REFLECTANCE *PRI* DOES NOT EQUAL TRANSMITTANCE *PRI*

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ABSTRACT

Starting from leaf reflectance and transmittance measurements, we calculated two substantially different values of the Photochemical Reflectance Index (*PRI*) for each of 22 corn leaves having leaf chlorophyll concentrations ranging from high to low. Leaf reflectance and transmittance were measured simultaneously, precluding changes in leaf light use efficiency (LEU) between measurements. We propose the proportion of leaves reflecting v. transmitting direct beam sunlight toward a canopy reflectance sensor is a potential source of variability in estimates of canopy bidirectional *PRI*.

Index Terms – photochemical reflectance index, PRI, light use efficiency, LEU, photosynthesis, remote sensing

1. INTRODUCTION

In remote sensing, use of the Photochemical Reflectance Index (*PRI*) provides an evaluation window into the photosynthesis processes that occur inside the leaves of a plant canopy [1]-[14]. *PRI* is linked to photosynthetic light use efficiency (*LUE*), which is dry matter produced per unit of absorbed radiation [4]. Photosynthetic *LUE* varies with leaf environmental conditions, including incident light level and deviations from both optimal temperature and optimal amounts of available water and nutrients. Thus, *PRI* provides indication of the level of stress in a remotely sensed canopy due, for example, to environmental conditions that are non-optimal for plant growth such as too much or too little water, nutrients or incident sunlight [1],[2],[9].

Validation – establishing robust ties between *PRI* and canopy or ecosystem health – remains an ongoing challenge. While in a broad sense *PRI* values provide information about canopy photochemistry, those values have been shown to vary not only with plant canopy stress levels but also with variables not directly tied to plant canopy stress levels, such as plant species, leaf pigment composition, percent vegetation cover, visibility of soil background, shadows and canopy structure [9].

Researchers have noted pronounced *PRI* variation as a function of sun and view directions [3],[10]. Hilker et al. [5], [8], proposed algorithms to exploit the variation with view direction.

PRI for a leaf or canopy is estimated from reflectances, R_{531} and R_{570}, measured within two narrow wavelength bands [1],[2],[9]. One band, centered at 531 nm, lies within a xanthophyll pigment absorption region, a spectroscopic feature tied to leaf *LUE*. The second band, centered at 570 nm, lies outside the xanthophyll absorption region. Thus, in the calculation of *PRI*, the reflectance, R_{531}, contains information about the leaf photosynthesis process while the reflectance, R_{570}, allows in-band/out-of-band comparison (numerator) and normalization (denominator)

$$PRI = \frac{R_{531} - R_{570}}{R_{531} + R_{570}} \tag{1}$$

Here we show that, as expected, *PRI* values of individual reflecting leaves vary with leaf chlorophyll concentration, underscoring the value of *PRI* as a photosynthesis monitor. But our results also show that the *PRI* values of reflecting leaves compared to *PRI* values of transmitting leaves differ substantially.

2. METHODS

During a field experiments conducted at the USDA Beltsville Agricultural Research Center near Beltsville, Maryland, an adapted corn (*Zea mays* L.) variety was planted and fertilized with 0, 50, 100, and 200% of the N rate (140 kg N/ha) recommended for corn production on these soils. Using a SPAD-502 leaf chlorophyll meter (Spectrum Technologies, Aurora, Illinois), we measured the chlorophyll concentration, in SPAD units, [15], of 20 upper fully expanded corn leaves during early dent stage of development.

Immediately after harvest each corn leaf was placed in an ice chest partially filled with ice covered with cloth and transported to the lab for reflectance and transmittance measurements. The color of the corn leaves harvested ranged from very dark green to light yellow green, suggesting that chlorophyll concentrations in the harvested leaves ranged from high to low.

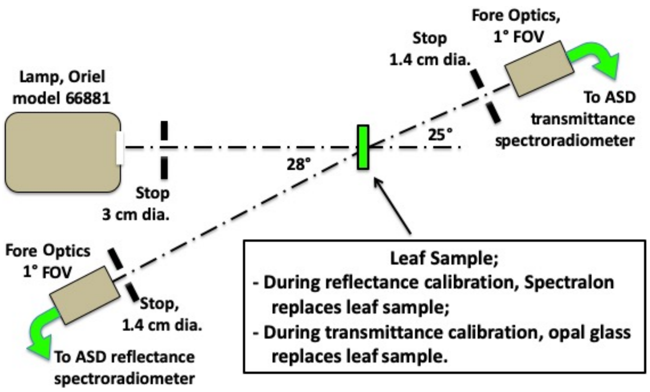

Fig. 1. Plan view of setup, which allowed estimation of leaf reflectance and leaf transmittance. For calibration purposes, approximately every 20 minutes we removed the leaf sample and measured first the reflectance DN of the Spectralon followed by the transmittance DN of the opal glass.

In the lab when a corn leaf sample was needed for measurement purposes, we mounted the trimmed, square leaf sample in the sample holder and placed the sample holder with leaf sample on the optical bench, Fig. 1.

For measurement of leaf reflectance and transmittance, we illuminated the leaf sample with a collimated beam of white light provided by a current controlled lamp (Oriel Instruments, Irvine, California, USA, model 6681) with 120 watts lamp power, and collected leaf spectral data with the aid of two Analytical Spectral Devices (ASD) FieldSpec Pro spectroradiometers (ASD — a Malvern Panalytical Company, Cambridge, UK). During collection of data for the two wavelengths, 531 and 570 nm, five spectra of 50 scans each were acquired using the reflectance and transmittance spectrometers, Fig. 1.

We calibrated the leaf reflectance data using measurements collected approximately every 20 minutes of a Spectralon calibration surface (Labsphere, Inc., North Sutton, New Hampshire, USA), which replaced the leaf sample, Fig. 1. We calibrated the leaf transmittance data using measurements collected approximately every 20 minutes of a diffusely transmitting, 50x50mm plate of opal glass, which replaced the leaf sample, Fig. 1. The leaf bidirectional reflectance and transmittance factors are found

$$R_{Leaf} = \frac{[\text{reflectance DN leaf, Fig. 1}]}{[\text{reflectance DN Spectralon, Fig. 1}]} * R_{Cal} \tag{2}$$

$$T_{Leaf} = \frac{[\text{transmittance DN leaf, Fig. 1}]}{[\text{transmittance DN Opal glass, Fig. 1}]} * CTR * R_{Cal} \tag{3}$$

where the Calibration Transfer Ratio, *CTR*, is defined

$$CTR = \frac{[\text{DN Opal glass, Fig. 2a}]}{[\text{DN Spectralon, Fig. 2b}]} * \frac{[\text{DN Spectralon, Fig. 2b}]}{[\text{DN Spectralon, Fig. 2c}]} \tag{4}$$

and where R_{Cal} is the spectral bidirectional factor of the Spectralon calibration standard.

We took particular care to ensure the two fiber optic cables connecting spectrometers and fore optics remained immobile throughout collection of all data - leaf and calibration - and during movement of the Oriel lamp, Fig. 2.

3. RESULTS AND DISCUSSION

The results, Fig. 3, show that the value of *PRI* for the corn leaf samples depends not only upon the leaf SPAD value, which is a surrogate for the leaf chlorophyll concentration

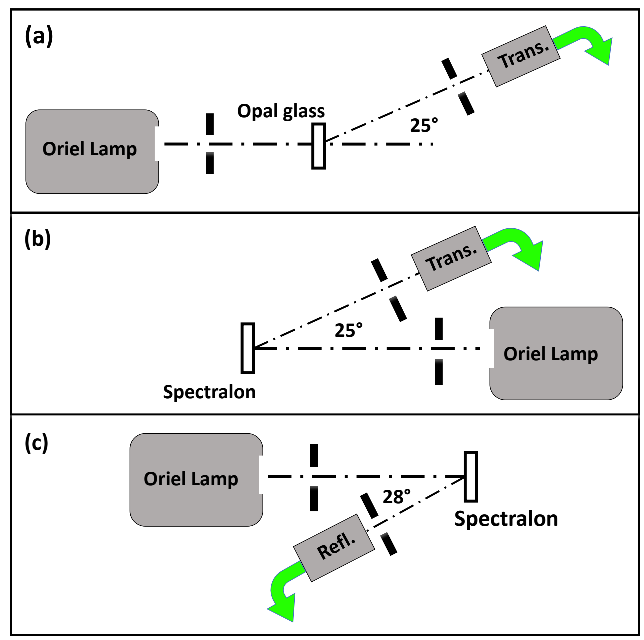

Fig. 2. Following collection of all leaf data, we estimated the Calibration Transfer Ratio, CTR, using setups (a), (b) and (c). Setup (a) allowed us obtain the opal glass transmittance DN provided by the transmittance spectrometer; setup (b), the Spectralon reflectance DN provided by the transmittance spectrometer; setup (c), the Spectralon reflectance DN provided by the reflectance spectrometer. The Oriel lamp operated at normal power as we slowly and carefully moved it from the reflectance side of the sample, setup (a), to the transmittance side, setup (b) and back to the reflectance side, setup (c).

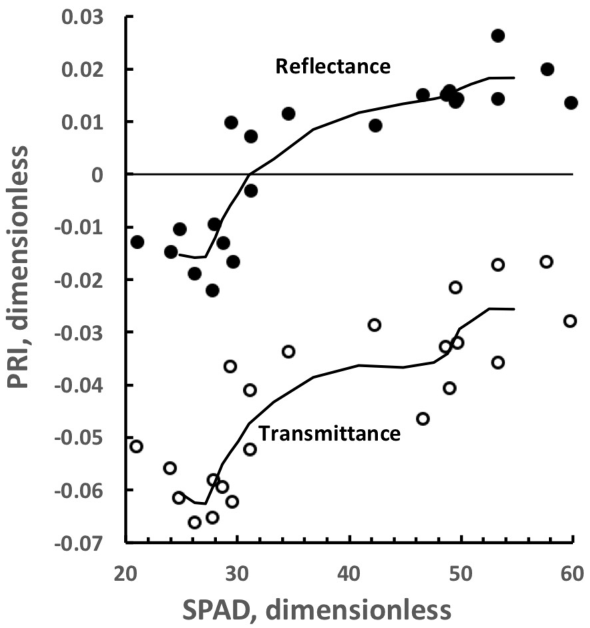

Fig. 3. *PRI* depends upon SPAD value and upon whether it is estimated from leaf reflectance or leaf transmittance measurements. SPAD is a surrogate for leaf chlorophyll concentration; a value 20 represents a low chlorophyll concentration; 60, high; typical is SPAD=35 to 45.

(SPAD=20 represents a low corn leaf chlorophyll concentration; 60, a high chlorophyll concentration; 35-45 is typical), but also upon whether the *PRI* value is calculated from leaf reflectance or leaf transmittance measurements. The two solid lines, Fig. 3, which represent the results of a moving cosine window smoothing function applied to each data set, show *PRI* values differ substantially for leaf reflectance and leaf transmittance. *PRI* values for SPAD less than approximately 30, which correspond to leaves having relatively low chlorophyll concentrations, are negative for both reflectance and transmittance measurements. In contrast, for SPAD greater than approximately 30, *PRI* is positive when estimated from reflectance measurements but negative when estimated from transmittance measurements. In Fig. 3, the two *PRI* curves (representing smoothed reflectance and transmittance measurements) appear to roughly coincide when offset vertically by approximately *PRI*=0.05.

During observation of a plant canopy, the proportion of leaves reflecting and transmitting direct beam sunlight toward a sensor depends upon sun and view directions. In the hotspot view direction, every visible leaf reflects direct beam sunlight. With increasing angular distance away from the hotspot direction, the proportion of observed reflecting and transmitting leaves may change, depending upon the plant canopy architecture. Particularly for oblique view directions toward the solar azimuth, as Fig. 4 illustrates, both reflecting and *transmitting* leaves may appear in the field of view of a canopy *reflectance* sensor, depending upon the canopy architecture.

Examination of the corn canopy in Fig. 4 suggests that perhaps more leaves in the image are transmitting direct beam sunlight than reflecting it. Potentially, *PRI* will vary with the changing proportion of leaves reflecting and transmitting direct beam sunlight toward the sensor. From the results, Fig. 3, the value of the *PRI* for this corn canopy, Fig. 4, measured in these specific sun and view directions might well be negative rather than positive. Taken together, the results, Figs. 3 and 4, suggest that sun-view directions and canopy architecture potentially just might be overwhelmingly important for explaining bidirectional *PRI* variation for some plant canopies

Based upon our results here and personal observations of many plant canopies, we propose that direct beam sunlight transmitted by leaves toward a canopy reflectance sensor is at times a ubiquitous component part of canopy bidirectional reflectance and, therefore, of canopy bidirectional *PRI.* For certain agricultural crops, corn and wheat for example, the leaf or leaves at the plant top during the last stages of vegetative growth tend to be more vertical so as to better intercept sunlight incident at lower sun elevations. Leaves that appear during earlier development stages of these crops tend to display a more spherical leaf angle probability density function (LAPDF). This means that, depending upon sun-view directions, more leaves should transmit direct beam sunlight toward a sensor during late, as compared to early vegetative development stages; accordingly, bidirectional *PRI* values should vary with the development stage of these crops, independent of the canopy LUE.

Fig. 4. Corn leaves both reflect and transmit direct beam sunlight toward a camera located above the canopy and pointed 60° off nadir toward the solar azimuth. Solar elevation is 47°.

Finally, we note another potential source of variation in canopy bidirectional *PRI* estimates: the wind. Presumably even a gentle wind could alter, momentarily or not, the canopy architecture, thereby changing the proportion of leaves reflecting versus transmitting direct beam sunlight toward an observing sensor even as that sensor is measuring the canopy.

4. CONCLUSIONS

We report that values of leaf *PRI* – calculated from either leaf reflectance or leaf transmittance – differ substantially for our corn data. We anticipate that, depending upon sun-view directions and canopy architecture, direct beam sunlight incident on canopy leaves and *transmitted* through a leaf to a canopy *reflectance* sensor can contribute substantially to canopy bidirectional *PRI* values. We propose that wind-driven leaf movement and weather-vaning is an important source of variation in estimates of canopy bidirectional *PRI*, again depending upon sun-view directions and canopy architecture.

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