Reflectance Indices for the Detection of Water Stress in Greenhouse Plants

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Abstract

This study determines various waters stress related indices, which are based on crop-reflected radiation in different wavebands, for early plant water stress detection in greenhouse cultivation. It also provides recommendations for the most appropriate reflectance indices to be used for irrigation scheduling in greenhouses. Reflectance indices are evaluated according to recent literature, including PRI, NDVI, WBI, VOGREI and other indices of the spectral band, while measurements of physiological water stress indices are also outlined. The results of different experimental irrigation techniques based on spectral band and optimization of irrigation schemes for greenhouse plants are presented and the most appropriate for small-time scale stress detection are defined. The most practical and cost effective indices are evaluated in terms of their ability to detect plant water status under greenhouse conditions and some possible applications are summarized.

INTRODUCTION

It is generally accepted that agricultural practice requires precision irrigation in emerging greenhouse management of water resources, for improving yield profitability and productivity and at the same time, decreasing the financial costs for water and energy consumption. Much progress has been made on optimizing water supply, based on numerous methods for scheduling irrigation, such as solar radiation or substrate moisture (Kittas, 1990; Katsoulas et al., 2006). However, only a limited number of methods use plant-based physiological indicators to detect plant water stress. Reflectance sensors collect such plant-based data, from the visible and near infrared spectral band, capturing the energy reflected and emitted by the plants.

Leaves have certain reflectance characteristics within the electromagnetic spectrum, which can lead to plant water stress detection (Amatya et al., 2012). Healthy plant has a small peak at the green band (G: 550-650 nm) and a small drop at the blue (B: 450-550 nm) and red bands (R: 650-700 nm). The small drops in blue and red bands are caused by the light absorption from leaf pigments (chlorophyll, xanthophylls and carotenoids). Moreover, a healthy plant shows a rising peak at the near infrared band (NIR, 700-1000 nm), due to diffraction that is caused by the existing air in voids of the leaf spongy parenchyma. According to Kim et al. (2010), water stressed plants would show an increase in green and red bands of reflectance, while the reflectance in near infrared region would be decreased. However, in some studies the reflectance of stressed plants decreases in the green region and increases in the near infrared region (Jones et al., 2004; Gaalen et al., 2007). On the other hand, Amatyas et al. (2012) found that the reflectance of lower water content groups had slightly decreased in the green and increased in the near infrared region. Thus, the spectral data present some limitation in providing accurate estimates of biophysical characteristics, due to water deficiency. Baring that in mind, indices were estimated by the combination of two or more spectrum areas, in order to provide additional detail to water stress detection. Numerous successful case studies related to the reflectance indices and other complex combinations for different species in different irrigation treatments, have been studied, mostly in field cultivars (long time of irrigation cycle), but not extensively in greenhouse cultivars (short time of irrigation cycle). The most effective spectral indices are presented in Table 1. PRI and NDVI are the most commonly used and analyzed indices in different environmental and plant growth conditions for the assessment of plant water stress. Other reflectance indices, like WI, mNDVI, rNDVI, mrSRI and VOGREI have been used with either positive or negative results.

In this work, the variation of the spectrum reflectance pattern with the plant water stress progress was studied, from the beginning of irrigation holding. Furthermore, the most effective reflectance indices in water stress detection were analyzed based on greenhouse tomato (*Solanum lycopersicum*). The main goal was to examine the day to day pattern of spectrum reflectance and the values of the reflectance indices (mostly in the first two days of irrigation holding), based on spectroradiometer's data and for different time periods during the day, based on multispectral camera's data. The experiment took place in a growth chamber, so that errors from sunlight angles and the cloudy sky could be avoided. The potential use of these spectral indices was compared with soil water content.

MATERIALS AND METHODS

The growth chamber is placed in the experimental farm of the University of Thessaly, in Velestino, Greece (39^o 44' N, 22^o 79' E). Inside the chamber, light intensity is controlled with high pressure sodium lamps, 600W/each. Lights were on from 6:00am to 10:00am, with all 18 lamps being on from 8am to 8pm, while, during the transition periods of 6am-7am and 9pm-10pm there were 6 lamps on, and during the periods of 7am-8am and 8pm-9pm there were 12 lamps on. At the beginning of the experiment, well-irrigated plants were used as a reference point (control). Moreover, water stressed plants were applied by withholding water, through the removal of drippers. Mainly, is studded the reaction of plants the first two days of the water stress progress (moreover, mean daily reflectance and soil moisture values of the days before and after the experiment were recored, in order to obtain sufficient statistical data). Perlite slabs contained 67-69 % solution at field capacity.

Plant reflectance was measured using an ASD FieldSpec Pro spectroradiometer (350-2500 nm) (by Analytical Spectral Devices, Boulder, CO, USA) and a multispectral camera (R: 590-680 nm, infrared: 690-830 and NIR: 830-1000 nm) (Custom model, Quest Innovation, Ohio, USA). The spectroradiometer includes 25^o field of view fiber optics and measures the reflectance in contact with the leaf. A white spectralon was used for the estimation of the reflectance every 20 minutes. Plant radiance measurements were taken by averaging 18 leaves, in order to optimize time integration and eliminate errors that were caused by different leaf compounds. Measurements were taken on a daily basis, at the same time period (7am-8am). The multispectral camera (1280×1024 pixels) includes an F-type lens and a CMOS-type sensor technology. It was used to record a young, fully developed leaf between the 3rd and 6th branch from the top, of the middle plant, from a distance of 100cm. Measurements were taken on a hourly basis (6:15am-7:30pm), every day. Each image was obtained by averaging measurements from 10 images, in order to eliminate time integration. Before each measurement, white (*W*) balance was estimated by placing a white board in front of the lens under different light signal levels. Furthermore, a spectrally flat black surface was placed as a background, in order to ensure a constant field of view without any shadows. Plant reflectance (*r*) was calculated by the ratio of the difference of actual image reflectance (*R*) and the dark reference (*D*), over the difference of white and dark references ($r=(R-D)/(W-D)$). Dark image was acquired by covering the lens with a cap. The MATLAB software package (by MathWorks®) was used for image analysis.

RESULTS AND DISCUSSION

The healthy plants of tomato follow the typical spectral signature. As plant water stress was developing, the spectral reflectance of the leaves was increasing, mostly in the NIR region. Initially, on the first day of the experiment when all the plants were in a proper water content, the reflectance values, mostly in the red-NIR spectrum, were similar (the difference between them was less than 0.01 units). On the next day (1st day of irrigation-holding for the second treatment), the spectral reflectance variation in the red band was too small, while the mean spectral reflectance in the red-NIR was increased by 4.8%. Additionally, on the third day of the experiment (2nd day of irrigation-holding for the second treatment), the difference between the two treatments was similar to the previous day (0.03 units). Table 2 presents the day-to-day mean value of the spectral ranges 550-650, 650-680 and 680-800 nm, based on the spectroradiometer sensor measurements. Figure 1 shows the plant reflectance values (350-2500 nm) for the control and the stress plant, during the second day of the experiment (1st day of irrigation-holding). According to Table 2 and Figure 1, the plant spectral profile showed small differences with plant water deficit, due to the fact that the data were taken by the spectroradiometer once a day, early in the morning for the plants, when the plants contained sufficient amount of water (during the night, water is moved to the top of the stem, following a positive hydrostatic pressure). Furthermore, the mean spectral reflectance of the same treatment plants, varies non-linearly during the days of the experiment, due to external parameters, such as light intensity, time interval of the sensor's contact with the leaf and sensor noise. Thus, the differences were observed by comparing data between control and treatment plants.

On the other hand, the combination of more than one spectral region, leaded to errors elimination, even early in the morning. Thus, some of the most effective spectral indices for plant water stress assessment were calculated (Table 1). Table 3 displays the indices values for the three days of the experiment (1st Day: normal irrigation, 2nd and 3rd Day: irrigation-holding) and presents the correlation coefficients between these indices and the soil moisture content. Each correlation coefficient was calculated by the daily mean of indices values and soil water content. The best indices for plant water stress detection were $NDVI_{800}$ and rNDVI, with R^2 values of 0.847 and 0.828, respectively. Figure 2 shows a scatter plot of $NDVI_{800}$ and rNDVI. Other indices with good correlation with soil moisture content were mrNDVI and mrSRI, with R^2 values of 0.752 and 0.799, respectively (Table 3). PRI showed medium correlation with soil moisture content, due to the low light intensity emitted by the sodium lamps in blue and green spectral regions. Thus, PRI is not independent of light conditions and must be further studied, with higher values of light intensity.

The multispectral camera measures the reflectance in more than one leaves simultaneously, and it was used to detect plant water stress deficit during the day. Different spectral signatures during the day were observed, mostly in the NIR region (maximum variation of 0.02 units) (Figure 3). The maximum variation among the days was detected some hours after midday, with a 15% increase the 1st day of water stress progress and a 10% increase the 2nd day of water stress progress. The low values of spectrum in 830-1000 nm were caused by the low light intensity in that spectral area.

Taking into account the fact that multispectral cameras measure the mean of the regions 590-680, 690-830 and 830-1000 nm, a new simple ratio reflectance index was calculated (SRI), based on those spectral areas. The new SRI was the ratio between the mean reflectance in 690-830 nm and in 590-680 nm. It was evaluated using both types of sensors (multispectral camera and spectroradiometer) and gave a good correlation with soil moisture content in both cased (R^2=0.745 and R^2=0.754, respectively) (Figure 4). The values of SRI decreased with the plant water stress progress. However, a delay between the time of irrigation signal and the increase of SRI was observed (Table 4). In Table 4, the first measurement of SRI (at 6:15am) represented the pre-dawn value (8.80), in which the plant contained the maximum amount of water. The value of the next measurement was decreased by half (4.6) due to transpiration needs. From that moment, the SRI increased for one hour and half after the irrigation dose at 10am, remained stable after the irrigation dose at 12pm, decreased after the irrigation dose at 2pm (probably the irrigation dose was not enough) and increased after some minutes of the irrigation dose at 4pm.

Further study of the SRI with transpiration rate, soil moisture content, sap flow and leaf temperature, would contribute to more solid conclusions about the leaf water content variation during the day. Moreover, it includes the mean values of a wide spectral area (mean in 690-830 and mean in 590-680 nm), and as a result, a considerable amount of information is lost. Hence, a different protocol, based on hourly variation, must be conducted and reflectance indices with better correlation coefficients than SRI, such as NDVI, rNDVI, mrNDVI and mrSRI, based on hyperspectral camera measurements, should be studied, in order to create a proper tool for irrigation management in greenhouse plants.

CONCLUSIONS

In this work, the behavior of several spectral reflectance indices for water stress detection in tomato plants was investigated and a new index for that purposed was developed. An experimental setup inside a fully controlled growth chamber was developed, using a spectroradiometer and a multispectral camera for taking reflectance measurements of well irrigated and water-stressed plants. The first day of irrigation-holding, the reflectance differences between healthy and water-stressed plants were found mostly in the near-infrared region of the spectrum. Among the eight most effective spectral indices for plant water stress detection, $NDVI_{800}$ and rNDVI had the higher correlation with soil moisture content (R^2=0.845 and R^2=0.828, respectively). These indices must be further studied to predict soil moisture content in short-time periods for irrigation management in greenhouse plants. Due to the fact that the multispectral camera is a relatively low-cost sensor that measures reflectance in more than one leaves, it was used to evaluate a new simple ratio reflectance index (SRI) in the 690-830 and 590-680 nm regions. The index was calculated using both types of sensors and showed a good correlation with soil moisture content (around R^2=0.75). A hyperspectral imaging system should be used to study the aforementioned indices, based on short time period soil moisture content and other plant characteristics variations.

ACKNOWLEDGEMENTS

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Tables

Table 1. The most effective reflectance indices for plant water stress detection.

Index	Index's calculation	Reference

PRI	$\frac{(R531-R570)}{(R531+R570)}$	(Sarlikioti et al., 2010), (Suárez et al., 2009)
WI	$\frac{(R970)}{(R900)}$	(Jones et al., 2004), (Clevers et al., 2008)
$NDVI_{(800\text{-}680)}$	$\frac{(R800-R680)}{(R800+R680)}$	(Köksal et al. 2010), (Genc et al., 2011)
$NDVI_{(490\text{-}620)}$	$\frac{(R490-R620)}{(R490+R620)}$	(Shimada et al., 2012)
rNDVI	$\frac{(R750-R705)}{(R750+R705)}$	(Kim et al., 2010), (Amatya et al., 2012)
mrNDVI	$\frac{(R750-R705)}{(R750+R705-2*445)}$	(Kim et al., 2010), (Amatya et al., 2012)
mrSRI	$\frac{(R750-R445)}{(R705-R445)}$	(Amatya et al., 2012)
VOGREI	$\frac{(R740)}{(R720)}$	(Vogelman et al., 1993)

Table 2. Mean values for several spectral regions, between control and stress treatment.

Spectral band	Control plant Day 1 (good water content)	Stressed plant Day 1 (good water content)
G (550-650 nm)	0.160038	0.161159
R (650-680 nm)	0.107753	0.107462
R-NIR (680-800 nm)	0.603054	0.616028
Spectral band	Day 2 (good water content)	Day 2 (1st day of irrigation holding)
G (550-650 nm)	0.176854	0.181539
R (650-680 nm)	0.106233	0.107241
R-NIR (680-800 nm)	0.576499	0.604617
Spectral band	Day 3 (good water content)	Day 3 (2nd day of irrigation holding)
G (550-650 nm)	0.17523	0.176002
R (650-680 nm)	0.115225	0.114207
R-NIR (680-800 nm)	0.590010	0.618418

Table 3. Mean spectral indices based on spectroradiometer sensor and the correlation between spectral indices and soil moisture content.

Spectral Indices	Index Values 1st Day	 2nd Day	 3rd Day	R^2
WI	1.043353	1.041825	1.043323	0.564
PRI	0.042318	0.042538	0.039813	0.453
NDVI490	0.040027	0.044823	0.041334	0.548
NDVI800	0.690235	0.685057	0.679465	0.847
rNDVI	0.537329	0.531714	0.528951	0.828
mrNDVI	0.838079	0.849008	0.849954	0.752

mrSRI	12.03196	13.14167	13.70528	0.799
VOGREI	1.632183	1.620708	1.62077	0.565

Table 4. Timetable of irrigation programs and water doses during the 1st Day (well water-content plants), with times of image capturing and the corresponding SRI values.

Time	Irrigation dose (ml/hydr. bag)	Time of image capture	SRI values
		18:14	8.804861
19:02	393	19:15	4.691235
		20:15	4.564084
		21:17	4.444531
22:01	393	22:19	4.370113
		23:20	4.420807
00:02	393	00:21	4.393197
		01:23	4.315177
02:01	393	02:24	4.279687
		03:25	4.169692
04:01	393	04:27	4.237772
		05:28	4.223455
06:01	393	06:29	4.178614
07:32	393	07:31	4.206999

Figures

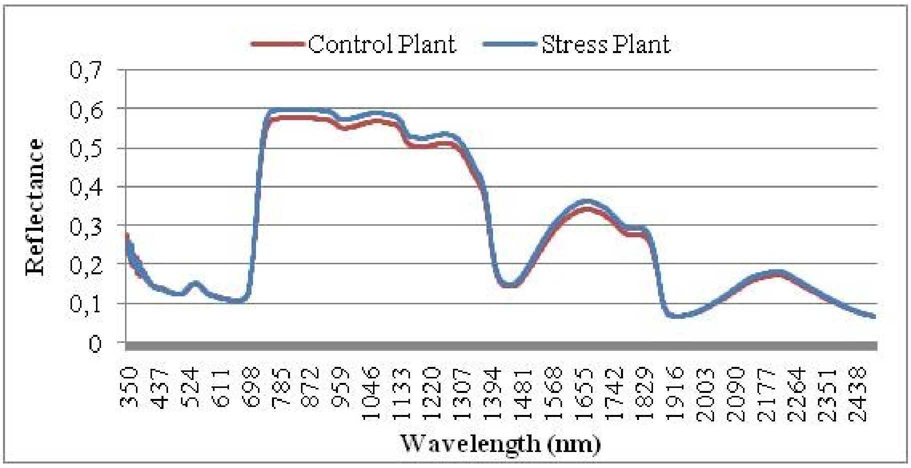

Figure 1. Tomato spectrum profile (350-2500 nm) between irrigated and not irrigated plants the first day of water stress progress, during the same time period (7am-8am), based on the spectroradiometer.

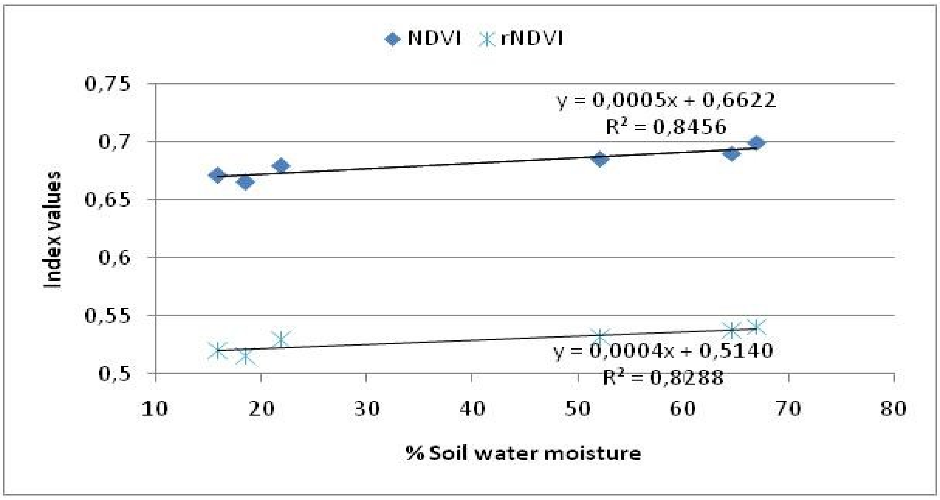

Figure 2. $NDVI_{800}$ and rNDVI response to soil moisture content, based on the spectroradiometer.

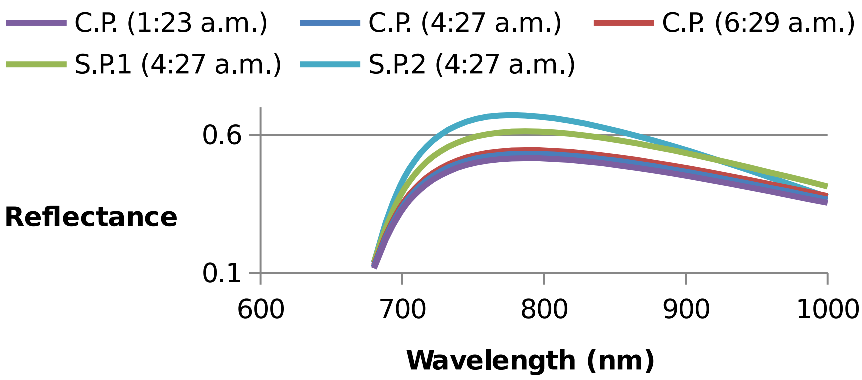

Figure 3. Control plants spectral profile (C.P.) based on multispectral camera, for different time periods during the day (1:23pm, 4:27pm, 6:29pm) and stressed plants spectral profile (S.P.) the 1st and 2nd day of water stress progress.

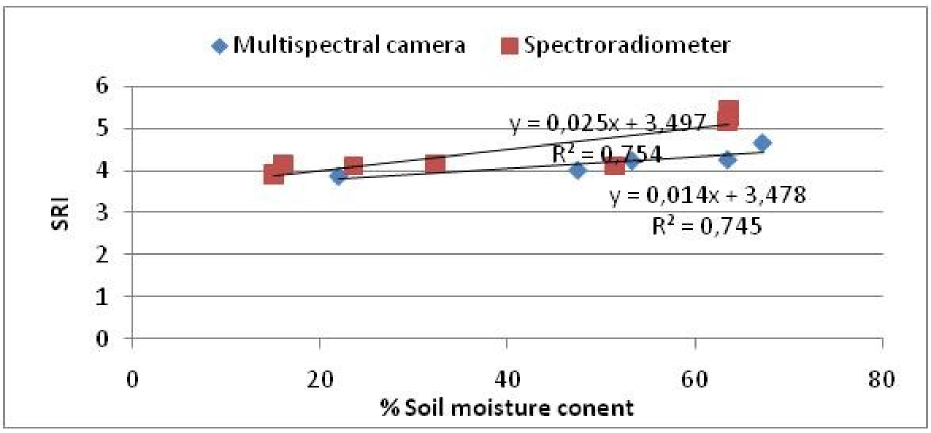

Figure 4. SRI response to soil moisture content for two different sensor types (spectroradiometer and multispectral camera).