netherland) and leaf photosynthesis (LCpro+, ADC BioScientific Ltd., UK) were carried out. Finally, the sap flow in tomato plant stem was measured by means of sap flow sensors (SF-SP 5 PR, Phytech, Israel). The above data were recorded every 10 min in a data logger (ZENO®-3200, Coastal Env.Systems, Inc., Seattle, WA, USA).

Calculations

Based on plant 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 case of TSD_{meas} index, the leaf temperature of water stressed plants was measured, while the leaf of well watered plants was calculated through equation (2). In case of TSD_{field}, the temperature of non-stressed and unknown leaf water content was measured. CWSI combines information from leaf temperature (of non-stressed plants, plants with unknown level of water stress and fully stressed plants) with VPD and other environmental conditions following equations (1) and (2).

$$T_M = T_a + \frac{R_s}{g_a \rho C_p} \quad (1), \qquad T_m = T_a + \frac{\left(\frac{1}{g_a} + \frac{1}{g_M}\right)\frac{R_s}{\rho C_p} - \frac{VPD}{\gamma}}{1 + \frac{\Delta}{\gamma} + \frac{g_a}{g_M}} \quad (2), \qquad CWSI = \frac{T_c - T_m}{T_M - T_m} \quad (3)$$

where, T_a is the air temperature (°C), g_a is the aerodynamic conductance (m s^{-1}), g_M is the maximum stomatal conductance (m s^{-1}), ρ and C_p are the density (kg m^{-3}) and the specific heat capacity of 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

During the experiment, intense variation of the environmental conditions was observed, as the highest value of air temperature at noon was around 35°C while the average daily temperature was 25.5ºC. Solar radiation intensity was at 560 W m^{-2} during midday and the average relative humidity was equal to 65%. The maximum value of SSD for the well watered and healthy plants was less than 0.6 during noon. The water stressed plants presented positive values, greater than 0.6 from the first day of irrigation holding, as the maximum values of the index reached the value of 1. In Figure 1, the SDD variation based on stressed plants is shown and is compared to the index values of healthy plants. During the next two days, the maximum canopy to air temperature difference of the water stressed plants was higher than 2ºC during midday.

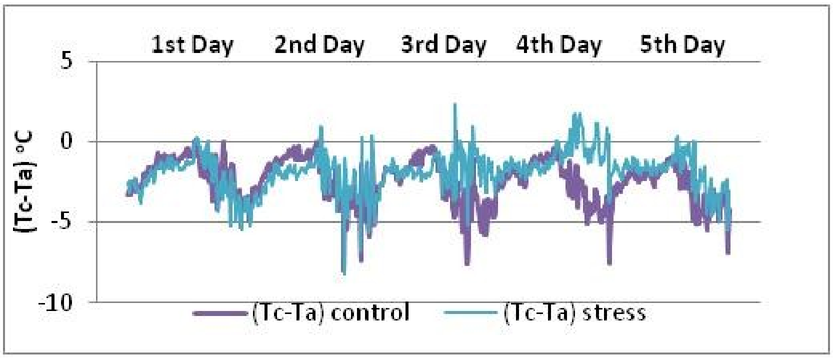

Figure 1. Hourly variation of thermal index SDD based on T_c-T_a difference at the 1st day (well irrigated plants), 2nd, 3rd, 4th day (water stressed plants) and 5th day (re-irrigated plants).

The mean, min and max values of the TSD$_{field}$ and TSD$_{meas}$ are shown in Table 1. The TSD$_{field}$ was equal to -0.29 during the first day of the experiment (well watered plants in both treatments), while positive index values were observed during the morning. The second 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 2degrees. 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 of high importance. On the other hand, TSD$_{meas}$ could detect plant water stress without measuring the temperature of well watered plants (using a sensor), as the minimum temperature (i.e., that of a healthy plant in certain environmental conditions) was calculated based on the Penman-Monteith equation. Despite the fact that TSD$_{meas}$ values were higher than TSD$_{field}$, they followed similar variation with TSD$_{field}$ as the plant water stress was developing. More specifically, the first day of the experiment, TSD$_{meas}$ was equal to 3.95 while the second day of the experiment TSD$_{meas}$ increased by more than 1and by 1.5 during the third and the fourth day of the experiment respectively, due to water stress influence.

In addition, in Figure 2, the development of plant sap flow in relation to TSD$_{field}$ and TSD$_{meas}$ is shown. The index values followed opposite variation from the direction of sap flow rate values, with the exception of the first day of irrigation holding and the first day of re-irrigation. Generally, the amount of water that was lost through the transpiration process decreased the plant water potential in order to develop negative hydrostatic pressure, causing water movement from the roots to the leaves. The first day of the experiment, the healthy plants showed low sap flow values during the day, while high values were observed during the night. During the night, the stomata close, transpiration rate stops and the plant water potential increases for balancing with substrate moisture content. In the case that the plants are under water stress condition, the substrate water is not enough to fill the leaf air cavities during the night. In this case, sap flow values tend to increase to maintain the amount of water that goes from the roots to the leaves.

Table 1. Daily average, maximum, minimum value of TSD_{field} and TSD_{meas}, and standard deviation of the sample, 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).

	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

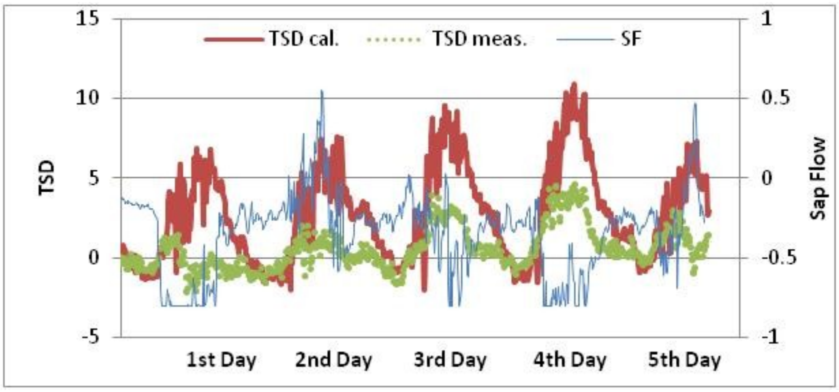

Figure 2. Hourly development of plant sap flow and TDS_{field} during the 1st day (well irrigated plants), 2nd, 3rd and 4th day (water stressed plants) and 5th day (re-irrigated plants).

In Figure 3, the correlation between the TSD_{cal} and TSD_{field} with substrate moisture content is illustrated. It is noticed that TSD_{field} had a good correlation with substrate moisture content ($R^2=0.7$), while the TSD_{meas} gave medium correlation ($R^2=0.6$). Further, TSD_{meas}, similarly with SDD index, was affected by the environmental conditions variation. Figure 4 presents the linear regression between TSD_{meas} and TSD_{field} with VPD, where it seems that only TSD_{meas} (and not TSD_{field}) was influenced by the VPD. Further normalization by dividing the index with the maximum canopy temperature in specific conditions, could eliminate the fluctuation of the environmental conditions. This normalization method transforms TSD_{meas} to CWSI. In Figure 5, the development of CWSI from 10:00 a.m. to 6:00 p.m. is presented, during the days of the experiment. CWSI gave lower values in the morning. The index tended to increase until late in the afternoon. Katsoulas et al (2002) noted that the high values of CWSI observed during dusk, were caused by low light radiation and should not be taken into consideration. The average daily value of CWSI for the well watered plants varied from

0.43 to 0.48 (Table 2), while the respective values for the water stressed plants increased from 0.42 to 0.71 as the plant water stress was developing. The maximum index value (0.71) was observed during the fourth day of the experiment, in which water stress was sufficiently high. During the last day, in which the drippers were placed back to 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 plant water stress without the influence of VPD variation.

By comparing the thermal indices with photosynthetic rate variation, it was concluded that the aforementioned thermal indicators could detect tomato water stress one day before it could be detected by the decrease in the rate of photosynthesis. The second day of irrigation holding, the photosynthetic rate of water stressed plants was lower (2%) than the photosynthesis of well-watered plants, while the third day of irrigation holding, the photosynthesis decreased by more than 25%. During the last day of the experiment, photosynthesis of the second treatment (water stressed plants) approached the values of the non-stressed plants, due to irrigation restart.

Table 2. Daily average of CWSI values and standard deviation 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 ($\mu \pm \sigma$)				
	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

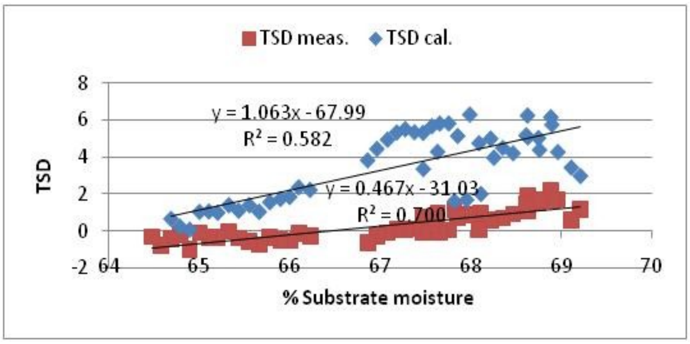

Figure 3. Correlation between TSD_{field} and TSD_{meas} with substrate moisture variation.

Discussion

The leaf temperature and the thermal indices SDD, TSD_{field}, TSD_{meas} and CWSI could be appropriate indicators for water stress detection on a daily basis. However, on an hourly basis, different types of stress lead to leaf temperature increase and severe index variations, as explained before. For this reason, further emphasis should be given to environmental conditions during the measurements inside the greenhouse, while the 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, while it detected plant water stress from the first day of irrigation holding. Moreover, TSD_{field} had a good correlation with substrate moisture variation (R^2=0.7). However, the existence of well-irrigated plants is necessary, as a reference point during the measurement procedure, something that is not always feasible in greenhouse conditions. On the other hand, TSD_{meas} could detect plant water stress without the need of well watered plants, as the minimum temperature was calculated through the Penman-Monteith equation.

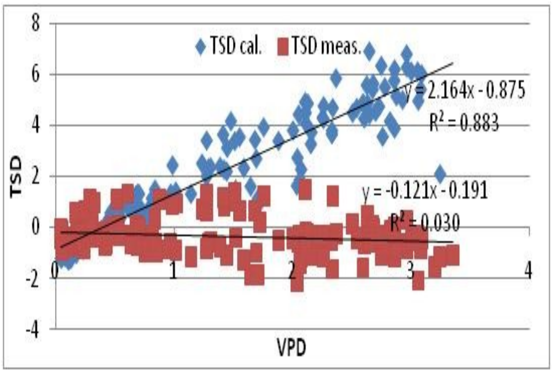

Figure 4. Correlation between TSD_{field} and TSD_{meas} with VPD.

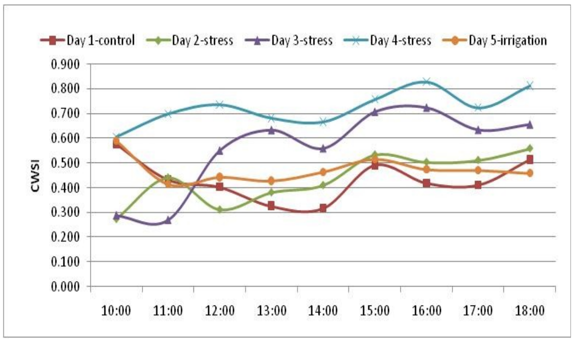

Figure 5. Daily evolution of CWSI for the water stressed plants, at the 1st day (well irrigated plants), 2nd, 3rd, 4th day (water stressed plants) and 5th day (re-irrigated plants).

Nevertheless, TSD_{meas} was drastically influenced by the environmental conditions and gave medium correlation with the decrease of substrate moisture (R^2=0.6). CWSI was not affected by the environmental conditions as much as it was affected by stomatal conductance. However, it was able to detect plant water stress from the very first day of irrigation holding. SDD was another indicator that detected water stress from the first day of irrigation holding, showing positive values greater than 1, mostly during noon in which the indicator reached its maximum value. In any case, the aforementioned thermal indicators could detect tomato water stress one day before it could be detected by the decrease in photosynthesis rate. Overall, the crop temperature variation relative to different plant water levels during the day is too limited and difficult to be studied, mainly due to the major variation of greenhouse environmental conditions. Further study of the thermal indices based on hourly variation in 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 novel thermal indicators.

The ultimate target of greenhouse climate and irrigation control is to obtain healthy, well developed crops with high yield & quality production using least resources. So far, greenhouse climate and irrigation control is based mainly on measurements at a single point in the middle of the greenhouse and thus, uniform climate set points or water and fertiliser applications across the entire greenhouse are applied, without accounting for climatic and crop variability within specific sectors of the greenhouse. The remote sensing approach used in this work gives the opportunity to easily monitor plant water status in more than a single position inside the greenhouse and accordingly, offers the possibility to spatially apply different climate and irrigation control inside the greenhouse.

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