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Remote sensing of canopy light interception and plant water deficit stress under greenhouse conditions

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1. Introduction, Knowledge, Objectives

The increased concern of consumers for food safety and environmental pollution during the last decades led to an increase in greenhouse production. However, greenhouse cultivation is not an easy task as it includes a series of practices, different from those applied in open field farming (Katsoulas et al., 2016; Max et al., 2012). Therefore, there is a crucial need for information and technologies in order to optimize crop yields and quality, manage production costs, and minimize the risk of ground water and nitrogen contamination.

According to Schmidt and Zinkernagel (2017), Zinkernagel et al. (2015) and Kahlen et al. (2015), knowledge has to be generated for crop management adapted to climate change. To achieve this, it is more advantageous to develop a real-time plant canopy health, growth and quality monitoring system with multi-sensor platforms. Hyperspectral machine vision is a non-contact and non-destructive sensing technology that enables multi-dimensional sensing capabilities by extracting various information from a targeted object including spectral data (Story and Kacira, 2015; Katsoulas et al., 2016; Elvanidi et al., 2018). In this work, hyperspectral machine vision was used to quantify the effect of canopy density and architectural changes in pixel-level reflectance variation under greenhouse conditions, in order to detect plant water deficit stress in cucumber plants. Previous efforts, however, concerning machine vision and sensing have been successful in determining plant status by monitoring a single leaf or a single plant and mostly under controlled light conditions (Elvanidi et al., 2018). To use machine vision under greenhouse conditions is not an easy task. Even the most advanced hyperspectral sensors present some instability in measurement over time, due to the intense effects of solar radiation in the target area. In this work, the response of the hyperspectral camera was analysed under greenhouse conditions to study the impact of the environment factors on the measurements. Additionally, an effort to study the impact of crop water deficit to the reflectance data was performed.

2. Material and Methods

The experiment was conducted in a single span float-glass covered greenhouse, located at the University of Geisenheim, Germany (49°59′4″N 7°58′2″E). Cucumber plants (*Cucumis sativus* 'Aramon' (Rijk Zwaan, De Lier, The Netherlands)) were grown in six lines consisting of peat substrate and drip irrigation. In order to study the effects of background signal as well as plant density and architecture on crop reflectance response to water deficit stress, four treatments were applied. Two crop density treatments: (a) 1.85 plants per m^2 (high density treatment: HD) and (b) 0.92 plants per m^2 (low density treatment: LD), in plants that were (c) regularly irrigated with 100 % coverage of their water needs (control treatment: C; irrigation start: -25 hPa substrate water potential, 200 ml/plant*irrigation event) and (d) irrigated only with the 60-80 % of their water needs (water deficit stress treatment: WS; irrigation start: -120 to -200 hPa, 120 ml/plant*irrigation event). Each combination of irrigation and crop density treatment was arranged in a randomised block design with three replications.

A hyperspectral camera Imspec V10 (Spectral Imaging Ltd, Finland) operated between 400-1000 nm was used. Extra illumination of the target area (70 x 100 cm) by four quartz-halogen illuminators (500 W each), was used to provide validation wavelength from 400 to 900 nm. Details about the sensor's technical specifications, the calibration method and plant reflectance calculation followed are presented in Katsoulas et al. (2014; 2016) and Elvanidi et al. (2018). In order to quantify the camera's reflectance response due to background, and crop density and architecture the reflection for several bands of a white board (W; 70 x 100 cm) positioned 0.8 m in front of the sensor was recorded with (B) and without placing black surface (nB) behind and below the target scene. The image noise characteristics were further determined by comparing the reflection values acquired by the young and fully developed leaves (YFDL) of cucumber plants (P), with and without placing black surface as a background. The camera system was placed on a moving cart so that images of the vertical axis of the target scene could be obtained. Each cycle of measurements performed in each block within the greenhouse, was carried out under different conditions of solar hour angle (3 cycles per treatment from 12:00 to 16:00 local time).

The studied mean reflectance difference (ΔDN, %) between B and nB images was resulted by the average information expressed in digital numbers (DN), that each pixel received. The images recorded twenty days after transplanting (15 days after the irrigation treatments were applied) when the plants were about 1 m in height. Plant reflectance was also measured using a CompactSpec ETH spectroradiometer (380-2150 nm) (Tec5 AG, Oberursel, Germany), that measured irradiance by placing the fibre optic input of the equipment at the leaf surface. Reflectance measurements of 9 YFDL per treatment were taken randomly within the canopy. Comparison of means was performed by applying one-way ANOVA at a confidence level of 95 % ($p \leq 0.05$) using SPSS (Statistical Package for the Social Sciences, IBM, USA).

3. Results

As already mentioned, to use machine vision under greenhouse conditions is not an easy task since the measurements present some instability over time, due to the intense effects in the target area of solar radiation and the neighborhood shadows resulted by the crop density/architecture and greenhouse skeleton frame. In the current study, the impact of solar angle and background noise to the hyperspectral data is quantified by taken hyperspectral images of the vertical surface of the white panel with and without background noise in different position within the greenhouse. The measurements recorded in 0^o and 30^o of solar angle. The resulted difference between the pixels of two images is presented in Figure 1a. Particularly, when the measurements recorded at noon, in which the solar hour angle was 0º, the ΔDN values in the HD block, was more than 6 %, mostly in the visible region. The ΔDN values observed in the near-infrared region was less but still significant. The same holds were observed in the LD block. However, when the solar hour angle was 30º, the ΔDN values of LD block was further increased, while the values of HD block were decreased. To better understand the reverberation of the plant water stress to the camera's reflectance response, the daily mean of ΔDN values performed by the YFDL per irrigation and crop density treatment, were examined (Fig. 1b). According to the findings, the ΔDN values observed in the YFDL followed different pattern. In fact, the ΔDN values observed in well-watered cucumbers leaves of HD treatment were less than 9 % over the entire studied spectrum region. On the other hand, the ΔDN values observed in well-watered plants of LD treatment increased from the values observed in HD treatment, mostly in NIR, more than 15 %. The above results indicate that the red and near-infrared region can give more stable measurements and be saturated less by HD vegetation conditions. Moreover, it is worth to notice that the ΔDN values observed in water-treated cucumbers leaves of both HD and LD treatments, increased in region between 740-890 nm, more than 8 %. The morphological changes such as leaf curling due to loss of cell turgidity may have caused this reduction.

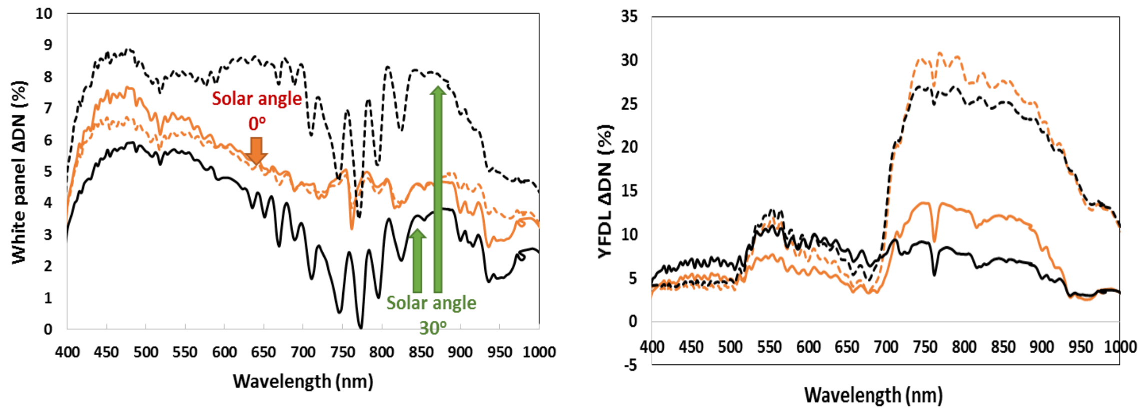

Fig. 1. ΔDN values (%) observed in (a) the vertical surface of white panel, measured under two different solar hour angles and (b) YFDL at two different irrigation treatments. Solid line: HD treatment; dot line: LD treatment; colour line: (a) 0º solar hour angle or (b) WS treatment; black line: (a) 30º solar hour angle or (b) C treatment.

In addition, to correlate the resulted spectral data of different wavelengths with plants' biophysical characteristics, the data should be further normalized by following the method described in Katsoulas et al. (2016). In the current research, the normalized reflectance values observed without background noise in YFDL of well-watered plants in HD treatment, followed the typical reflectance signature of a common healthy green cucumber leaf (Fig. 2a). However, by comparing the reflectance data obtained by hyperspectral camera and portable spectroradiometer that measure in contact with the leaf, significant difference in the spectral values was observed between 730-800 nm and 840-1000 nm. This is happening because when the spectral profile is recorded by hyperspectral camera, the observations are affected by the orientation of the scatters (leaves). According to Asner (1998), leaf orientation has a strong effect on the expression of leaf optical properties at canopy scale and may be a result of different water deficit in the mesophyll area of the leaf. On the other hand, when recording the spectral profile at a single point of the leaf, errors due to the directional reflectance behavior of vegetation canopies are no longer prevail. In order to have a clear indication between the spectral properties and the plant physiology status, the reflectance data should be examined for trends rather than absolute values. In this sense, the reflectance values observed in YFDL of water deficit plants cultivated in HD significantly increased from those observed in healthy plants, mostly in the visible region and between 830-1000 nm (Fig. 2b). The maximum difference observed at 550 nm and around 1000 nm and was equal to 62 % and 35 % respectively.

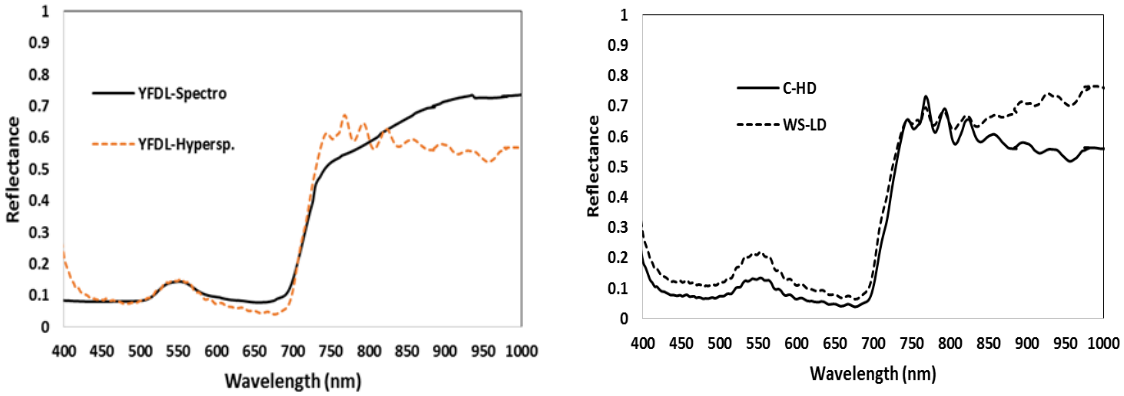

Fig. 2. Reflectance of (a) YFDL of C plants, measured by two types of sensors and (b) C and WS plants, cultivated under HD conditions.

4. Discussion

Under greenhouse conditions light intensity and quality distribution within the growing space is inhomogeneous. To this effect hyperspectral camera is not possible to use direct reflectance measurements as a metric of leaf water concentration. Nevertheless taking in consideration that the camera parameters are not constant, mathematic models could be a rapid and more cost-effective solution to further eliminate the errors originating from different noise sources (de Visser et al., 2014). This forces the need for quantifying the impact of the illumination to the recorded hyperspectral images in order to manage correlating the resulted reflectance values with crop water deficit stress. In the current research intense variation in light diffusion and canopy reflectance characteristics within the greenhouse is presented due to the background noise mostly in low density crops. Typically the plant reflection cultivated under high density vegetation conditions changed by about

9 %, and under low density by about 15 % mostly in NIR spectrum as a function of background and canopy architecture aspect. According to those findings, crop density at 60 cm is more appropriate for estimating cucumber plant water deficit stress through hyperspectral camera under greenhouse conditions. Similar findings were presented by Asner et al. (1998) without the added complexity of the atmosphere.

In addition, the results presented in this work indicate that the water status differences among the plants of the different treatments were directly linked to changes in crop radiation reflectance. The most sensitive spectral region, due to the effect of water deficit stress, was found to be the region in the visible region and between 830-1000 nm. The above are in agreement with Elvanidi et al. (2018) that indicated similar increase of reflectance under water deficit stress in tomato crop.

5. Conclusions

The results of the present study confirmed that similar to other crops, cucumber reflectance increases under water deficit stress. Also confirmed that the spectral properties of leaves are not only influenced by plant water status, but also by factors such as canopy density/ architecture and background noise. These factors can introduce variations that reduce the correlation between water stress in greenhouse plants and leaf spectral response. The performance of reflectance indices data can be improved by filtering the measurements form valid recording images. However, the calibration methods of optical sensors, especially the hyperspectral imaging system need to be further analysed to generate more stable data.

6. Literature

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