Calibration Methodology of a Remote PRI Sensor for Photosynthesis Rate Assessment in Greenhouses †

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Abstract: Early detection of different types of crop stress under greenhouse cultivations is critical in order to optimize yield and resource use efficiency. The objective of the present work is to develop a system which, based on remote sensing, will recognize plant stress by combining microclimate and crop physiology data. The innovation of the platform is based on the integration of a remote PRI sensor that is used to correlate PRI measurements and photosynthesis rate (Ps). In this work, the methodology that is used for the PRI sensor calibration and acquisition is presented. The values that were recorded by means of the PRI sensor were correlated with the Ps rate that was obtained with a handheld photosynthesis system. Data of the PRI and Ps values were collected under different lighting, temperature and plant water status conditions of a greenhouse tomato crop. The basic statistical parameters of the mean and standard deviation values are used to estimate the spectral correlation at 530 nm and 570 nm on the interested leaf area. The determination coefficient ($R^2$) of the linear regression that was obtained between the PRI and Ps data was about 0.9. The obtained equation will be integrated in the sensing system and the data will be used to train a machine learning model to detect different type of crop stress under greenhouse conditions.

Keywords: remote sensing; photosynthesis rate; multisensory platform; plant stress; plant water status

1. Introduction

The double effect of the up-coming growth population and the need for more sustainable agriculture led to a call for higher yield production without expanding agricultural land use. Additionally, due to the COVID-19 pandemic, there are increasingly alarming reports about imminent threats on a global scale regarding economic sustainability and food security and quality. Due to this, protected cultivation, where crops are cultivated in a controlled environment (especially soilless—growing a crop without soil), has become an important part of the agricultural industry.

However, in order to increase productivity in the existing greenhouse-covered area, there is a need to redesign the operational control system, among others, to establish more demonstrative greenhouses. Nowadays, in order to maintain the desired indoor climate, a great variety of controllers are used. The controllers are supported by automated control models that are based on the obtained environmental data. However, to achieve satisfactory results, one should consider not only controlling the greenhouse climate, but also the crop. Monitoring of the plant responses and processes under specific environmental and root conditions in real time could improve climate and irrigation control and the overall production over time and space [1]. Especially in commercial production systems, it is more advantageous to apply a real-time plant canopy health, growth, and quality monitoring system with multi-sensor platforms [2].

Up to now, it has not been feasible to monitor crop physiological parameters in real time without requiring plant contact or destructive sampling. Current computational...
intelligence techniques have allowed the development of a hyperspectral optic system that supplies information about crop physiology and morphology. Based on the current technology, a series of reflectance indices, such as Normalized Vegetation Index (NDVI) and Photochemical Reflectance Index (PRI), were significantly correlated with crop green biomass and photosynthesis rate [3]. Originally, PRI was interpreted as a reflectance parameter enabling detection of the spectral signature of xanthophyll cycle pigments that were involved in the dissipation of excess light through non-photochemical quenching [4,5].

Optic systems of measuring canopy reflectance factors offer advantages over the traditional approach of leaf-scale measuring reflectance factors using integrating spheres [6]. However, these methods are high-cost sensors, difficult to handle, and unable to be adjusted in a multi-sensor platform. The recent development of remote soft-sensors (i.e., mathematical models using real-time sensor data) allows the development of models that integrate plant-based indices/indicators. Based on the current robust, easier to use methodology, the hourly variation of Ps under different climatic and fertigated conditions can be studied, not only for a few days, but for the entire cultivation season.

In the current research, a remote Spectral Reflectance Sensor (SRS) that measured crop PRI in distance was used to estimate crop Ps remotely under greenhouse conditions. The aim of the present research was (a) to study the sensor’s behavior; (b) to develop a regression that could estimate Ps by using PRI values. To achieve this goal, tomato crop was cultivated in perlite slabs, while the remote PRI values were evaluated with the Ps values that were recorded by a portable sensor in contact with the leaf.

2. Materials and Methods

The calibration procedure was performed in June of 2020 in a multi-tunnel greenhouse with a total ground area of 1500 m² (250 m² each compartment). The establishments were located at the facilities of the University of Thessaly, Velesino, Volos (Latitude 39°22′, longitude 22°44′ and altitude 85 m), in the continental area of eastern Greece. The greenhouse was covered by a transparent film and equipped with fans, a thermal screen, a heating system, and a cooling system. The air temperature and relative humidity were automatically controlled with the help of a climate control computer (SERCOM, Automation SL, The Netherlands), in order to achieve the optimal indoor climate conditions.

The tomato plants were cultivated rockwool slabs (Grodan Delta, NL 100 × 15 × 7.5 cm, 0.18 g cm⁻³, 90% water retention capacity). The plants were fertigated with fresh nutrient solution with set-points of electrical conductivity (EC) around 2 dS m⁻¹ and a pH of 5.8. The water that was used to prepare the NS had a pH of 7.1 and an EC of 0.8 dS m⁻¹. The nutrient solution that was supplied to the crop was a standard nutrient solution for tomato, grown in open hydroponic systems, adapted to Mediterranean climatic conditions, with the following composition: 5.2 mM L⁻¹ Ca²⁺; 2.9 mM L⁻¹ Mg²⁺; 2.5 mM L⁻¹ K⁺; 1.5 Na⁺; 11 mM L⁻¹ NO₃⁻; 0.8 mM L⁻¹ H₂PO₄⁻; 23.50 µM L⁻¹ Fe; 5.00 µM L⁻¹ Mn; 3.80 µM L⁻¹ Zn. Moreover, micronutrients were added to NS: chelated with EDTA containing Fe 6%; Mn 13%; Zn 15%; B 21%; Cu 0.3%; Mo 0.2%.

PRI was measured through an SRS sensor (SRS-PRI sensor; METER Group Inc., NE Hopkins Court, Pullman, WA 99163, USA,) (Figure 1). The remote PRI sensor was radiometrically calibrated by default to a NIST-traceable standard and centered at 532 nm and 570 nm with a 10 nm FWHM. The corrected PRI was calculated as the ratio between reflected and incident radiation, measured using down-looking and up-looking sensors, respectively. The readings of both up and down-looking sensor are PRI outputs (Equation (1)):

\[
PRI = \frac{(R_{531} - R_{570})}{(R_{531} + R_{570})}
\]

where R is the reflectance in units of the radiant flux density (W m⁻² nm⁻¹) in nanometers, the PRI is calculated. In the reading outputs, the ratio between R531 and R570 is also adjusted. The up-looking SRS sensor was mounted above the canopy with an unobstructed view of the sky. The down-looking SRS sensor was placed 2 m above the ground, 0.20 m from the crop, at a constant angle of 45° from the vertical axis, in order to view a leaf.
area of young and fully developed leaves. The sensed surface area was approximately 2000 mm$^2$. Additionally, a solar radiation sensor (Rn, W m$^{-2}$; SP-SS, Apogee Instruments, North Logan, UT 8432, USA) was used to measure the light intensity above the canopy. The microclimatic sensors that are installed in the greenhouse are connected to a device-to-web data logger, which feeds a respective database. The measurements were performed every 30 s and the 5-min average was recorded.

![Figure 1](image)

**Figure 1.** The daily progress of: (a) incident radiation and PRI recorded by SR and SRS up-looking sensor (dot line: SR values; solid line: SRS up values); (b) incident and reflected PRI recorded by SRS up-looking and down-looking sensor, respectively (dot line: SRS up values; solid line: SRS down values).

The mean PRI of the crop that was measured using remote sensing ($\text{PRI}_R$) was correlated by the mean of the PRI sensor ($\text{PRI}_L$) performing measurements in contact with the leaf (PlantPen PRI Meter, Alpha Omega-Electronics, Spain) for the same dataset. Additionally, the $\text{PRI}_R$ values were correlated with the photosynthesis rate ($A_s$, µmol m$^{-2}$ s$^{-1}$), which was obtained using a portable photosynthesis measurements system (LCpro, ADC Bioscientific Ltd., Hoddesdon, Herts, EN11 0NT, London, UK) for the same leaf set. The correlation was performed under different climatic conditions and light intensity.

3. Results

3.1. $\text{PRI}_R$ Indicator Based on Light Signal

Figure 1a presents the incident PRI that was recorded by the up-looking SRS sensor established above the canopy with an unobstructed view of the sky. The data follow the same trend with the incident radiation that was measured by the solar radiation sensor. As expected, the maximum values were observed around noon. The differences that were observed between the SRSup and the conventional SR sensor occurred due to the different position of the sensors and their effect on the neighborhood materials shadows in the measured area.
The daily progress of the down-looking sensor that restricts the field of view of the specific leaf target is presented in Figure 1b. The PRI intensity of the down-looking values contained high amounts of variability due to the environmental changes and observation conditions. The spurious data points occurred due to the removal of the low light intensity, since those data result in indeterminate or undefined calculations of PRI estimation. However, the daily movement of the sun did not affect the progress of the down-looking values, otherwise, a concave pattern would be noticed.

3.2. Photosynthesis Rate Estimation Based on Remote PRI Sensor

The calculated PRI$_R$ that was estimated by the SRS sensor was correlated with the values that were recorded by the PRI$_L$ sensor in contact with the leaf (Figure 2). When plotting remote PRI$_R$ vs. contact PRI$_L$ values, a strong linear relationship was achieved, while the determination coefficient ($R^2$) of the aforementioned regression was found to be higher than 0.90 ($p < 0.05$). The differences between the canopy PRI and actual leaf PRI depend on the atmospheric conditions.

![Figure 2](image2.png)

Figure 2. Relationship between PRI$_L$ with PRI$_R$ and Ps variation observed in young and fully developed leaves of tomato crop (dot: PRI$_L$ vs. Ps; square: PRI$_L$ vs. PRI$_R$).

Figure 2 also presents the correlation between the PRI$_L$ and the Ps values, recorded by portable equipment that measured the $A_s$ in contact with the leaf. When plotting the PRI$_L$ vs. contact Ps values, a strong linear relationship was found, while the $R^2$ of the mentioned regression was found to be higher than 0.92 ($p < 0.05$). Moreover, a strong correlation was obtained between the PRI$_R$ and the actual Ps values.

Figure 3 presents the daily evolution of PRI$_R$ and the calculated Ps values during the time period in which the light intensity was higher than 100 W m$^{-2}$. According to the calculated data, the daily mean Ps was about 18 $\mu$mol m$^{-2}$ s$^{-1}$. The maximum values of the photosynthesis rate were achieved after noon, while minimum values of around 7.4 were observed occasionally throughout the day.

![Figure 3](image3.png)

Figure 3. Corrected PRI data collected remotely at five-minute intervals and the calculated photosynthesis rate values obtained from a tomato canopy under greenhouse conditions (dot line: Calculated Ps; solid line: PRI$_R$).
4. Discussion

The fraction of photosynthetically active radiation that was absorbed by the canopy can be estimated by remotely sensed vegetation indices. The PRI for instance, derived from narrow-band spectro-radiometers, is a spectral index that is increasingly being used as an indicator of photosynthetic efficiency [7].

Gammon et al. [8] were among the first to present a correlation between the physiological reflectance index and the depoxidation state of the xanthophylls cycle pigments. Thenot et al. [9] carried out experiments under greenhouse conditions to connect PRI with a correlated Photosynthetic Active Radiation-PAR level of 1800 mmol m$^{-2}$ s$^{-1}$ in Chenopodium quinoa with significant results. Sarlikioti et al. [10] used a handheld sensor to measure PRI in tomato crop under greenhouse conditions. According to their data, a good correlation was observed ($R^2 > 0.6$) between the PRI and relative water content, CO$_2$ assimilation, stomatal conductance, operating efficiency of PSII (Photosystem II) and NPQ. However, the resulted correlation was significant only when the light intensity was higher than 700 mmol m$^{-2}$ s$^{-1}$. In the current research, the index was measured remotely and the correlation between PRI and Ps variation was observed when the light intensity within the greenhouse reached the minimum value of 100 W m$^{-2}$ s$^{-1}$.

Ground-based remote sensing is well established as a tool for assessing crop eco-physiological variables; it has gained wide interest from agricultural practitioners to track crop performance with higher temporal and spatial resolution than the handheld sensors [11]. The mechanistic basis for PRI index has changed from leaf scale to canopy and larger scales [7,12]. In the current calibration process, a difference between the canopy PRI and actual leaf PRI due to atmospheric conditions was noticed. The resulting values, however, were strongly influenced by the canopy shading that was caused by the sun angle. As a result, the PRI$_{L}$ recorded signal was less intense than the PRI$_{I}$ signal. Magney et al. [12] used a spectral remote sensor to evaluate PRI under different environmental conditions. Their results showed that the use of a smoothing algorithm eliminated the data variation due to the ambient conditions.

Supplementary Materials: The poster presentation can be downloaded at: https://www.mdpi.com/article/10.3390/IECAG2021-10018/s1.

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References
1. Elvanidi, A.; Katsoulas, N.; Bartzanas, T.; Ferentinos, K.P.; Kittas, C. Crop water status assessment in controlled environment using crop reflectance and temperature measurements. Precis. Agric. 2017, 18, 332–349. [CrossRef]
2. Katsoulas, N.; Elvanidi, A.; Ferentinos, K.P.; Kacira, M.; Bartzanas, T.; Kittas, C. Crop reflectance monitoring as a tool for water stress detection in greenhouses: A review. Biosyst. Eng. 2016, 151, 374–398. [CrossRef]
3. Garbulsky, M.F.; Peñuelas, J.; Gamon, J.A.; Inoue, Y.; Filella, I. The photochemical reflectance index (PRI) and the remote sensing of leaf, canopy and ecosystem radiation use efficiencies: A review and meta-analysis. Rem. Sens. Environ. 2011, 115, 281–297. [CrossRef]
4. Kováč, D.; Veselovská, P.; Klem, K.; Večerová, K.; Ač, A.; Peñuelas, J.; Urban, O. Potential of photochemical reflectance index for indicating photochemistry and light use efficiency in leaves of European Beech and Norway Spruce Trees. Remote Sens. 2018, 10, 1202. [CrossRef]

5. Demmig-Adams, B.; Adams, W. The role of xanthophyll cycle carotenoids in the protection of photosynthesis. Trends Plant Sci. 1996, 1, 21–26. [CrossRef]

6. Lukeš, P.; Homolová, L.; Navrátil, M.; Hanuš, J. Assessing the consistency of optical properties measured in four integrating spheres. Int. J. Remote Sens. 2017, 38, 3817–3830. [CrossRef]

7. Gammon, J.A.; Peñuelas, J.; Field, C.B. A narrow-wave band spectral index that track diurnal changes in photosynthetic efficiency. Rem. Sens. Environ. 1992, 41, 35–44. [CrossRef]

8. Thenot, F.; Methy, M.; Winkel, T. The photochemical reflectance index (PRI) as water stress index. Intern. J. Rem. Sens. 2002, 23, 5135–5139. [CrossRef]

9. Sarlikioti, V.; Driever, S.M.; Marcellis, L.F.M. Photochemical reflectance index as a mean of monitoring early water stress. An. App. Biol. 2010, 157, 81–89. [CrossRef]

10. Mull, D.J. Twenty five years of remote sensing in precision agriculture: Key advances and remaining knowledge gaps. Biosyst. Eng. 2013, 114, 358–371. [CrossRef]

11. Inoue, S.; Kinoshita, T.; Matsumoto, M.; Nakayama, K.I.; Doi, M.; Shimazaki, K. Blue light-induced autophosphorylation of phototropin is a primary step for signaling. Proc. Natl. Acad. Sci. USA 2008, 105, 5626–5631. [CrossRef] [PubMed]

12. Magney, T.S.; Eitel, J.U.; Huggins, D.R.; Vierling, L.A. Proximal NDVI derived phenology improves in-season predictions of wheat quantity and quality. Agric. For. Meteorol. 2016, 217, 46–60. [CrossRef]