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Full Length Article

Effect of Canopy Geometry on Estimation of Leaf Area Index in Winter Wheat Using Multi-angle Spectrum

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Abstract

This study presents a method for quantitatively estimating leaf area index (LAI) in winter wheat by exploring bi-directional reflectance distribution function (BRDF) data. In BRDF data, near-infrared reflectance (NIR) which is sensitive to crown component, canopy cover and crown shape, is affected by illuminated crown component, while red reflectance is sensitive to canopy gaps and controlled by illuminated ground component. Considering the effect of NIR/red ratio on the reflection of canopy and ground parameters, two new spectral vegetation indices, normalized difference ratio index (NDRI) and enhanced ratio vegetation index (ERVI), have been improved from normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI). The efficacy of two new indices in estimation of LAI has been validated using the data sets from multi-angular observations. The results showed that: (a) the LAI estimation models by NDVI or EVI should be established separately for winter wheat with different canopy geometric structures; (b) the NDRI and ERVI at view zenith angle (VZA) of 40° had the highest accuracy for estimating LAI in winter wheat with different crop geometric characteristics, comparison with other commonly used spectral vegetation indices (e.g. NDVI) or the values from other view angles; (c) the NIR/red ratio at VZA of 40°can represent canopy cover and crown shape in the canopy geometry. This study provides a novel method to estimate LAI for a variety of crops with different canopy geometric features using BRDF data in large scale, which can provide reference for developing multi-angle airborne or space-borne sensors in the future.

Keywords: Winter wheat; Bi-directional reflectance difference function (BRDF) data; Normalized difference ratio index (NDRI); Enhanced ratio vegetation index (ERVI); Leaf area index (LAI); NIR/red ratio

Introduction

Leaf area index (LAI), defined as one half of the total foliage area per unit ground area, is a key biophysical variable influencing a variety of ecosystem processes, such as net photosynthesis, the interception of light and water, and carbon cycle is extensively used to drive ecosystem productivity models (Chen and Black, 1992; Fang and Liang, 2005; Maire *et al.*, 2010; Gu *et al.*, 2011). It provides information on crop yield and growth status (Baze-Gonzalez *et al.*, 2005; Sridhar *et al.*, 2008). Accurate and timely estimation of LAI at a large scale are essential for crop diagnosis and yield prediction.

Nevertheless, inversion of LAI in plants by traditional methods is laborious and difficult to execute, especially on a regional scale (Gower *et al.*, 1999). Conversely, remote sensing technology applications for assessing LAI at the regional scale have been explored extensively in recent decades. Currently, the methods for estimating LAI using remotely sensed data can be categorized in two types: (1) physically-based model inversion (Knyazikhin *et al.*, 1998a; Fang *et al.*, 2003; Houborg *et al.*, 2009) and (2) statistical methods based on the relationship between LAI and vegetation indices (Chen and Cihlar, 1996; Turner *et al.*, 1999; Wang *et al.*, 2007). Empirical models based on regression analysis can be conveniently established and are effective in estimation of LAI; therefore, statistical methods are more common. However, at-nadir, some problems also exist in this method, such as the relationship between LAI and spectral indices usually saturates as LAI exceeds 2.0, and the inversion accuracy of LAI is affected by the diversity of canopy structure (Pocewicz *et al.*, 2007). In comparison with single view from vertical canopy, multi-angular observations can acquire more rich plant information by considering more canopy parameter. Consequently, this study attempts to invert LAI in winter wheat using BRDF data.

Previous studies have shown the potential advantages

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to detect forest canopy structural features and estimate LAI using BRDF data (Sandmeier *et al.*, 1999; Gascon *et al.*, 2007). Knyazikhin *et al.* (1998a) developed an algorithm, based on a three-dimensional formulation of the radiative transfer process in vegetation canopies, to measure LAI from MODIS and MISR data. Durbha *et al.* (2007) proposed a methodology for LAI estimation by inverting PROSAIL model using support vector machines over multiangle imaging spectroradiometer (MISR) data. However, selection of the model parameters is not simple (Gu *et al.*, 2011). After the introduction of the Hotspot-Dark-spot index (HDS) and the discovery of the normalized difference between hotspot and dark spot (NDHD), calculating from multi-angle data, many studies have shown that there are strong correlation between foliage clumping index and both HDS and NDHD (Chen *et al.*, 2005; Hasegawa *et al.*, 2010; Pisek *et al.*, 2011). Hasegawa *et al.* (2010) proposed that the normalized difference vegetation index (NDVI), when incorporating HDS, can provide better quantitative estimation of LAI than NDVI alone by accounting for foliage clumping. Hot spot is the peak in reflectance when the view zenith angle and the solar zenith angle coincide in the back-scattering region. In general, the observation geometry of these sensor, the difference of solar zenith angles at the time of the BRDF observations and canopy geometric structure of plant cause the BRDF data to capture incomplete data on the hotspot, where the apparent roughness is the largest (Maignan *et al.*, 2004; Comar *et al.*, 2012). Therefore, many models were used to simulate or reproduce the directional signatures in order to obtain hot spot signature (Maignan *et al.*, 2004; Yan *et al.*, 2008). However, the physical BRDF model is complex, nonlinearity and therefore is still an under-determined problem (Yan *et al.*, 2008; He *et al.*, 2012). Consequently, it is necessary to develop a simple statistical method for measuring LAI from BRDF data.

The goal of this study is to develop a simple but effective statistical method for assessment of LAI of winter wheat with contrasting canopy architectures using multi-angle spectral measurements. To achieve such a goal, we took into account the changes in canopy geometry and biochemistry as time goes by incorporating vegetation indices at multiple view angles.

Materials and Methods

Study Area

Our experiment was designed and conducted at Beijing Xiaotangshan Precision Agriculture Experimental Base from September 2006 to June 2007. The experimental site is located in Changping district, Beijing (40°11′ N, 116°27′ E) with a mean annual precipitation of 507.7 mm and a mean annual temperature of 13°C. The soil at the field site was classified as the silty clay loam with the nutrient content as follows: organic matter 14.2-14.8 g/kg, available potassium 117.6-129.1 mg/kg, and available phosphorus 20.1-55.4 mg/kg.

In our experiment, a total of eight winter wheat varieties were investigated: three-erectophile varieties (Jing 411, Laizhou 3279 and I-93); two-planophile varieties (Chaoyou 66 and Jingdong 8); and three-horizontal varieties (Linkang 2, 9428 and Zhouyou 9507). The effect of canopy architecture and LAI on canopy reflectance (%) was investigated in winter wheat with contrasting canopy architectures. Each variety was planted in a field size of 45×10.8 m^2 under the same treatments of sowing, fertilization and irrigation. A plot with an area of 1×1 m^2, which could represent the average growth status for each wheat variety, was randomly selected and investigated.

Field Measurement

***In situ* canopy reflectance spectrum:** An ASD FieldSpec Pro spectrometer (Analytical Spectral Devices, Boulder, CO, USA), fitted with a 25°-field-of-view fiber optic adaptor and operated in the 350-2500 nm spectral range, was used to measure canopy reflectance under clear sky conditions between 10:00 a.m. and 14:00 p.m. (Beijing local time). All canopy reflectance was collected at a height of 1.3 m above ground, and a 40×40 cm^2 $BaSO_4$ calibration panel was used to calibrate the reflectance. For each sample plot, twenty scans were performed within the same 1×1 m^2 plot to record the irradiance measurements and the average was calculated as the final value.

Canopy BRDF reflectance spectrum: To obtain the information of plants from various angles, the same spectrum instrument was employed just as was used in situ canopy spectral measurements to obtain canopy bi-directional reflectance (BRDF) at the principle plane and the cross-principle solar plane. In our study, in accordance with the measuring method introduced by Huang *et al.* (2006), a rotating bracket was used to fix the spectrum instrument to collect multi-angular spectral data. The view zenith angle was arranged from -60° to 60° with an interval of 10°, where positive angle corresponds to back-to-the-sun, and negative angle corresponds to facing-the-sun.

LAI Measurements: After the spectral measurements were finished, the wheat plants in the plot (0.3 m^2) were collected, and placed in cooled black plastic bags and transported to the laboratory. In the laboratory, the Li-Cor 3100 Area Meter was used to measure the leaf area of a subsample (LA_{sub}) of plant leaves and the weight of leaves was then obtained when the leaves were dried at 105° for 10 min and then at 65° for 5 h. Afterwards, the LAI of 0.3 m^2 sample area could be calculated as follows:

$$LAI = \left[LA_{sub} \times \frac{\text{total leaves weight}}{\text{subsample leaves weight}} \right] \div \left[\text{sample area} \right] \quad (1)$$

Methods

Many studies have focused on the relationship between LAI and vegetation indices such as NDVI and enhanced vegetation index (EVI) (Curran, 1992; Gutiérren-Rodríguen *et al.*, 2006; Fan *et al.*, 2009). However, Malet (1996) reported that vegetation indices derived from remote sensing or ground data (at nadir) are usually insufficient to estimate LAI unless canopy architecture is known. Increase in gap size results in a higher red reflectance, but near-infrared reflectance (NIR) shows the increasing trend with decreasing gap size, which is opposite to crown cover (Gerard *et al.*, 1997). Therefore, some other ancillary parameters could be considered and we attempted to use the NIR/red ratio at each view angle to represent the canopy cover and canopy gap. Sellers *et al.* (1992) also confirmed a strong mechanistic basis for the correlation relationship between simple infrared/red ratio and Fraction of absorbed Photosynthetically Active Radiation (FPAR), which portrayed vegetation canopy function and absorption capacity (Sellers *et al.*, 1992; Peng *et al.*, 2012). Huang *et al.* (2006) also used the canopy reflectance of 800 nm at the erecting and elongation stage to distinguish the canopy geometric structure, which allowed the near-infrared reflectance to be represented by the reflectance of 800 nm (Huang *et al.*, 2006). At the same time, the chlorophyll absorption feature near 680 nm was used to discriminate the green vegetation and non-green vegetation (Datt, 2000), so the reflectance of 680 nm was used to represent the red reflectance. Therefore, R_{800}/R_{680} at each view angle was used to represent the canopy cover and canopy gap.

Based on the above theoretical considerations, two new spectral vegetation indices, normalized difference ratio index (NDRI) and enhanced ratio vegetation index ratio index (ERVI), are further improved from regular NDVI and EVI by incorporating the effect of NIR/red ratio on the reflection of canopy and ground parameters. The vegetation indices (NDVI, EVI, NDRI and ERVI) were calculated as follow (Huete *et al.*, 1997; Goward *et al.*, 1985):

$$\text{NDVI}=(R_{nir}-R_{red})/(R_{nir}+R_{red}) \quad (2)$$

$$\text{EVI}=2.5\times(R_{nir}-R_{red})/(R_{nir}+6\times R_{red}-7.5\times R_{blue}+1) \quad (3)$$

$$NDRI(i)=NDVI\times(R_{800}/R_{680})(i) \quad (4)$$

$$ERVI(i)=EVI\times(R_{800}/R_{680})(i) \quad (5)$$

Where, R_{nir}, R_{red} and R_{blue} are the spectral reflectance in the near-infrared (800 nm), red (680 nm), and blue (443 nm) bands, respectively. And *i* is the view angle. NDVI and EVI are derived from nadir-viewing canopy reflectance.

Results

Relationship between LAI and Vegetation Indices (NDVI and EVI)

As shown in Table 1, under the different approximate LAI values, the average canopy reflectance in the near-infrared band (800 nm and 1100 nm) and EVI value of horizontal varieties are significantly ($P\leqslant 0.05$) greater than that of erectophile varieties. This confirms that the canopy reflectance is influenced by both LAI and canopy architecture. Using the same regression equation (LAI-EVI), the LAI values of the erectophile varieties were underestimated and overestimated for horizontal varieties as LAI greater than intermediate value, which is opposite when LAI lower than intermediate value (Fig. 1b). By contrast, it can be seen that the relationship between LAI and NDVI usually saturates when LAI exceeds 2.0 and the trend lines (LAI-NDVI) of the two kinds of canopy structures were different (Fig. 1a). Therefore, Fig. 1 illustrates that the different relationships (at nadir) between LAI and both NDVI and EVI in winter wheat can be attributed to the differences between erectophile and horizontal varieties. It can also be concluded that it is difficult to measure LAI using the relationship between LAI and NDVI when LAI exceeds 2.0.

Relationship between LAI, NDRI and ERVI

Considering different geometric structures of the wheat canopy, the relationship between LAI and NDRI and ERVI at each view angle can be seen in Fig. 2. Each of these figures includes three trend lines between LAI and NDRI or ERVI for winter wheat of different canopy structures at the corresponding angle. To accurately invert LAI of winter wheat, it is required to find a solution for allowing the trend lines between LAI and both NDRI and ERVI to as close to

Table 1: The average spectral reflectance and EVI value for different canopy structures under different LAI. (LSD: least significant differences ($P\leqslant 0.05$) for the erectophile varieties vs. horizontal varieties)

Mean LAI	Crop geometry	LAI	443 nm	560 nm	680 nm	800 nm	1100 nm	EVI
LAI≈1.60	Erectophile	1.54	1.94	4.74	3.25	33.46	36.46	0.55
	Horizontal	1.68	2.12	5.20	2.77	37.89	40.51	0.63
	LSD	0.39	0.54	0.89	1.08	1.91	3.26	0.04
LAI≈3.45	Erectophile	3.47	1.90	4.35	1.96	44.57	44.45	0.75
	Horizontal	3.44	1.77	4.43	1.76	48.83	47.56	0.80
	LSD	0.44	0.97	1.66	0.91	1.18	1.68	0.01
LAI≈4.85	Erectophile	5.00	1.60	3.74	1.47	47.60	45.44	0.8
	Horizontal	4.68	2.41	5.93	2.25	58.61	56.04	0.92
	LSD	0.96	0.25	0.59	0.43	5.01	5.82	0.06

be 1:1 as possible for different canopy structures. As can be seen, it can be concluded that 40° was the optimal angle (Fig. 2). At such an angle, trend lines (LAI-NDRI and LAI-ERVI) of the three kinds of canopy structures were

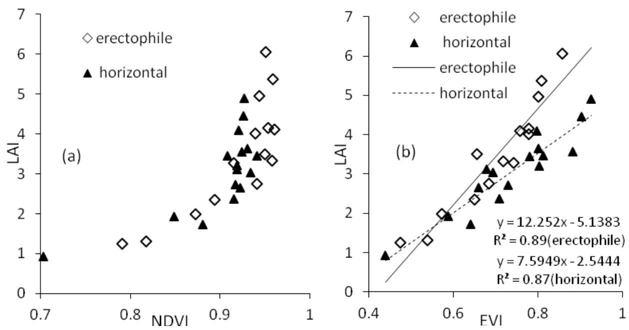

Fig. 1: Relationship between LAI and NDVI (a), EVI (b) of winter wheat considering different canopy geometric structures

the closest, as compared to other view angles. The coefficients of determination (R^2) were 0.76, 0.95 and 0.83 for LAI-NDRI and 0.86, 0.86, and 0.86 for LAI-ERVI, respectively, which showed a significant correlation. It can be concluded that the NIR/red ratio at VZA of 40°can better represent canopy cover and crown shape in the canopy geometry.

Comparison between NDVI/NDRI(40)/EVI/ERVI(40) and LAI

The relationship between NDVI and LAI shows the approximation of the exponential function and NDVI cannot effectively distinguish LAI (>2.0) (Fig. 3a). By contrast, it was revealed that NDRI (40) and LAI are linearly related, with an R^2 of 0.82 and a root mean square error (RMSE) of 0.51, which clear indicates that NDRI (40) greatly reduces the saturation problem (Fig. 3b). In comparison with EVI, ERVI (40) not only has the stronger correlation with LAI (R^2 = 0.86) but also has the smaller RMSE of 0.45 (Fig. 4).

Discussion

Multi-angle spectral data is capable of providing rich spectral and angular information for extracting the structure parameters and inverting LAI (Knyazikhin *et al.*, 1998b; Kimes *et al.*, 2006; Hasegawa *et al.*, 2010). This study indicated that estimation of LAI could be accurately performed when considering the effect of canopy geometry characteristics from measured BRDF data. The vegetation indices NDRI (40) and ERVI (40) calculated from BRDF data were more effective to estimate LAI compared with commonly used spectral vegetation indices (e.g., NDVI), which was extremely significant for crop diagnosis and yield prediction. But the result could

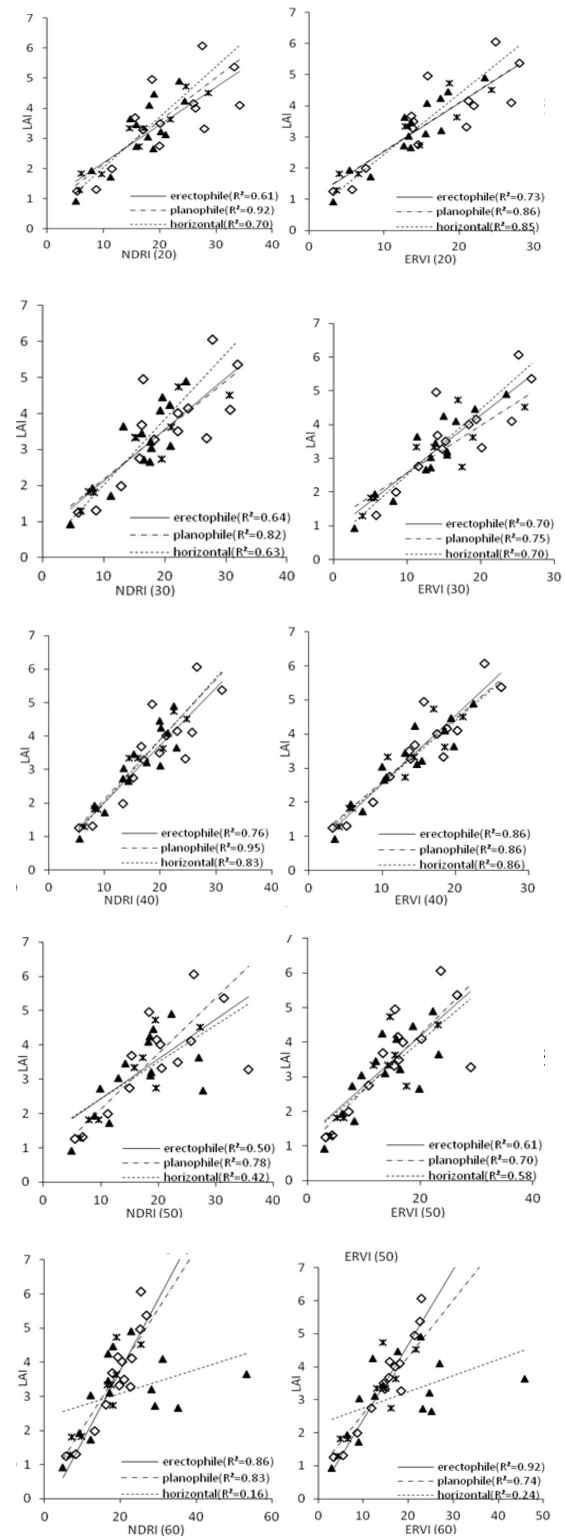

Fig. 2: Relationship between LAI and NRVI and ERVI at each view angle in winter wheat for different canopy structures. Where, ◇, * and △ represent the data points of erectophile, planophile and horizontal varieties, respectively

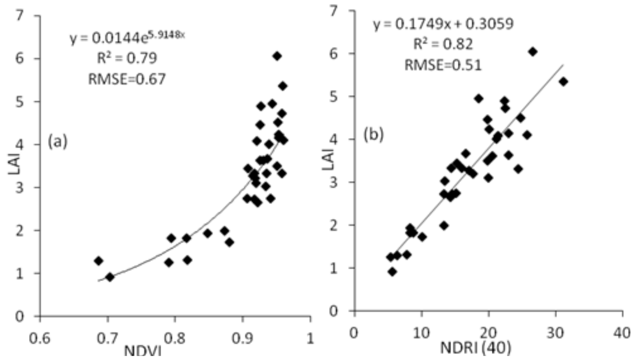

Fig. 3: Relationship between LAI and NDVI (a) and NDRI (40) (b)

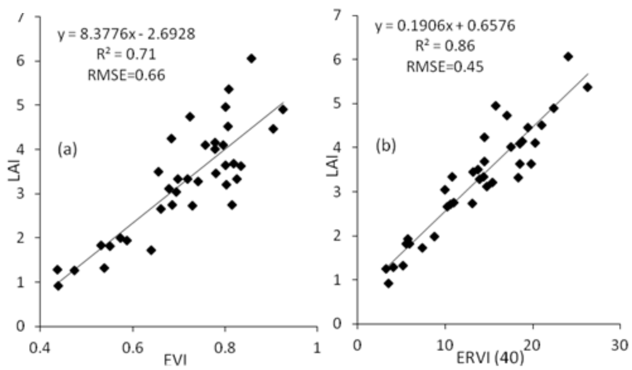

Fig. 4: Relationship between LAI and EVI (a) and ERVI (40) (b)

not be directly used for other plants. Specifically, the influence of the solar zenith angle (SZA) was not studied in our study, so it was difficult to judge whether the optimal angle was affected by SZA. In following studies, more experiments and analysis will be required to validate the results and evaluate how this method can be used for multi-angle satellite sensors (e.g., CHRIS) at regional scales (Vuolo *et al.*, 2008).

In comparison with single view from vertical canopy, multi-angular observations acquired more plant information by considering more canopy parameters. In general, an optimal view angle or combination of different angles exited in retrieving various plant parameters. However, for most of current optical sensors, the spectral or image information is always acquired in vertical canopy direction. It can be predicted that more multi-angular satellite sensors will be launched to satisfy the needs for plant parameters in the near future. This study provide a case study to find out the best angle to estimate LAI in winter wheat, which can lay a foundation for designing satellite with multi-angle sensors for quantitative crop monitoring.

In conclusion, this study initially confirmed that the relationship between LAI and NDVI or EVI should be established separately for winter wheat cultivars with different canopy geometric structures. The NIR/red ratio at each view angle was then introduced to represent the canopy cover and canopy gap. Based on this theoretical consideration, two new spectral vegetation indices, normalized difference ratio index (NDRI) and enhanced ratio vegetation index (ERVI), are further improved from commonly used NDVI and EVI by incorporating the effect of NIR/red ratio on the reflection of canopy and ground parameters. The results showed that 40° is the perfect angle and both NDRI (40) and ERVI (40) are linearly related to LAI, which seems to greatly reduce the saturation problem. The acquired multi-angular spectral and LAI data sets derived from Beijing Xiaotangshan Precision Agriculture Experimental Base have confirmed the efficacy of two new indices. Moreover, NDRI (40) and ERVI (40) calculated from BRDF data are superior to NDVI and EVI for estimation of LAI in winter wheat. We conclude that it will be more accurate to estimate LAI by BRDF data than vertical canopy observations, when considering the canopy geometry effect.

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