Remotely measured canopy temperature of greenhouse strawberries as indicator of water status and yield under mild and very mild water stress conditions

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ABSTRACT


Strawberry plants were submitted to mild and very mild water stress regimes in a tunnel (simple semicircular greenhouse) by planting them in two plots fertirrigated when the soil matric potential reached −0.07 MPa and −0.01 MPa, respectively. The plants were monitored for water stress by measuring the foliage temperature with a hand-held infrared thermometer. Parallel to this, weather variables, the difference between leaf and air temperature, the derived crop water stress index (CWSI), the soil matric potential, the leaf water potential, the photosynthetic gas exchange rates, the transpiration rates, photosynthetic pigments, sugars, starch, canopy structure and accumulated yield were measured. The wet treatment (WT) presented a higher yield and higher leaf area index (LAI). In WT, leaves were disposed mostly in a monolayer oriented to the south, whereas in dry treatment (DT) leaves were distributed in a multilayer pattern and oriented to the north. During the hotter part of cloudless days and before irrigation took place, the canopy temperature of WT was about 3°C less than that of DT. Accumulated stress degree days (SDD) were then higher in DT. WT presented lower average CWSI values, between 0.045 and 0.54, while those of DT were between 0.32 and 0.70. It was concluded that leaf temperature, its difference with air temperature (dT) and the derived indices, such as SDD and CWSI, are useful for the assessment of even these mild and very mild water stresses in strawberries under protected conditions. Regression analysis showed that under the very mild water stress conditions tested in WT, the contribution of air vapor pressure deficit to variation in leaf water potential was significant. This did not happen under the mild water stress of DT.

INTRODUCTION

Crop production is dependent on the supply of various resources such as water, nutrients and sunlight. Water is the major limiting factor in crop productivity (Howell and Musick, 1984), therefore it is important to satisfy crop
water needs. To obtain the best irrigation regime, the available measurements on water needs are based on meteorology, soil water content and plant parameters. Most physiological indices of plant water stress (leaf water content, xylem water potential, leaf diffusion resistance) involve point measurements that are complex, time consuming and difficult to integrate. In addition, measurements such as leaf water potential or stomatal resistance for a large number of individual leaves are not only labor-intensive, but are also subject to errors (Meyer et al., 1985). Thus, non-destructive and instantaneous methods are desirable for assessing the physiological water status of an entire crop in the field.

The surface temperature of a leaf is the tangible manifestation of its energy balance and, therefore, is affected by environmental and plant factors. The most salient of the latter are the stomates which, by closing, limit the amount of energy that can be dissipated by transpiration and consequently cause the leaf temperature to increase (Raschke, 1960; Nobel, 1983). The use of canopy and leaf temperatures to detect water stress in plants is then based on the assumption that transpired water evaporates and cools the leaves (Berliner et al., 1984). As water becomes limiting, transpiration is reduced and leaf temperature increases above the air temperature because of absorbed radiation. The most serious problem is the need for spatial integration to obtain a meaningful average (Fuchs and Tanner, 1966; Pearcy et al., 1989). Most of these problems can be overcome by sensing the thermal radiation emitted by the canopy as a whole. Many samples must be taken to adequately characterize the leaf and foliage temperature. The simple non-contact and portable infrared thermometers allow rapid and accurate measurements of leaf and foliage temperature in the field, which has renewed interest in the use of foliage temperature as an indication of plant water status. The combination of having an atmospheric window between 8 and 14 μm, and a valid relationship between absolute temperature and emitted radiance, allows the estimation of surface temperatures by remote means (see the references in Jackson (1986)) and non-destructively. Infrared thermometers are easy to use, they can measure one or many leaves at the same time and, therefore, give an average of the plant water status, and they can monitor rapidly changing conditions in a canopy (Johns et al., 1981). There are problems in surface temperature measurements by infrared thermometers, such as correction for emissivity or the fact that infrared thermometers cannot be used on canopies that are not well developed. At least 75% of the ground should be covered (Kirkham, 1985) so the technique is well adapted to horticultural crops (Throssell, 1985).

Consequent to all these characteristics, several canopy temperature-based indices for crop water stress assessment, yield prediction and irrigation scheduling have been proposed: stress degree days (SDD) based in canopy–air temperature differences (Idso et al., 1977; Pandey et al., 1984), the canopy temperature variability within a crop plot (CTV), the canopy temperature
difference (CTD) between a stressed and unstressed plot crops (Sandhu and Horton, 1978; Berliner et al., 1984), and the crop water stress index (CWSI) derived from canopy–air temperature differences versus the air vapor pressure deficit relationship (Idso et al., 1981; Jackson et al., 1981). CWSI seems to be one of the best indices because it incorporates meteorological parameters. Theoretical considerations of Jackson (1982) and the empirical results of Nakayama and Bucks (1984) and Idso and Reginato (1982) emphasize the validity of CWSI in monitoring water stress and programming irrigation in the field crops of arid regions. The information necessary to compute the CWSI may be obtained instantaneously and non-destructively by monitoring foliage temperature ($T_f$) using infrared thermometry and ambient air wet and dry bulb temperatures. The CWSI is intuitively appealing because it was defined by Jackson et al. (1981) as $1 - (E_T/E_{TP})$ where $E_T$ is the actual evapotranspiration and $E_{TP}$ is the potential evapotranspiration. Therefore, CWSI is of universal significance among water scientists and of direct inference to crop water status and yield (O'Toole and Hatfield, 1983). The validity of the CWSI has been shown through studies of the relationships with other plant parameters, such as leaf water potential, leaf stomatal conductance and net photosynthesis (Idso et al., 1982; Reginato, 1983).

We wanted to verify the validity of all these indices and CWSI, based on leaf and foliage temperature measured by infrared thermometry, to describe crops under a tunnel and under mild and very mild water stress conditions like those expected in well-run crops of our Mediterranean area. Thus, we studied them in a strawberry crop, which is very common in coastal Catalonia. Our aim was also to evaluate the relationships among parameters related to air, plant and soil water and those derived from foliage temperature under the studied conditions in order to improve the difficult question of the prediction of water status from foliage temperature (Campbell and Norman, 1990).

MATERIALS AND METHODS

Treatments

Strawberry (Fragaria × annanassa D. cultivar Chandler) plants were planted in a simple semicircular greenhouse structure covered with polyethylene in the IRTA Cabriols experimental fields located 41°25'N 2°23'E. Strawberries were planted on 10 November 1989 on a Typic Xerorthent soil. The crop grew until 11 July 1990. Two watering treatments were established in two plots of four beds each. Each plot was 6 m long by 4.5 m wide. Plants were set 30 cm apart within the row. The rows were spaced 32 cm apart. Water was supplied by trickle irrigation using turbulent flow emitters spaced at 30 cm. Three laterals per bed were installed.
Fertirrigation was applied in each plot when the soil matric potential reached $-0.01 \text{ MPa}$ in the wet treatment (WT) and only when it reached $-0.07 \text{ MPa}$ in the dry treatment (DT). Soil matric potentials within each plot were measured by daily readings of paired 10 and 20 cm deep tensiometers (Soilmoisture 2725, Santa Barbara, CA) located 15 cm apart from the emitter. There were three pairs of tensiometers per treatment. Available tap water was adjusted according to Steiner’s method (Steiner, 1966) to obtain the following nutrient equilibrium $1:0.5:1.8$ and $1:0.7:2.5$ ($\text{N:PO}_4\text{O}_5:K_2\text{O}$) for vegetative and productive periods, respectively. Soil matric potentials were determined with the tensiometers mentioned above. Volumetric soil water content was determined from the water retention curve of the soil calculated experimentally.

**Temperature-related measurements**

Foliage temperatures and dry and wet bulb air temperatures were taken on both plots together with infrared thermometer measurements. The days surveyed were those 141, 160, 161, 167, 179, 186, 189 and 202 after planting for both treatments, Days 134, 138 and 203 only in WT, and Days 223, 229 and 239 only in DT. All readings were taken under full sunlight in the early afternoon, a good time of day for taking leaf temperature measurements (Hatfield et al., 1983).

Foliage temperatures were obtained with a Raynger R2AG model infrared thermometer (Raytek, Santa Cruz, CA) with a $15^\circ$ field of view. The average temperature of eight randomly selected plants in each plot was obtained by hand-holding the thermometer directly over each plant, mainly looking down to the southeasterly oriented leaves in both treatments, at about 1 m above the surface and at an angle of about $60^\circ$ from the horizontal that always allowed plant cover surveillance. The surface area sensed by the instrument was approximately $500-600 \text{ cm}^2$. Since we do not know precisely what the canopy emissivity is, we operationally assumed it to be 0.98. The resulting error, if it occurred, should cause a constant bias, but would not affect the principles involved. The temperature of some leaves of each treatment was also surveyed with directly attached thermocouples, and with the porometer and infrared gas analyser.

A Thies No. 400 Assmann aspirated psychrometer (Göttingen) was held 1.5 m above the canopy to obtain wet and dry bulb air temperatures. Interpretation of leaf temperature requires simultaneously measured radiation data so the photosynthetic flux density (PFD) was always measured with a quantum sensor (LI-COR LI-190S, Lincoln, NE). Supplementary measurements of wind speed were made with a Thies model 4.3303 cup anemometer installed 2 m above the soil outside the tunnel, but giving us a rough idea of the changing wind conditions inside the tunnel, which always remained with its lateral lids open during daylight hours.

We calculated CTV, defined as the range of maximum minus minimum of
all infrared (IR) thermometer-sensed temperatures within a plot during a particular measurement period (Clawson and Blad, 1982), and SDD, defined as the difference between the foliage temperature $T_f$ and the air temperature $T_a$ (Idso et al., 1977).

The CWSI values were calculated using the combined energy balance-aerodynamic relationship (Penman, 1948) as a function of net radiation and vapor pressure deficit (Monteith and Szeicz, 1962), developed by Jackson et al. (1981). The upper limit of $T_f - T_a$ can be found by allowing the canopy resistance to increase without bound, and the lower bound can be found by setting $r_c = 0$. The upper limit of $T_f - T_a$ was calculated using the equation

$$T_f - T_a = \frac{R_n r_a}{\rho C_p}$$

where $T_f$ is the foliage temperature ($^\circ$C), $T_a$ is the air temperature ($^\circ$C), $R_n$ is the net radiation (W m$^{-2}$), $r_a$ is the aerodynamic resistance (s cm$^{-1}$), $\rho$ is the density of air (kg m$^{-3}$) and $C_p$ is the heat capacity of air (kg m$^{-3}$ °C$^{-1}$).

For a given air temperature, this represents the maximum values of $T_f - T_a$ expected for zero transpiration in the stressed crop.

The lower bound was determined using the equation

$$T_f - T_a = \frac{R_n r_a}{\rho C_p} \frac{\delta - e_a^* - e_a}{\delta + \gamma}$$

where $\delta$ is the slope of the saturated vapor pressure-temperature relationship (Pa °C$^{-1}$), $\gamma$ is the psychrometric constant (Pa °C$^{-1}$) and $e_a^* - e_a$ is the vapor pressure deficit of the air (Pa).

The values of the variables used are the averages recorded during the period of measurement: $T_c = 30^\circ$C; $T_a = 20^\circ$C; $\delta = 0.66$ Pa °C$^{-1}$; $\rho$ (20°C) = 1.204 kg m$^{-3}$; $C_p = 1010$ J kg °C$^{-1}$; $R_n = 468$ W m$^{-2}$; $\gamma = 131.5$ Pa °C$^{-1}$.

A major difficulty is to measure or predict aerodynamic resistance, $r_a$. Micrometeorological variables, such as wind speed, and plant morphological variables were used in estimating the aerodynamic resistance, $r_a$, as in Nobel (1983)

$$r_a = \frac{\delta_{bl}}{D}$$

and $\delta_{bl} = 4.0 (l/\nu)^{1/2}$

where $\delta_{bl}$ is the thickness of the boundary layer, $D$ is the water vapor diffusion coefficient in air at 20°C ($2.4 \times 10^{-5}$ m$^2$ s$^{-1}$), $\nu$ is wind speed in m s$^{-1}$ and $l$ is leaf length in wind direction.

**Hydric status and yield-related parameters**

The leaf water potentials of eight young fully expanded leaves in each treatment were measured with a Scholander pressure chamber Soilmoisture 3005
Transpiration rates and stomatal diffusive resistance, $r_s$, were measured with a LI-COR Model LI-1600 steady-state porometer in eight leaves inside the infrared surveyed canopy area. CO$_2$ gas exchange rates and stomatal conductance were measured with a LI-COR 6000. Leaf area index (LAI) was calculated by measuring central leaf length and area in 12 plants of each treatment. The total area was then estimated from the linear regression of experimentally established area (21.49 length – 52.62 ($n = 16$ and $r^2 = 0.936$)) on 10 January 1990. Specific leaf weight (SLW) was determined by separating plant components and determining the leaf area of each sample with a leaf area meter LI-COR 3000. Plant components were then dried at 60–70°C in an oven until constant weight was reached. Strawberry fruits were harvested at 3 day intervals, from 110 to 248 days after planting.

Leaf nitrogen content was obtained with an automatic nitrogen analyzer (Carlo Erba NA 1500). Chlorophylls a and b were determined according to Inskipp and Bloom (1985). Carotenoids were extracted simultaneously with the chlorophyll and determined using the equations proposed by Lichtenhaler and Wellburn (1983). Starch was determined according to Fraser and Fenton (1968). Soluble sugars were determined by spectrophotometry in dry samples according to Wristler and Wolform (1962). The samples were dried for 24 h at 80°C to prevent the sugars decomposing. Stomatal density was determined in the abaxial surface. All measurements were begun after the crops attained full cover in March. Multiple regressions, correlations and analysis of variance (ANOVA) of all the studied parameters were computed according to the statistical program package Statgraphics 4.0 (STSC, Inc., Rockville, MA).

RESULTS AND DISCUSSION

Production-related parameters

Even though the water and nutrient stresses they experienced were very mild or only mild, WT (above $-0.01$ MPa) and DT (above $-0.07$ MPa) showed clear differences in fruit production (Fig. 1A) (WT 8.32 (standard error (SE) 0.21) and DT 5.64 (SE 0.38) kg m$^{-2}$) and LAI (Fig. 1B). Yields of both treatments were very high relative to those habitual in the area (about 3 kg m$^{-2}$). Yield was lower in the DT because of slightly decreased mean fruit weight (WT 16.82 (SE 0.24) and DT 13.92 (SE 0.39) g) and a diminished fruit number (WT 76.98 (SE 1.80) and DT 63.41 (SE 2.65) fruits per plant). SLW was not different for both treatments in spring, but it was higher in DT in summer at the end of the crop season (5.68 (standard deviation (SD) 0.42) mg cm$^{-2}$ in WT and 7.83 (SD 0.18) mg cm$^{-2}$ in DT).

Hence, we found that this mild water stress — accompanied by lower al-
though not limiting nutrient supply — was already enough to have a strong effect on the vegetative and generative growth of strawberry plants. Over a season, the amount of radiation intercepted and absorbed is determined by leaf area extension and duration, plant morphology and transmission characteristics of leaves which in turn are affected by soil and crop management. Small water deficits decreased the rate of dry matter production by influencing both the amount of solar radiation intercepted and the efficiency with which it was used.

Leaves mostly used osmoregulation to regulate water use and orientated mostly to the north in DT, and regulated water use by tissue elasticity and orientated mostly to the south in WT (Peñuelas et al., 1991). This behaviour was that expected under well-developed stress: some plant species orientate their leaves to be normal to incident sunlight if well watered and to be parallel to the light when stressed. In other cases, an apparent reduction of ground cover as substantial as 80% has been described (Byrne et al., 1979).

However, there were no significant differences in photosynthetic rates
(12.63 (SE 1.26) μmol CO₂ m⁻² s⁻¹ in WT and 13.72 (SE 1.11) μmol CO₂ m⁻² s⁻¹ in DT), chlorophyll and carotene concentrations on both a mass and area basis (about 3 mg chlorophyll a g⁻¹ dry weight (dw) in spring and 2 mg chlorophyll a g⁻¹ dw in summer, and about 0.35 mg carotenes g⁻¹ dw in both treatments), leaf nitrogen content (1.95% dw), starch (1.197% dw), sugars (10.3% dw and 7.46% dw for spring and summer, respectively) or upper epidermis stomatal density (249 (SE 6) stomata mm⁻² in WT and 237 (SE 6) stomata mm⁻² in DT). Maybe the differences were developed in the initial phases and then the higher LAI allowed the higher production, even though the photosynthetic rates were not significantly different.

Foliage temperature and derived parameters

Infrared thermometer temperature was highly correlated with the temperature measured with thermocouples \((r=0.986, n=108, P=0.000)\), so we found it to be an acceptable measurement of foliage temperature.

Similar trends were found for the foliage temperature, its difference with air temperature and the CWSI (Fig. 2(A), 2(B) and 2(C)). Mean foliage temperature measured between 13:30 and 14:30 h was 2°C cooler to 8°C hotter than the ambient air temperature \((T_a)\). The difference \(T_r - T_a (\delta T)\) in DT was always higher than the \(\delta T\) in WT. This difference was significant in days previous to irrigation, when selected threshold soil matric potentials levels were reached (Fig. 2). Thus, as also had been found by Khera and Sandhu (1986), canopy temperature generally showed a prompt response to every irrigation. When considering the measurements carried out just before irrigation only, the difference was statistically significant \((P=0.013)\); the mean differences were 2.6°C (SE 0.78°C) for WT and 5.34°C (SE 0.52°C) for DT). The differences were not significant when considering all measurements, including those carried out immediately after irrigation (3.25°C (SE 0.369) and 4.01°C (SE 0.367) for WT and DT, respectively).

All this was translated into higher accumulated SDD in DT. Of course, there was more SDD accumulation in days prior to irrigation (Fig. 3). The other stress index based on temperature variability, CTV, was not significantly higher (Fig. 3). Maybe these mild water deficits avoided the variation found in other studies (Clawson and Blad, 1982).

Therefore, even though the water deficits tested were so low it seems there was enough limitation in transpiration to be translated into different temperatures when water was only slightly restricted. Leaf temperatures increased in DT because there was less cooling by transpired water as it evaporated from the leaf surfaces. That made simple measurement of the early afternoon canopy temperature and its differential with air temperature good indices of mild plant water stress.

Leaf orientation plays a major role in the temperature regime. Gardner et
Fig. 2. Temporal variation of foliage temperature, foliage–air temperature difference (δT) and CWSI for WT and DT. Arrows in the X-axis indicate the irrigations carried out in DT. Measurements were carried out between 13:30 and 14:30 h solar time. Values are means ± SE (n = 6).

al. (1981) reported a slight tendency for southerly exposed leaves to be warmer than those with a northerly exposure. We only measured southerly orientated leaves in both treatments, which may have maximized the differences be-
cause there were more northerly orientated – and therefore cooler – leaves in the dry treatment (Peñuelas et al., 1991).

The leaf and canopy temperatures may be either warmer or cooler than that of the air depending on environmental factors that can, for the most part, be specified. In humid environments, as in our experiments (midday average relative humidity 56.6% and all-day average relative humidity 80%), canopy temperatures will be near to or higher than air temperatures, with only a small range of variation. In arid conditions, canopy temperatures may be more than 10°C below air temperature and have a range of perhaps 15°C (Jackson, 1982). So if the temperature method to characterize water status seems to work in our humid experimental conditions, in more arid areas, where a well-run irrigation schedule is more urgently needed, these temperature and temperature-derived parameters can work even better.

In our study, foliage temperature was usually higher than that of the air. This is understandable because of the humid conditions already mentioned, because plants were inside tunnels and because the leaves were mostly horizontal, and mostly perpendicular to sunlight in the afternoon, when they were measured.
CWSI values for DT were clearly higher than those for WT (Fig. 2(C)). Changes in CWSI showed a general correspondence with those of foliage temperature, as commented on above (Fig. 2(A) and 2(B)). Critical values of all these temperature indices need to be established for various crops, including the strawberry crop. For example, a CWSI of 0.3 may be the critical value for wheat, but not for cotton (Jackson, 1982). In the strawberry crop that we studied, even though the water stress was mild, the CWSI was quite high (around 0.5; Fig. 2(C)).

*Relationships of ΔT and CWSI with water status parameters*

No significant relationships were found among temperature-derived parameters and water status parameters such as soil water content, leaf water potential and transpiration rates (Fig. 4). The scatter of data points may be caused by the inherent heterogeneity in soil moisture distribution. It may also be due to net radiation changes, wind speed effects, and experimental errors involved in measuring the canopy, wet bulb and dry bulb temperatures.

Under the very mild water stress conditions of WT, where water is not lim-
iting, atmospheric factors such as vapor pressure deficit (VPD) seem to become the ruling driving force of leaf water potential, as shown by the fact that water potential decreased with VPD in WT \((r = -0.5632, n = 46 \text{ and } P = 0.000)\) and this did not happen in DT (Fig. 5).

In order to account for environmental influences on \(T_f - T_a\) values, aerial factors such as VPD, net radiation and the aerodynamic character of the atmosphere must all be considered simultaneously (Boissard et al., 1990). The \(\delta T\) values are valid indications only if wind speed and net radiation are invariant or computed and taken into account. Sadly, we did not measure wind speed inside the greenhouse, but it surely was not very different inside because lateral lids were always open wide. Besides, the wind speed was in any case the same in both treatments. In other studies of foliage temperature, this measurement should be taken into account when monitoring crop water status because changes in horizontal wind speed affect canopy temperature readings (Berliner et al., 1984; Boissard et al., 1990). Wind speed has been found to be a primary factor causing erroneous estimation of the upper limit of \(T_f - T_a\) and, hence, CWSI values. Those measured at low wind speed overestimated the level of water stress, while those measured at high wind speed underestimated it (O’Toole and Hatfield, 1983).

In our experiments, variations due to stomatal control and hence \(T_f\) were, therefore, found even under the mild water stress conditions tested. Mild soil water stress can then be added to well-developed soil water stress (Hatfield, 1983), ambient vapour pressure deficit (AVPD) or foliage vapour pressure deficit (FVPD) (Morison and Gifford, 1983), root and leaf diseases (Pinter, 1979), nitrogen stress (Seligman et al., 1983) and salinity (Howell and Musick, 1984) as conditions that change leaf and foliage temperature. Thus, another potential application of infrared thermometry can be considered in agricultural experimentation.

![Fig. 5. Leaf water potential versus VPD for WT (soil matric potential above \(-0.01\) MPa) and DT (soil matric potential above \(-0.07\) MPa). Values are means ± SE \((n = 6)\).](image-url)
CONCLUSIONS

Mild water deficits decreased the rate of dry matter production, LAI, yield and even leaf exposure of strawberry plants.

Foliage temperature, measured with an IR thermometer, was shown to be a useful technique for checking changes in plant hydric status and yield, even at the mild water stress levels produced by soil matric potentials of $-0.01$ and $-0.07$ MPa. Significant differences in foliage temperature, $T_f - T_a$, CWSI and SDD have been found between the two treatments.

This technique may then be a good simple tool for scheduling irrigation and for evaluating plant water status.

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