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Relationships between Reflectance and Water Status in a Greenhouse Rocket (*Eruca sativa* Mill.) Cultivation

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Summary

Crop water status is an important parameter for plant growth and yield performance in greenhouses, and thus early detection of water stress is essential for efficient crop management. Therefore, the aim of this work was to study the relationship between crop reflectance and common soil and crop water status indicators. Two different irrigation regimes, namely 50 and 100 % of the crop potential evapotranspiration were imposed to rocket plants (*Eruca sativa* Mill.) grown in pots filled with soil inside a greenhouse. Leaf area index and mid-season crop coefficient, which are essential for irrigation schedulling were estimated. Crop reflectance indices were calculated using the radiation reflected by the crop in 8 narrow wavelength bands (10 nm in width), centred at 460, 510, 560, 610, 660, 710, 760 and 810 nm. Canopy reflection measurements were carried out during July and August 2010 in a greenhouse located in Arta, Greece. The results showed that crop reflectance to radiation ranging from 510 to 710, and at 810 nm, is strongly related to water stress in rocket plants. Crop reflectance has not been extensively studied under greenhouse conditions and seems to be a promising, easy-to-use, non-contact and non-destructive tool for crop water status assessment.

Key words. crop coefficient – crop water stress – evapotranspiration index – spectral index

Introduction

Irrigation management in modern greenhouses is based on by computer-controlled systems which utilize a range of mostly indirect inputs to achieve accurate delivery of water according to crop requirements. When water supply to the plant does not meet its transpiration demands, water stress occurs. Stomatal opening is directly affected (reduced) by water stress and this influences other factors like leaf temperature (Jackson et al. 1981; Katsoulas et al. 2009) and net photosynthetic rate (Chaves et al. 2002; Sarlikioti et al. 2010). Crop reflectance (Knipling 1970), chlorophyll fluorescence (Norikane and Kurata 2001) and thermal radiation transmittance (Jones and Schofield 2008) are also affected. Several studies have attempted to detect and quantify water stress using reflectance inside the visible and the near infrared regions (Schlemmer et al. 2005; Wheeler 2006; Zakaluk and Sri Ranjan 2007; Sarlikioti et al. 2010). The crop water stress index (CWSI), which was based on infrared radiation temperature measurements, proved to be one of the most successful relevant tools for crop water stress detection (Jones and Schofield 2008; Erdem et al. 2010).

Although remote sensing has been successfully used for years in open fields and relevant reflectance calculation models have been developed (Jacquemoud et al. 2009), it has not been extensively tested for greenhouse crops. Open field methods cannot directly be applied in greenhouses due to difficulties arising mainly from reflections and shadows casted by the greenhouse frame and equipment. Such problems could be addressed by combining data from two or more spectral bands to form vegetation indices (Kacira et al. 2005; Grant et al. 2006; Zakaluk and Sri Ranjan 2007; Sarlikioti et al. 2010). According to Zakaluk and Sri Ranjan (2008), the most common forms of reflectance indices are: a) reflectance ratios corresponding to the ratio of two spectral bands, which are referred to as simple ratio (SR) vegetation indices and b) normalized difference (ND) vegetation indices, which are defined as ratios of the difference in reflectance between two spectral bands to the sum of the reflectance at the same bands.

Previous research advocates the use of the short wave infrared (SWIR) region to estimate plant water content (Ceccato et al. 2002). Reflectance sensors that feed models for plant water status in the visible region would therefore be more economically viable for an irrigation scheduling system as less sensors than those needed for i.e. substrate moisture or leaf temperature monitoring are needed to cover a given cultivation area (Decagon Devices 2011). Justification for using visible light reflectance as an indicator of plant water status is based on the interrelationships between plant water status, photosynthesis, and irradiance load on the leaf (Schlemmer et al. 2005; Wheeler 2006). Zakaluk and Sri Ranjan (2007) found that an RGB (red green blue) digital camera could determine leaf water potential under greenhouse conditions.

The objective of the present work was to explore the relationship between multispectral canopy reflectance, at wavelengths of visible and near-infrared radiation spectrum and soil or plant water status. For this purpose, two different irrigation treatments were applied [50 and 100 % of crop evapotranspiration (ET_c)] in a greenhouse rocket crop. Rocket is traditionally a soil-cultivated plant with good adaptability in both field and greenhouse cropping systems (Padulosi 1995) and its cultivation has increased in the Mediterranean area during the last decades because of a constantly increasing consumer demand (Nicola et al. 2003; Akoumianakis et al. 2008; Omirou 2009).

Materials and Methods

Greenhouse facilities and plant material

The experiment was carried out from June to August 2010 in a twin-span glass-covered greenhouse, E-W oriented, located at Arta, Greece (39° 07' N, 20° 56' 4"E, 5 m alt.). The geometrical characteristics of the greenhouse were as follows: eaves height = 3.15 m, ridge height = 4.4 m, span width = 6.5 m, length = 46 m, ground area = 600 m^2. The greenhouse was ventilated by means of roof (total opening area of 43 m^2) and side vents (total opening area of 23 m^2), which were opened whenever greenhouse air temperature exceeded 22 °C. An aluminized thermal screen, located horizontally at the eaves level, was used for greenhouse shading. The climate control was based on a greenhouse climate controller (Argos Electronics, Greece).

Six units comprising 6 pots (4 L, dimensions in cm, upper diameter/bottom diameter/height: 20/14/14) each, were used (Fig. 1). The pots were filled with silt loam soil (USDA Soil Texture Classification, Allen et al. 1998) mixed with 20 % white peat (Klasmann-Deilmann GmbH, Geeste, Germany) and a gravel layer of about 2 cm in thickness at the bottom. The mean volumetric moisture of the mixture at field capacity (measured according to Dane and Topp 2002, using 10HS-Volume Soil Moisture Sensor, Decagon Devices Inc. WA, USA) was 0.315 m^3 m^{-3}.

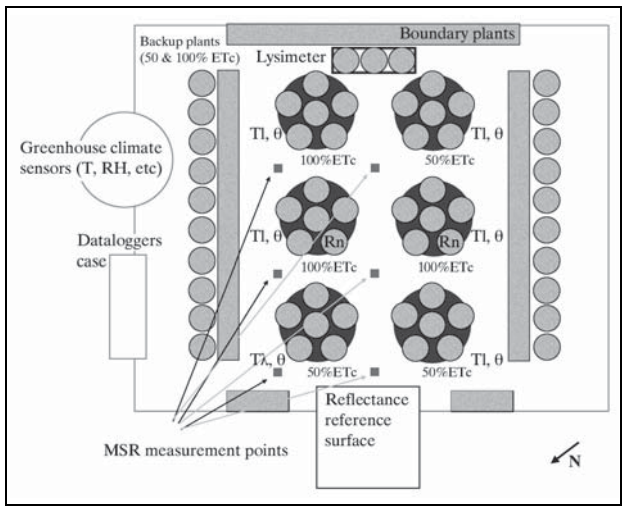


Fig. 1. Experimental setup and sensor's placement.

Basic fertilization was applied at the time of soil preparation using a 6:15:13 NPK fertilizer (400 g m^{-2} of BIO ILSA/Progress Micro, Verona, Italy). The average level of soil nitrate-nitrogen during the period of measurements was approximately 25 mg L^{-1} NO_3^-, measured using a Merkoquant® N test strip (Merck KGaA, Darmstadt, Germany). Rocket seeds (*Eruca sativa* Mill., 'Rocket Commun 2', FytroSeeds, Athens, Greece), also known as arugula (Omirou 2009), were sown directly to the pots on June 1, 2010. Thirty days after sowing, the plants were thinned to 5 plants per pot which resulted in a total plant density of 59.5 plants m^{-2}. The plant density used was lower than that usually applied in commercial rocket crops (200 plants m^{-2}, according to Padulosi and Pignone 1996), but it was similar to that applied by other investigators (Omirou 2009; Padulosi 1995).

Water was supplied via a drip system and controlled by a commercial time irrigation controller (model Miracle AC 06, Netafim, Tel Aviv, Israel). Irrigation scheduling was initially designed using an hypothetical crop coefficient K_c equal to 1. Two weeks after sowing and onwards, K_c was regularly estimated using the lysimeter data and the relevant adjustments were made in the applied watering dose.

In order to study the effects of irrigation water deficit on crop reflectance characteristics, two different irrigation treatments were applied for 15 days, starting on July 24, during the mid-season period of the cultivation (55 days after sowing): 50 % and 100 % of ET_c. The latter was regarded as the reference treatment. The amount of water supplied during the above period was 220 and 440 mL pot^{-1} d^{-1} (1.73 and 3.76 mm d^{-1}), respectively; given in three irrigation events per day (at 10:00, 16:00 and 20:30 local time). The experimental treatments were set following the Complete Randomised Block Design with three blocks (units) each (Fig. 1).

Measurements

Air temperature (T, in °C) and relative humidity (RH, in %) were measured using two temperature-humidity sensors (model HD9008TR, DeltaOhm, Italy), calibrated before the experimental period and placed inside and outside the greenhouse 2 and 4.5 m above the ground level, respectively. Using the T and RH values, the air vapor pressure deficit (D) was calculated. Solar radiation inside ($R_{g,i}$, in W m^{-2}) and outside ($R_{g,o}$, in W m^{-2}) the greenhouse was recorded using two solar pyranometers (model SKS 1110, Skye instruments, Powys, U.K.) located 2 and 4.5 m above the ground level, respectively. Wind speed (u, in m s^{-1}) inside the greenhouse was measured using a ultrasonic anemometer (model WindSonic Gill, Hampshire, U.K.) located 2 m above ground level. Net radiation (R_n, in W m^{-2}) was measured using a pyradiometer (model LP-NET 07, DeltaOhm, Italy) located inside the greenhouse at 0.75 m above the canopy. Leaf temperature (T_l, in °C) was measured in both treatments using copper-constantan thermocouples (wire diameter of 0.5 mm, type T, Omega Engineering, Manchester, U.K.) attached to the underside of leaves. Canopy temperature T_c was calculated as the mean value of T_l measurements in five healthy leaves distributed randomly within the canopy. Soil volumetric water content (θ, v/v) was estimated using capacitance sensors (model 10HS-Volume Soil Moisture Sensor, Decagon Devices Inc. WA, USA) vertically positioned in the pot which measured average θ from pot surface to 0.1 m. The depth of 0.1 m corresponded to the average root depth of rocket crop about 30 days after sowing. The θ values presented in this paper are the means of measurements obtained from 3 pots per treatment. Crop evapotranspiration (ET_c in kg m^{-2}) was measured using a weighing lysimeter. The device included an electronic balance (model 60000 G SCS, Presica, Dietikon, Switzerland, scale capacity of 62 kg, resolution of ± 1 g) equipped with a tray carrying three pots and an independent system of water supply and drainage (Fig. 1). Irrigation of these pots was as in the 100 %ET_c treatment. The weight loss measured by the electronic balance was assumed to be equal to crop evapotranspiration. Using the slope of the regression line between calculated reference evapotranspiration (ET_o) and measured crop evapotranspiration (ET_c) the K_c ($K_c = ET_c/ET_o$) was estimated. All the above-mentioned measurements were automatically recorded in a data logger system (DL2e Logger, Delta-T Devices Ltd, Cambridge, UK). Measurements took place every 30 s and the 10 min average values were recorded.

The leaf area index (I_{LA} in m^2 leaf m^{-2} of total cultivated surface, including pots groups and space between them) and the total number of leaves per pot of the 100 % ET_c treatment were determined through destructive measurements using plants which were randomly sampled from each treatment. Measurements were carried out two times during the experimental period (25 July and 10 August), using a scanner (ScanJet 4850, HP, USA). The pots used for destructive measurements were replaced by back-up pots (Fig. 1).

The radiation reflected by the canopy was monitored every 15 min between 10:00 to 18:00 from 25 July to 10 August, using a portable multispectral radiometer (model MSR87, CropScan Inc., Rochester, USA), in 8 narrow bands (10 nm bandwidth) centered at the following wavelengths (in nm): 460, 510, 560, 610, 660, 710, 760 and 810. The radiometer was moved manually from block to block and the measurements were performed from predefined positions (Fig. 1). MSR was located 1 m above the canopy level which resulted a sampled canopy area of 0.2 m^2. During the period of radiation reflection measurements the thermal screen was not used for greenhouse shading. The reflectance was measured over healthy plants that formed a completely covered canopy with no empty spaces between them. The reflectance values presented are the mean values calculated from the measurements carried out in three replications for each treatment. In order to block out reflection from the greenhouse floor between the pots, these areas were covered using black velvet textile. To overcome the reflection differences due to greenhouse frame shadows and reflections and measure true percent reflectance, a special measuring technique was performed (Nantt, CropScan Inc., personal communication). In particular, a white low-density polyethylene sheet of known reflectance, glued on a wooden panel, was positioned 1 m below the sensor and its measured reflectance served as a normalizing reference for all readings. Thus, a measurement on the white surface, which could factor out most of the varying light and shadowing conditions was taken before each measurement on plants.

Calculations

Based on the available reflectance measurements the following vegetation indices were calculated and evaluated to explore their relationship to water stress:

- SB, Single Bands (reflection at 460, 510, 560, 610, 660, 710, 760 and 810 nm);
- SR, Simple Ratio vegetation indices (all possible ratio combinations of SB);
- Three selected Normalized Differences of Vegetation Indices, particularly WDRI1 (Water Deficiency Reflectance Index 1), WDRI2 and WDRI3, which were selected based on literature references (Peñuelas et al. 1994) and promising results from SB and SR. The three selected normalized differences of vegetation indices are defined as follows: WDRI1 = (R560 − R510)/(R560 + R510), WDRI2 = (R810 − R710)/(R810 + R710) and WDRI3 = (R810 − R560)/(R810 + R560). The WDRI1 is an index which uses wavelengths very close to those of the Physiological Reflectance Index (Peñuelas et al. 1994). It has to be noted that PRI uses the radiation reflected at 530 and 550 nm. However, the instrument used in this study to measure radiation reflectance

could not measure at these bands and thus, the values measured at 510 and 560, respectively, were used.

The crop water stress index CWSI (Eq.1) was calculated following the formulas provided in Baille et al. (2001) using R_n (W m^{-2}); T_i (°C); ρ (kg m^{-3}) and C_p (J kg^{-1} °C^{-1}) density and specific heat of air, respectively; crop aerodynamic conductance g_a(m s^{-1}); D_i (kPa), greenhouse air vapour pressure deficit; Δ, slope of the saturation water vapour pressure at T_i (kPa K^{-1}) and γ (kPa K^{-1}), psychrometric constant. For the calculation of g_a the assumption that the intercepted net radiation was equal to the net radiation above the dense cultivation canopy was used. The average value of g_a calculated during the period of measurements was approximately 0.005 m s^{-1}.

$$CWSI = \frac{T_c - T_m}{T_M - T_m} \quad (1)$$

where T_c is the canopy temperature (°C), T_M (°C) is the highest possible temperature a canopy can achieve and T_m (°C) is the lower limit of canopy temperature which was assumed to be achieved with maximum canopy conductance (Baille et al. 2001).

Statistical analysis

Comparison of means was performed by applying the t-student test at a confidence level of 95 % using the PlotIT software package (Scientific Programming Enterprises, USA). Means are followedvby the standard error in the text. Linear regression was applied to obtain the best fit of measured values.

Results

The mean values of greenhouse and outside climate variables (average over the period 10:00–18:00 h local time) during the period of measurements are presented in Table 1. The leaf area index of the rocket crop during the period of measurements was 2.63 (± 0.21) m^2 m^{-2}, while the average leaf density was 327 (± 6.70) leaves m^{-1}.

The measurements performed in the present work allowed calculation of K_c during the mid-season cultivation period, as proposed by Allen et al. (1998) using the reference (ET_o) and crop (ET_c) evapotranspiration. The ET_c rate in the 100 % ET_c treatment was found to be between 2.7 and 3.8 mm d^{-1} which is within the range of ET_c commonly observed in greenhouse crops under Mediterranean summer conditions (Fernandez et al. 2010). The slope of the linear relationship between ET_c and ET_o, which corresponds to K_c, was 0.82 with a standard error of 0.006 and a determination coefficient (R^2) of 0.88. To our best knowledge, there is no information in the literature regarding the crop coefficient K_c of rocket plant and accordingly the value estimated in the present study could not be compared with previous results.

As shown in Fig. 2, before the application of deficit irrigation, θ was at a similar level in both treatments. After the initiation of deficit irrigation, θ values in the 50 % ET_c treatment started to decrease gradually. The

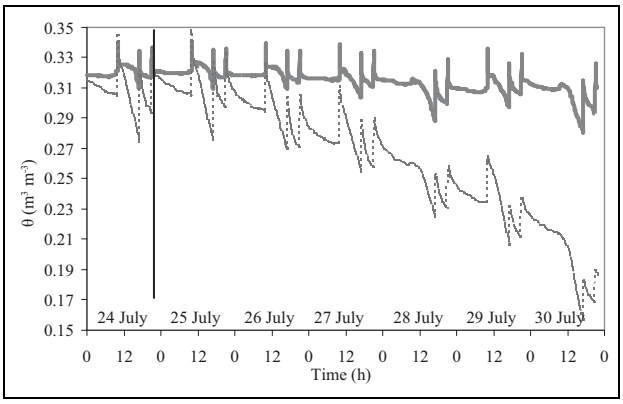


Fig. 2. Evolution of soil volumetric water content (θ, m^3 water m^{-3} soil) for the different irrigation treatments during the period of measurements; thick solid line: 100 % ET_c; dashed line: 50 % ET_c (the vertical line indicates initiation of deficit irrigation treatment).

Table 1. Monthly average values (period 10:00–18:00) of greenhouse and outside climate parameters during the period of measurements. The standard error of means is given in parentheses.

Period	T_i[a] (°C)	RH_i[b] (%)	D_i[c] (kPa)	R_{Gi}[d] (W m^{-2})	T_o[e] (°C)	R_{Go}[f] (W m^{-2})
June	34.0 (± 4.6)	58.5 (± 7.7)	2.7 (± 1.0)	260 (± 46)	27.0 (± 4.5)	576 (± 94)
July	38.8 (± 1.7)	50.0 (± 5.1)	4.3 (± 0.6)	276 (± 37)	30.6 (± 1.6)	614 (± 85)
August	38.9 (± 2.4)	54.2 (± 5.3)	3.4 (± 0.8)	268 (± 17)	31.4 (± 2.2)	589 (± 35)

[a] T_i is the greenhouse air temperature [b] RH_i is the greenhouse air relative humidity [c] D_i is the greenhouse air vapor pressure deficit
[d] R_{Gi} is the incoming solar radiation [e] T_o is the outside air temperature [f] R_{Go} is the outside solar radiation

evapotranspiration for each treatment was calculated using the relevant soil moisture difference. To validate this approach, the values calculated for the 100 % ET_c treatment pots were compared with these obtained by the lysimeter (the pots on the lysimeter were irrigated as in the 100 % ET_c treatment).

Table 2 shows the values of SB indices in the canopy of rocket plants irrigated at 50 % ET_c, and 100 % ET_c during three representative sunny summer day (28–30 July, average daily values 10:00–18:00, following the suggestion provided in Pisimanis et al. 1987) three days after the initiation of deficit irrigation (started on 25 July). Plants grown under lower θ showed higher reflectance at 510, 550, 610 and 710 nm. Statistical analysis of the data (t-student test at a confidence level of 95 %) showed that the spectrums of the 50 and 100 % ET_c treatments were significantly different except for the reflectance at 460 and at 760 nm.

The WDRI1 values observed during three indicative consecutive sunny days (28, 29 and 30 July), followed a similar course in both treatments (Fig. 3). A consistent relationship between irrigation treatment and WDRI1 was not found, however the lower values of WDRI1 were observed for the 50 % ET_c treatment. The mean daily values of WDRI1 for 50 and 100 % ET_c treatments were 0.23 (± 0.01) and 0.24 (± 0.01), respectively. Similar evolution trends were observed also for the WDRI2 and WDRI3 indices (data not shown), with mean values for WDRI2 and WDRI3 of 0.29 (± 0.01) and 0.64 (± 0.01) for 50 % ET_c, and 0.34 (± 0.01) and 0.67 (± 0.01), for 100 % ET_c, respectively (Table 3). Statistical analysis of the data (t-student test at a confidence level of 95 %) showed that the values of WDRI1, WDRI2 and WDRI3 differed significantly between the 50 and 100 % ET_c treatments.

The relationship between the mean daily values (average during the period between 10:00–18:00) of WDRI1 and θ, for the days from 25 to 30 July, was different for the two irrigation treatments (Fig. 4). It was found that, as θ decreased, WDRI1 gradually decreased and that a strong linear relationship existed between WDRI1 and θ values in the 50 % ET_c treatment ($R^2 = 0.90$). A linear relationship between WDRI1 and θ values existed also for the 100 % ET_c treatment but less strong than the one found for the 50 % ET_c treatment ($R^2 = 0.60$). On the other hand, no relationship could be found between θ and WDRI2 and WDRI3.

Table 2. Reflectance (%) of rocket crop at 10 nm narrow bands centered at 460, 510, 560, 610, 660, 710, 760 and 810 nm for the two irrigation treatments during three representative shiny mid-summer days (28–30 July); squares: 100 % ETc; triangles: 50 % ETc. The standard error of means is given in parentheses. Values in each column followed by the same letter are not significantly different (P < 0.05).

Wavelength nm)	460	510	560	610	660	710	760	810
Treatment	Reflectance (%)							
50 % ET_c	6.03[a] (± 0.25)	3.97[a] (± 0.03)	5.99[a] (± 0.10)	6.23[a] (± 0.24)	6.18[a] (± 0.06)	15.21[a] (± 0.10)	27.63[a] (± 0.12)	27.17[a] (± 0.07)
100 % ET_c	6.07[a] (± 0.65)	3.45[b] (± 0.13)	5.59[b] (± 0.12)	5.34[b] (± 0.20)	6.50[b] (± 0.14)	14.38[b] (± 0.34)	28.03[a] (± 0.30)	28.42[b] (± 0.12)

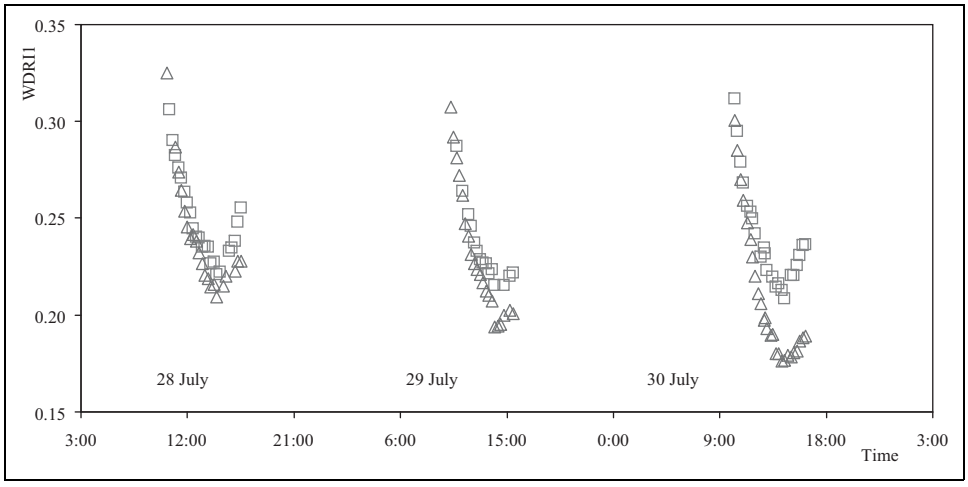


Fig. 3. Evolution of rocket crop WDRI1 values during three consecutive shiny mid-summer days (28 to 30 July) under different irrigation treatments; squares: 100 % ET_c; triangles: 50 % ET_c

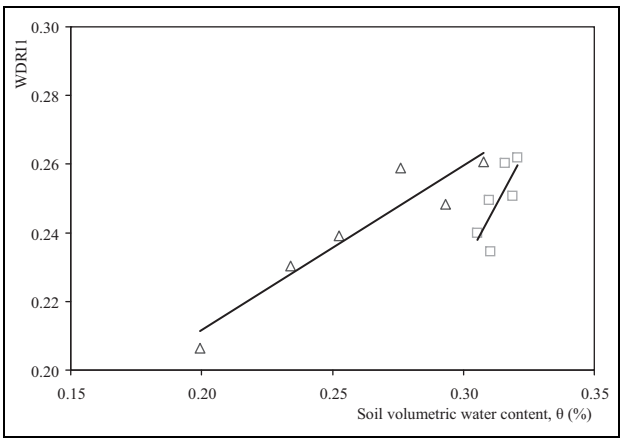


Fig. 4. Relationships between mean daily values of WDRI1 and soil volumetric water content (θ, m^3 water m^{-3} soil) as influenced by irrigation treatment; squares: 100 % ET_c; triangles: 50 % ET_c. Straight lines indicate the best fit of the linear relationships between the measured values of θ and WDRI1 (R^2 = 0.70 and 0.89 for 100 and 50 %ET_c, respectively).

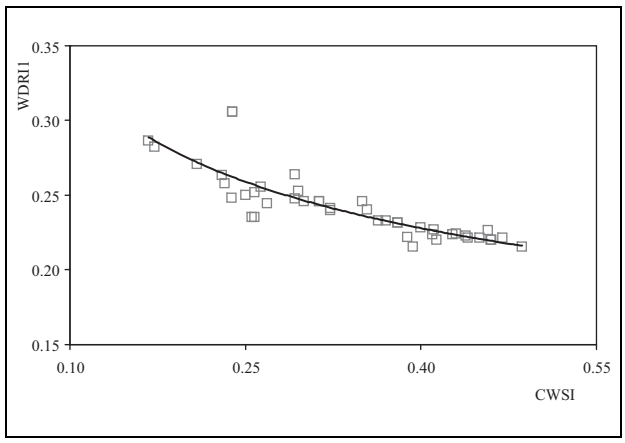


Fig. 5. Relationship between instantaneous values of WDRI1 and CWSI for the 100 % ET_c treatment during 28 to 30 July. The solid line indicates the best fit of the relationship between the measured values of CWSI and WDRI1 [WDRI1 = 0.178 $CWSI^{-0.27}$ (R^2 = 0.76)].

Table 3. WDRI2 and WDRI3 means for three indicative sunny days (28, 29 and 30 July). The standard error of means is given in parentheses. Values in each column followed by the same letter are not significantly different (P < 0.05).

	WDRI2	WDRI3
50 % ET_c	0.29 (± 0.01)[a]	0.64 (± 0.01)[a]
100 % ET_c	0.33 (± 0.01)[b]	0.67 (± 0.01)[b]

The canopy to air temperature difference ΔT_{c-i} has already been related to plant water stress (Jackson et al. 1981; Katsoulas et al. 2009). However, in the present study, no particular relationship could be found between the instantaneous measured values of ΔT_{c-i} and the calculated values of WDRI1, WDRI2 and WDRI3. Nevertheless, a good relationship was found between the instantaneous values of WDRI1 and CWSI. Fig. 5 shows the relationship observed between the above variables for the 100 %ET_c treatment (data for 28 to 30 July). It can be seen that as CWSI increases (θ decrease, data not shown), WDRI1 decreases. The relationship (non-linear regression, level of significance 0.05) found between CWSI and WDRI1 was of the type:

$$WDRI1 = 0.178\ CWSI^{-0.27} \quad (2)$$

with R^2 = 0.76.

Discussion

The use of multispectral crop reflectance indices has already found its way to commercial open-field crops. This technology is based on the measurement of reflectance in two or more wavelengths inside the visible region to monitor biotic and abiotic stress factors, including water stress. To develop practical and commercially applicable systems based on reflectance for monitoring crop stress in greenhouses, it is essential to determine the spectral footprint of each stress type for each crop species. In addition to this, it is critical to develop also techniques for the elimination of interferences, such as noises arising from the greenhouse structure and machinery, shadows and reflections, effects of heating systems, floor, plant parts like flowers, substrate reflectance, etc.

According to current knowledge, water stress is generally linked to reflectance rise at 560 to 710 nm and reflectance reduction above 760 nm (Cure et al. 1989; Koksal et al. 2011; Nantt 2011, CropScan Inc., personal communication). Indeed the results of the present experiment showed that the reflectance of the rocket canopy at the wavelengths 510, 560, 610, 660, 710 and 810 nm was affected by the irrigation treatment.

The values of WDRI1 (Fig. 4), WDRI2 and WDRI3 were lower in the 50 %ET_c treatment, which is in agreement with results of Peñuelas et al. (1994), who found that the Normalised Difference Vegetation Index [NDVI = (R850 − R680)/(R850 + R680)] decreases under water stress conditions. Previous research has indicated that the Physiological Reflectance Index [PRI = (R550 − R530)/(R550 + R530)] was a sensitive indicator of water stress (Peñuelas et al. 1994; Suárez et al. 2009; Sarlikioti et al. 2010). Peñuelas et al. (1994) and Sarlikioti et al. (2010), reported a decrease in PRI with time after application of water withholding. Sarlikioti et al. (2010) reported that under water stress conditions, tomato plants grown in rockwool slabs and PRI correlated well with substrate relative water content. In the present experiment, the

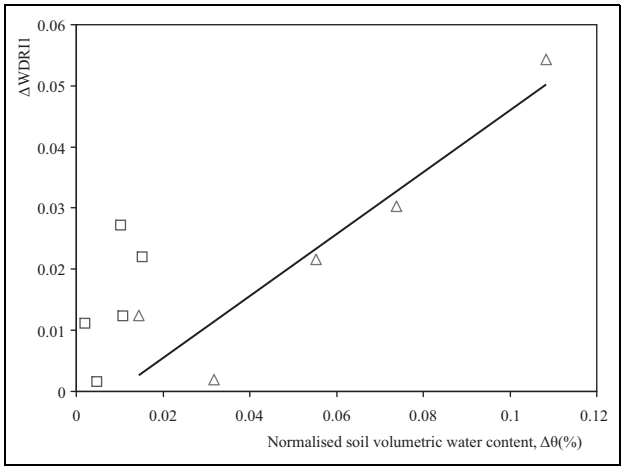


Fig. 6. Relationship between the normalized WDRI1 (ΔWDRI1) and θ values (Δθ) by the respective values of parameters during the first day of measurements; squares: 100 % ET_c; triangles: 50 % ET_c.

volumetric water content of soil decreased from about 31 % (100 % ET_c) to about 24 % (50 % ET_c after 3 days of deficit irrigation) and these differences in soil volumetric water content could be reflected in WDRI1 differences. Furthermore, it was shown that, as θ decreased, WDRI1 also decreased. Nonetheless, for the same value of θ observed in the two irrigation treatments, different values of WDRI1 were observed (Fig. 4). For that reason, in order to normalize the WDRI1 and θ values, the differences of mean daily WDRI1 and θ values to the WDRI1 and θ values on the day of irrigation treatments initiation (25 July) were calculated (ΔWDRI1 and Δθ, respectively). When plotting ΔWDRI1 values vs Δθ values for the 50 %ET_c treatment, a strong linear relationship was found (Fig. 6) of the type:

$$\Delta WDRI1 = 0.506\ \Delta\theta - 0.0046 \quad (3)$$

with $R^2 = 0.88$, while no significant relationship was found between ΔWDRI1 and Δθ in the 100 % ET_c treatment ($R^2 = 0.42$).

Suárez et al. (2009) reported an indirect relationship between PRI and water stress, which was indicated by a correlation of PRI with canopy temperature, but this was not the case in our study. Nevertheless, in the present study, a good relationship between CWSI and WDRI1 was obtained, which indicates that WDRI1 could also be used as a crop water status indicator. Some investigators found that PRI is sensitive to light levels, plant structure, plant optical properties and sun position as well (Barton and North 2001; Suárez et al. 2009; Sarlikioti et al. 2010). However, no response of the WDRI1 index to light level was found in the present study. In the Mediterranean region, where the present study was conducted, light is in abundance, especially in summer period and thus WDRI1 was successfully used to track crop water status.

To sum up, the results of the present study point out that WDRI1 could be used as an indicator of plant water stress in greenhouses, since its absolute or normalized values were correlated well with the crop water stress index and with changes in soil volumetric water content. Reflectance measurements in greenhouses could be integrated over time in order to trigger irrigation events. This concept is similar to the integration of solar energy measured by a pyranometer outside the greenhouse, which is a very common, yet cultivation independent technique for irrigation management. Furthermore, reflectance measurements might be utilized to provide alarm signals when the water status of a greenhouse crop reaches critical levels for optimal plant growth.

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