*Journal of Photoscience* (2000), Vol. 7(4), pp. 139 – 142

# ESTIMATION OF PHOTOSYNTHETIC LIGHT USE EFFICIENCY IN A SINGLE LEAF BY ANALYZING NARROW-BAND SPECTRAL REFLECTANCE

Kyehong Suh*
Division of Life Science, Taegu University, KyeongSan 712-714, Korea

To examine applicability of some optical indices from reflectance to estimate photosynthetic light use efficiency, photosynthesis, and narrow band spectral reflectance were simultaneously measured at various intensities of light with mongolian oak leaves. Narrow band of the broad-band NDVI was better than photochemical reflectance index and simple ratio to estimate photosynthetic light use efficiency in this study. Changes in spectral reflectance were detected at several wavelengths (540 nm, 690 nm, 740 nm, and 800 nm) associated with physiological status of plant leaves that could be components for new optical indices.

**key words:** narrow band, spectral reflectance, photosynthesis, light use efficiency

## INTRODUCTION

Broad band sensors have been used to derive indices for various characteristics of vegetation cover in the field of remote sensing. Although the broad-band normalized difference vegetation index (NDVI) [1], as the most frequently used index, correlates well with canopy features such as standing crop, leaf area index (LAI), and photosynthetic capacity of canopy [2], it often fails to sense physiological changes. [3]

The recent advances in portable spectrometers with high spectral resolution offers examining dynamic physiological processes occurring on fine temporal and spectral scales. Because of the link between leaf structure, function, and spectral reflectance, a number of important ecophysiological properties can be inferred from these reflectance indices, and some of these applications at a leaf and canopy scales have recently been reviewed [4]. These applications include various expression of chlorophyll [5], xanthophylls cycle pigments and related photosynthetic performance [6] and other measurements of integrated leaf stress [7]. However those optical indicators do work well for a specific leaves of plant species.

In this study I analyzed simultaneously measured data of narrow band spectral reflectances and gross photosynthesis at various intensity of light to examine applicability of some optical indices to estimate photosynthetic light use efficiency of mongolian oak leaf that is one of the dominant species in Korea.

*To whom correspondence should be addressed.
E-mail : khsuh@biho.taegu.ac.kr
Received 15 October 2000; accepted 30 November 2000

## MATERIALS AND METHODS

Leaves of mongolian oak (*Quercus mongolica* Fisch.) were used in all experiments. Plants were grown for 6 years in pots ($\phi$ =30 cm) under natural light and irrigated every day for the growing seasons. Every sample leaf was dark-adapted at least for 30 minutes before measuring of spectral reflectance and photosynthesis.

Photosynthetic rates were measured with a steady state gas exchange system (LCA2, ADC, England) at laboratory. Light intensity incident on 6.25 $cm^2$ in a modified Parkinson leaf chamber (PLC) was controlled at a range of 20 - 1240 (mol $m^{-2}$ $s^{-1}$ with neutral density filters and a halogen lamp. Air supplied at the rate of 250 ml min to the chamber was preconditioned to 40% of relative humidity at 25°C and 350 ppm of $CO_2$ concentration. Leaf temperature was monitored with a T-type thermocouple and maintained at 25°C with a Peltier cooler (Sungjoo Electronics, Korea) attached on the bottom of PLC and a temperature controller (MX7, Hanyong Co. Korea). Gross photosynthesis was regarded as the sum of net photosynthesis and respiration in dark. Photosynthetic light use efficiency was calculated as the gross photosynthesis divided by the photon flux density (PFD) incident on the leaf surface during the measurement.

For the simultaneous measurement of spectral reflectance and photosynthesis, a Parkinson leaf chamber (broad type, ADC, England) was modified. An optic fiber was inserted into the chamber to guide the light diffused from the sample leaf to a spectrometer (MMS, Zeiss, Germany). Spectral reflectance was determined in 256 bands (band width: ca. 3.3 nm) corresponding wavelength range of 350 - 1100 nm by dividing the radiance intensity reflected from sample leaf by that from a barium sulfate standard panel without leaf in the chamber. The barium sulfate panel was used to avoid errors due to drift in lamp or system electronics and to avoid the need for radiometric calibration. For spectral calibration the spectrometer was periodically scanned with a mercury argon line source (Model HG-1, Ocean Optics, Dunedin, FL. USA)

Photochemical reflectance index (PRI), narrow band NDVI ($NDVI_n$), and simple ratio ($SR_n$) were calculated as follows:

$$PRI = (R_{531} - R_{570}) / (R_{531} + R_{570})$$
$$NDVIn = (R_{800} - R_{660}) / (R_{800} + R_{660})$$
$$SRn = R_{660} / R_{800}$$

Where R refers to reflectance, and the subscripts refer to narrow wavebands in nm.

## RESULT AND DISCUSSION

*Photosynthesis.* Gross photosynthesis of leaf increased with increasing of light intensity until light saturation and slightly declined to 96% of its maximum value over 400 μmol $m^{-2}$ $s^{-1}$ (Fig. 1). Saturation light intensity was about 300 μmol $m^{-2}$ $s^{-1}$ and maximum photosynthesis was 5.05 μmol $m^{-2}$ $s^{-1}$. Photosynthesis pattern of the sample leaf showed characteristics of shade leaf. The maximum photosynthesis of this leaf is similar for that of shade treated leaf in Douglas-fir [8] and maple [9]. Photosynthetic light use efficiency which was 5.1% under low light (20 μmol $m^{-2}$ $s^{-1}$) decreased to 0.4% with increasing light intensities up to 1240 μmol $m^{-2}$ $s^{-1}$.

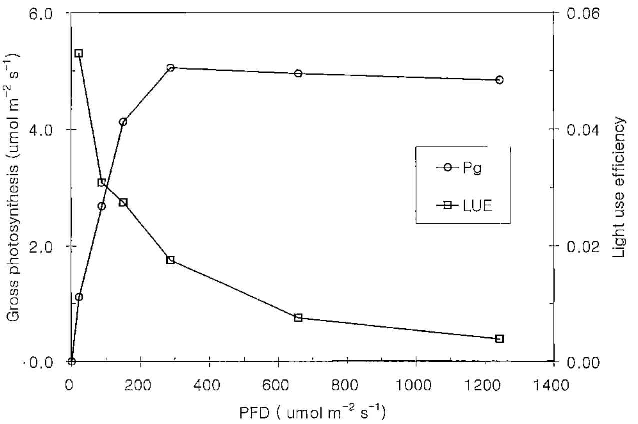


Fig. 1. Gross photosynthesis (Pg) and photosynthetic light use efficiency (LUE) of an intact leaf of a mongolian oak tree determined at steady state of photosynthesis after stepwise increasing of PFD. Gross photosynthesis was regarded as the sum of net photosynthesis and dark respiration of the leaf.

*Spectral reflectance.* Only a pair of spectral reflectances obtained under low (80 μmol $m^{-2}$ $s^{-1}$ of PFD) and saturating light (685 μmol $m^{-2}$ $s^{-1}$) is shown in Fig. 2 to clearly present spectral changes of reflectance between the light conditions. Both of spectral reflectances had a local maximum around 550 nm in the visible range resulted from strong absorption by chlorophylls that have its absorption peaks at the blue and the red region of visible light (Fig. 2). In addition, several shoulders were observed in the spectral range of 580 - 680nm, and red edge at 700 nm. The spectral reflectance under low light is lower than those under saturating light in the visible range, but is slightly higher in the near infrared range. This finding is generally consistent with that in red wood sorrel, wild cucumber, sunflower and holly fern leaves [10].

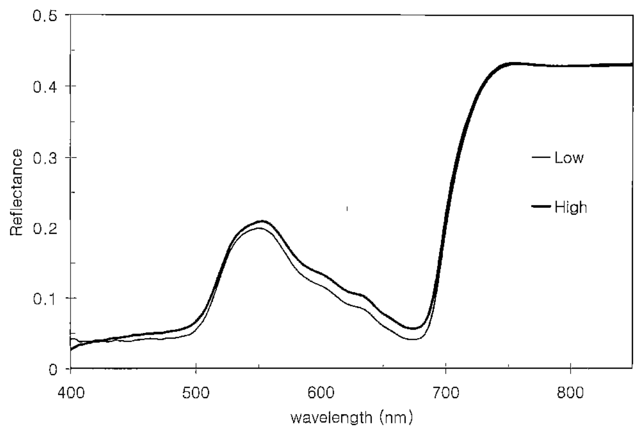


Fig. 2. Spectral reflectances of an intact leaf of a mongolian oak tree determined at steady state of photosynthesis exposed to low (Low) and high (High) light. PFD on a horizontal plane at the leaf surface was approximately 80 and 1240 μmol $m^{-2}$ $s^{-1}$, respectively.

*Difference spectrum.* Changes in spectral reflectance with light intensities were shown more clearly in difference spectra between reflectance under very low (22 μmol $m^{-2}$ $s^{-1}$) light and reflectance under low (87 μmol $m^{-2}$ $s^{-1}$), medium (150 μmol $m^{-2}$ $s^{-1}$) and high (685 μmol $m^{-2}$ $s^{-1}$) light (Fig. 3). The difference spectra plots emphasize changes in absolute reflectance value. Difference spectra under high light conditions were higher in visible range, but lower in near infrared range (>720 nm). This means that chloroplast relocation altered the optical property of the leaf as described by Brugnoli and Bjorkman [10].

Drop in difference spectra of reflectance was apparent around 540 nm, indicating that ΔpH-associated light scattering occurred and that it is possible to detect changes in ΔpH across thylakoid membrane by spectral reflectance if an appropriate reference is chosen. Local maximum of the difference spectra at 690 nm may possibly due to decreased absorptance of the leaf at that wavelength associated with chlorophyll. This result is in close agreement with that previously reported for leaves of *Oxalis oregana* [10]. Slight local minimum or change in slope of spectral reflectance under high light condition was observed around 740 nm. This effect was evident at 730 nm to 750 nm, and was most pronounced at 740 nm, indicating that leaf reflectance is affected by chlorophyll fluorescence as reported with that in single leaves and canopy of maple tree [11,12]. In spite of chloroplast relocation, changes in reflectance were relatively small around 800 nm. Therefore that wavelength could be a good reference to derive some physiological information from narrow band spectral reflectance for correcting chloroplast relocation.

These characteristics of spectral reflectance especially at 540 nm, 690 nm, 740 nm, and 800 nm implicate the possibility of new indices to assess physiological status of plant leaves with one or combination of reflectances at those wavelengths.

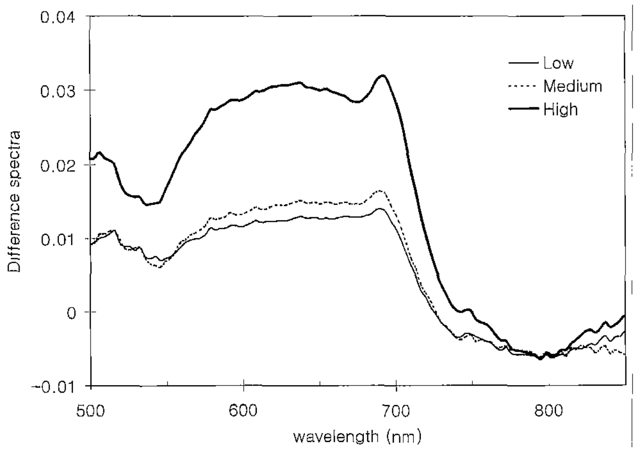


Fig. 3. Difference spectra determined at low, medium, and high light exposure from the spectra at 20 μmol $m^{-2}$ $s^{-1}$ of PFD. PFD on a horizontal plane at the leaf surface was approximately 80, 150, and 1240 μmol $m^{-2}$ $s^{-1}$, respectively.

*Optical indices.* The ranges of measured photochemical reflectance index (PRI), narrow band normalized difference vegetation index ($NDVI_n$), and simple ratio ($SR_n$) were 0.007-0.037, 0.743-0.850, and 6.80-12.90, respectively, under various conditions of light intensity in this study. These measurements are similar to those in *Quercus agrifolia* [13]. To compare all of indices in one plot, each of the optical indices was normalized to the values between 0 and 1 corresponding the minimum and the maximum values. The relationships between photosynthetic light use efficiency (LUE) and those optical indices- PRI, $NDVI_n$, and SRn were shown in Fig. 4. The statistical parameters for the equations of the relationships were determined by regression analysis as follows:

$$PRI = -0.0209 + 22.626 \times LUE$$
$$NDVI_n = -0.0895 + 20.963 \times LUE$$
$$SR_n = -0.1346 + 20.360 \times LUE$$

Correlation coefficients of PRI, $NDVI_n$, and $SR_n$ to photosynthetic light use efficiency were 0.962, 0.993, and 0.975, respectively. In this study $NDVI_n$ was the best index to estimate photosynthetic light use efficiency in a single leaf of mongolian oak.

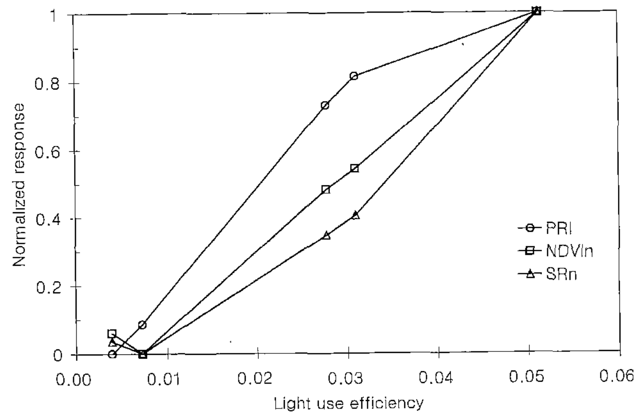


Fig. 4. Relationship between photosynthetic light use efficiency and narrow band optical indices - photochemical reflectance index (PRI), narrow band normalized difference vegetation index ($NDVI_n$), and simple ratio ($SR_n$). Indices were normalized to the values between 0 -1 corresponding the minimum and the maximum values to relatively compare each other.

*Acknowledgement –* This paper was supported by a grant (No. 971-0511-059-2) from the Korea Science and Engineering Foundation.

## REFERENCES

1. Tucker, C. J. (1979) Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sens. Environ.* **8**, 127-150.
2. Sellers, P. J. (1987) Canopy reflectance, photosynthesis, and transpiration. II. The role of biophysics in the linearity of their interdependence. *Remote Sens. Environ.* **21**, 143-183.
3. Running, S. R., and R. R. Nemani (1988) Relating seasonal patterns of the AVHRR vegetation index to simulated photosynthesis and transpiration of forests in different climates. *Remote Sens. Environ.* **24**, 347-367.
4. Gamon, J. A. and H-L Qiu (1999) Ecological application of remote sensing at multiple scales. *In: Handbook of functional plant ecology.* Ed. By Pugnaire, F. I. and F. Valladares, Marcel Dekker, New York pp. 805-846.
5. Gitelson, A and M. N. Merzlyak (1994) Spectral reflectance changes associated with autumn senescence of *Aesculus hippocastanum* L. and *Acer platanoides* L. leaves. Spectral features and relation to chlorophyll estimation. *J. Plant Phyiol.* **143**, 286-292.
6. Gamon, J. A., L. Serrano and J. S. Surfus (1997) The photochemical reflectance index: an optical indicator of photosynthetic radiation use efficiency across species, functional type, and nutrient levels. *Oecologia* **112**, 492-501.
7. Carter, G. A. (1994) Ratios of leaf reflectances in narrow wave

bands as indicators of plant stress. Int. J. Remote Sens. 15, 697-703.

8. Yoder, B. J. and R. H. Waring (1994) The normalized difference vegetation index of small Douglas-fir canopies with varying chlorophyll concentrations. Remote Sens. *Environ.* **49**, 81-91.
9. Weber, J. A., T. W. Jurik, J. D. Tenhunen, and D.M. Gate (1985) Analysis of gas exchange in seedlings of *Acer saccharum*: integration of filed and laboratory studies. *Oecologia* **65**, 338-347.
10. Brugnoli, E. and O. Bjorkman (1992) Chloroplast movement in leaves: Influence on chlorophyll fluorescence and measurements of light-induced absorbance changes related to $\Delta$ pH and zeaxanthin formation. *Photosynthesis Research* **41**, 23-35.
11. Zacro-Tejada, P. J., J. R. Miller, G. H. Mohammed, and T. L. Noland (2000) Chlorophyll fluorescence effects on vegetation apparent reflectance: I. Leaf-level measurements and model simulation. *Remote Sens. Environ.* **74**, 582-595.
12. Zacro-Tejada, P. J., J. R. Miller, G. H. Mohammed, T. L. Noland, and P. H. Sampson (2000) Chlorophyll fluorescence effects on vegetation apparent reflectance: II. Laboratory and airborne canopy level measurements with hyperspectral data. *Remote Sens. Environ.* **74**, 596-608.
13. Gamon, J. A., C. B. Field, D. A. Roberts, S. L. Ustin, and R. Valentini (1993) Functional patterns in an annual grassland during an AVIRIS overflight. *Remote Sens. Environ.* **44**, 239-253.