Communications in Soil Science and Plant Analysis, 40: 1240–1253, 2009

ISSN 0010-3624 print/1532-2416 online
DOI: 10.1080/00103620902754598

Canopy Spatial Distribution and Identification Using Hyperspectal Data in Winter Wheat

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Abstract: Winter wheat varieties (*Triticum aestivum* L.) with different leaf angle distributions (LADs) were used in this experiment. Results showed that varieties with planophile LADs had leaf orientation values (LOVs) ranging from 25.12 to 40.33, whereas varieties with erectophile LADs had LOVs ranging from 67.5 to 73.25. Canopy spectral reflectance was measured using a ground-based spectroradiometer. Correlation analysis indicated that LOV affected canopy spectra more than leaf area index (LAI) before the jointing stage. The LAI had the greatest effect after the ground was nearly completely covered. Discriminant analysis showed that simultaneous measurements of normalized difference vegetation index (NDVI) and cover can differentiate LADs in those wheat varieties with similar population magnitude at the jointing stage. In addition, by using increments of the canopy spectral reflectance at different growth stages, the planophile varieties with low LAIs can be differentiated from the erectophile varieties with high LAIs, which cannot be achieved using NDVI and cover. Using ΔR890 as the reflectance

Received 5 June 2007, Accepted 27 February 2008

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increment of booting stage and jointing stage and R890 as the reflectance of 890-nm energy at the jointing stage, different varieties presented distinctly different scatter plot representations (X = ΔR890, Y = R890). This analysis also indicted that varieties with different LADs can be clustered and identified qualitatively in the plot despite their population magnitude, also validated by discriminant analysis.

Keywords: Canopy reflectance, erectophile, leaf orientation value, NDVI, planophile

INTRODUCTION

Research shows that remote sensing technology offers a practical alternative to complicated, slow, and expensive chemical methods for estimating foliar chemical concentrations (Blackmer, Schepers, and Varvel 1994; Curran 1989; Walburg et al. 1982). Studies on estimating biochemical concentration by remote sensing have been extended from those on dried, ground leaves (Card et al. 1988; McLellan et al. 1991; Peterson et al. 1988) to fresh leaves (Curran et al. 1992; Dury and Turner 2001; Johnson and Billow 1996) and entire canopies (Johnson, Hlavka, and Peterson 1994; LaCapra et al. 1996). Many studies showed that spectral reflectance of vegetation in the visible band is primarily governed by the abundance of chlorophyll and other pigments absorbing most of the incident radiation (Thomas and Gausman 1977; Datt 1998). Tomas and Caula (2005) reported that macronutrient deficiencies in wheat reduced chlorophyll concentration, increased reflectance in the visible range, and caused a shift in the position of the red edge toward shorter or longer wavelengths. Broge and Mortensen (2002) showed that vegetation indexes (VIs) based on waveform analysis using narrow bands across the red edge may improve the prediction of canopy chlorophyll density (CCD) of wheat.

Several studies have estimated water content, nitrogen, and grain protein content using spectral data (Daniel and John 2003; Filella et al. 1995; Wang et al. 2004). However, there are many complex factors to be considered when using reflectance measurements of a canopy to determine these chemical parameters. These include the complexity of canopy characteristics, variation in leaf internal structure, and soil background effects (Asner 1998; Matson et al. 1994). Among the factors, canopy structure plays an important role in the interception, absorption, and scattering of solar radiation (Welles 1990; Chen et al. 1994). It also plays a critical role in the interpretation of remote sensing observations to estimate foliar chemical concentrations (Pu and Gong 2000). Stewart et al. (2003) showed that canopy structure mainly depends on leaf distribution and area. Leaf angle distribution (LAD) is one of the key parameters used to simulate radiative transfer and energy and mass balance of vegetative canopies (Mauro et al. 2001; Wang, Li, and Su 2007). Wheat varieties with different LADs had different influences on canopy spectral reflectance. Previous work has suggested that leaf orientation value (LOV) and LAD can be measured to check effectiveness of visual ratings of leaf orientation (Pepper, Pearce, and Mock 1977). However, the traditional method for determining LOV is laborious and time-consuming.

The development of sensor techniques has made it convenient to measure canopy spectrum and canopy cover. Detection of canopy leaf distribution using ground-based spectrometers may improve our understanding of radiative transfer in vegetation and enhance the interpretation of satellite data. It may also improve the precision of estimation of plant chemical parameters based on differentiating leaf orientation types. Few studies have identified different LADs in wheat using hyperspectral data. The objective of this research was to establish a method for differentiating LADs of wheat canopy based on LOV (Pepper, Pearce, and Mock 1977) and spectral sensing.

MATERIALS AND METHODS

Experimental Design

The experiments were conducted at the Experimental Station of the Institute of Crop Science, Chinese Academy of Agricultural Sciences (39° 57′ 55″ N, 116° 19′ 46″ E) in 2003–2006. Test plots were divided into two groups. One group was used to establish correlations between canopy structural characteristics and hyperspectral data (training plots), and the second group (validation plots) was used to validate the correlations determined from the first group. The training plots were established on a silty clay loam soil containing 1.4% organic matter, $67.9\,\mathrm{mg\,kg^{-1}}$ alkali hydrolysis nitrogen (N), $43.6\,\mathrm{mg\,kg^{-1}}$ available phosphorus (P), and $137.5\,\mathrm{mg\,kg^{-1}}$ available potassium (K). Ten winter wheat varieties (Table 1) were sown at a density of 300,000 $\mathrm{seeds\cdot ha^{-1}}$, which was normal density in field, and the same varieties were sown at a decreased density of 200,000 $\mathrm{seeds\cdot ha^{-1}}$. This provided different groups characterized by different densities and leaf orientations. All groups were fertilized with $150\,\mathrm{kg\,N\,ha^{-1}}$ at the jointing stage. The validation plots had the same treatment and soil nutrient information but consisted of different varieties.

Data Collection

Each plot was sensed at each development stage from jointing through grain filling. Leaf orientation values were used to confirm that the

Table 1. Leaf orientation values of wheat varieties used in test plots

Variety	LOV (°)
Planophile varieties	
J9428	25.12
JD8	30.95
ZY9507	38.02
CA9554	30.31
DF9817	40.33
$\bar{X} \pm SD$	32.95 ± 5.52
Erectophile varieties	
CA9901	70.33
P29	67.5
P0185	73.25
CY66	69.21
J411	73.17
$\bar{X} \pm SD$	70.69 ± 2.24

varieties were classified correctly according to leaf structure. Spectral reflectance data were used to calculate the normalized difference vegetation index (NDVI) and compare reflectance at different wavelengths. Digital images provided data to calculate the percentage of vegetative coverage of the plots.

Leaf Orientation Value

Leaf orientation value was measured in the field using a ruler and protractor and calculated according to Pepper, Pearce, and Mock (1977) as follows:

$$LOV = \sum_{i=1}^{n} \left[\theta(l_f/l)\right]_i \Big/ n \tag{1}$$

where θ is the leaf angle from horizontal at stalk, l_f is the length from the leaf collar to "flagging point" (cm), l is the total leaf blade length (cm), and n is the measured leaf number (n = 30).

Measurement of Spectral Reflectance of Canopy

Canopy spectral reflectance was determined under clear sky conditions between 10:00 and 14:00 (Beijing local time), from a height of 0.5 m above the canopy, using an ASD FieldSpec Pro spectrometer (Analytical Spectral Devices, Boulder, Col., USA). The spectrometer was fitted with 25°-field-of-view fiber optics, operating in the 350- to

2500-nm spectral region. The sampling interval was 1.4 nm between 350 and 1050 nm and 2 nm between 1050 and 2500 nm. The spectral resolution at 700 nm was 3 nm, and that at 1400 nm was 10 nm. A 40 cm × 40 cm barium sulfate ($BaSO_4$) calibration panel was used to calculate reflectance. Panel radiance measurements were taken before and after vegetation measurements, with two scans each time. Vegetation radiance measurements were done by averaging 20 scans at an optimized integration time, with a dark current correction at every spectral measurement. Calibration panel data were used for calculating the reflectance of the vegetation:

$$R_T^n = \frac{DN_T^n}{DN_R^n} \times R_R^n \tag{2}$$

where R_T^n and R_R^n are the canopy and panel spectral reflectance and DN_T^n and DN_R^n are their radiances.

Measurement of Canopy Cover

Canopy cover was extracted from digital images taken vertically at 0.5 m above the canopy with Matlab 6.0 (Math Works, Inc., Natick, Mass.). The process is based on the method of automatic classification. First, all digital images were saved in JPEG format. Second, images were read and converted from RGB to HLS. Third, features of wheat and background in RGB, hue (H), and lightness (L) were analyzed. Last, images were classified based on differences in RGB, H, and L values between wheat and soil background, then binarized (with soil denoted as 0 and wheat denoted as 1). As a result, the vegetation could be separated from the background. This method provided the percentage of vegetation coverage (Li et al. 2004).

Normalized Difference Vegetation Index (NDVI)

The NDVI, proposed by Rouse et al. (1974), is the difference between the NIR band and the red band divided by the sum of the NIR band and the red band. It ranges between −1.0 and +1.0, with vegetation having positive values. It is calculated using the following equation:

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{R})}{(\mathrm{NIR} + \mathrm{R})} \tag{3}$$

where R and NIR are the spectral reflectance in the red (R) and near-infrared (NIR) regions, respectively. Reflectance in the 670 ± 10 nm and the 890 ± 10 nm wave bands, as calculated from the spectrometer results, were used to calculate NDVI.

Leaf Area Index (LAI)

Specific leaf area (SLA), the ratio of leaf area to leaf mass, was measured by the dry-weight method. The leaf area (*a*) of 20 representative leaves and their dry weight (*w*) were measured and recorded. Leaf area index (LAI) was calculated as follows:

$$LAI = W \times SLA = W \times \frac{a}{w} \tag{4}$$

A and *W* are the total area and dry weight of all the leaves in a unit area. Leaf area was measured using a CI-203 Portable Laser Area Meter (CID, Inc., Wash., USA).

RESULTS AND DISCUSSION

Leaf Orientation Values (LOV) of Wheat Varieties

The results of leaf orientation tests indicated that the varieties were classified correctly according to leaf orientation. Based on the visual classification, the 10 wheat cultivars were grouped into planophile and erectophile varieties. The LOVs of planophile varieties ranged from 25.12 to 40.33°, whereas those of the erectophile varieties ranged from 67.5 to 73.25° (Table 1).

Canopy Spectral Reflectance at Different Growth Stages

Plants with different LOVs reflected light differently in several wave bands. However, differences between the two varietal groups varied according to stage of development (Table 2). In the visible region, bands including 470, 570, 610, and 670 nm were selected. In the NIR region, 710, 800, 890, 1090, 1220, 1640, and 2200 nm were selected in this study. The canopy spectral reflectance of the erectophile varieties was higher than that of the planophile varieties in the visible bands, but the opposite was the case in the NIR bands prior to the booting stage. The spectral reflectance of canopy in the NIR bands increased at the booting stage for both groups, but the difference between groups was less than that at the jointing stage. At the jointing stage, soil spectral reflectance had greater influence on canopy reflectance than at subsequent stages, and the level of influence in the two varietal groups was mainly determined by leaf distribution status. The coefficient of variation (CV) was also highest across bands at the jointing stage. Furthermore, canopy spectral reflectance at the jointing stage differed significantly ($P < 0.01$) between the planophile and erectophile varieties across bands, especially in the 470, 570, 610, 670, 710, and 2200 nm wave bands ($CV > 30\%$). Canopy cover in both groups of varieties

Table 2. Average canopy spectral reflectance (%) and coefficient of variation (CV) of planophile and erectophile wheat varieties

Stage	Variety	Wavebands (nm)											
		470	570	610	670	710	800	890	970	1090	1220	1640	2200
Jointing	Planophile	1.13	2.55	1.66	0.97	9.71	45.84	44.52	39.05	43.08	31.87	16.17	7.31
	Erectophile	1.99	4.39	2.97	1.82	6.15	39.88	38.85	32.64	37.18	24.85	10.51	4.10
	CV	0.39	0.38	0.40	0.43	0.32	0.10	0.10	0.13	0.10	0.18	0.30	0.40
Booting	Planophile	1.60	3.30	2.15	1.34	10.02	55.30	55.69	47.33	53.43	37.78	18.42	7.89
	Erectophile	2.13	4.56	3.01	1.89	7.48	50.66	51.05	41.40	48.14	31.53	13.63	5.26
	CV	0.20	0.23	0.23	0.24	0.21	0.06	0.06	0.09	0.07	0.13	0.21	0.28
Initial spiking	Planophile	1.99	3.76	2.68	1.83	7.71	45.45	45.22	36.28	42.46	27.80	13.71	6.04
	Erectophile	1.51	2.89	2.03	1.37	6.15	42.81	42.65	33.03	39.51	24.14	10.77	4.33
	CV	0.19	0.19	0.19	0.20	0.16	0.04	0.04	0.07	0.05	0.10	0.17	0.23
Anthesis	Planophile	2.02	3.88	2.83	1.94	7.69	41.08	41.83	34.65	40.12	26.73	12.26	5.12
	Erectophile	1.97	3.65	2.65	1.81	7.27	43.56	44.12	35.41	41.67	26.30	11.14	4.32
	CV	0.02	0.04	0.05	0.05	0.04	0.04	0.04	0.02	0.03	0.01	0.07	0.12

increased, and the canopy spectral reflectance differences became less pronounced with growth of the wheat. This result implies that the optimum stage to identify canopy structural types was from the jointing to booting stages, with the most profound results at the jointing stage.

Correlation Analysis between Spectral Parameters and LOV and LAI in Different Stages

The correlation coefficients between spectral parameters and LOV and LAI are listed in Table 3. The correlation between spectral parameters and LOV were weaker, whereas correlation between spectral parameters and LAI were stronger, as plant development progressed. Leaf orientation value had a more marked effect on canopy spectrum before the jointing stage, but LAI had better correlation with canopy spectral parameters after booting stage when the field approached full canopy coverage. This result indicated that LAI and LOV made different contributions to canopy spectrum at different growth stages. The main reason was that the field vegetation coverage was low and obviously different in the two profile types, but the difference affected by LOV nearly disappeared with the population development. At full canopy coverage, LAI became the main contributor to canopy spectrum.

Correlation between NDVI and Canopy Cover in Wheat Varieties with Different LADs

In this experiment, we further analyzed relationships between NDVI and canopy cover in wheat varieties with different LADs but the same density.

Table 3. Correlative coefficient between LOV and LAI and spectral characteristic parameters at different stages in wheat

Growth stages	Index	R550	R680	NDVI [670,890]	NDVI [890,980]	NDVI [920,980]
Erecting stage	LOV	-0.5516^{*}	0.5999^{**}	-0.5816^{**}	0.5396^{*}	0.5262^{*}
	LAI	0.483^{*}	-0.5544^{*}	0.382	−0.3616	−0.3423
Jointing stage	LOV	-0.6619^{**}	0.7199^{**}	-0.6979^{**}	0.6475^{**}	0.6314^{**}
	LAI	0.5796^{**}	-0.6653^{**}	0.4584^{*}	−0.4339	−0.4108
Booting stage	LOV	−0.2114	−0.0803	0.239	−0.021	0.0827
	LAI	−0.4406	-0.4506^{*}	0.4117	0.394	0.4139
Heading stage	LOV	0.2022	0.1704	0.0746	0.2158	0.1502
	LAI	-0.6839^{**}	-0.7273^{**}	0.6418^{**}	0.6070^{**}	0.6269^{**}
Flowering stage	LOV	0.1974	0.1494	0.0729	0.2107	0.1317
	LAI	-0.6678^{**}	-0.6375^{**}	0.6267^{**}	0.5927^{**}	0.5495^{*}

*, ** Significant 0.05 and 0.01 levels, respectively.

NDVI and canopy cover were positively correlated (Figure 1). Two important trends were observed as follows: 1) with increasing canopy cover, the NDVI increased but the difference between the two leaf types decreased, and 2) the NDVI of the erectophile varieties was higher than that of the planophile varieties with the same canopy cover. In addition, there were significant differences ($P = 0.00002$) in NDVIs between the erectophile and the planophile varieties before the jointing stage. Therefore, by combining the correlation between NDVI and canopy cover with growth stage data, the NDVI and canopy cover can be used to differentiate wheat varieties with different LADs, and the jointing stage is the best stage to do so.

Identifying Population Canopy Structure in Wheat Varieties with Different LADs and Densities

In practice, conditions often occur where wheat population has not only different LADs but different population sizes and different LAIs especially. Plants were analyzed to identify the spectral difference of those varieties preclassified into four clusters according to LAD and LAI. Results showed that the samples can also be identified using canopy spectral reflectance at different growth stages. ΔR890 denoted the change of canopy spectral reflectance from the jointing to the booting stage. The differences in ΔR890 are obvious between the different plant-type varieties. A scatter plot was made using two parameters: spectral reflectance at 890 nm (R890) at jointing stage and the difference in reflectance at 890 nm between the jointing and booting stages (ΔR890). The scatter plot showed that four groups can be classified according to their graphical distribution as A, erectophile varieties with low LAI; B, erectophile varieties with high LAI; C, planophile varieties with low LAI; and D, planophile varieties with high LAI (Figure 2). Reflectance of the

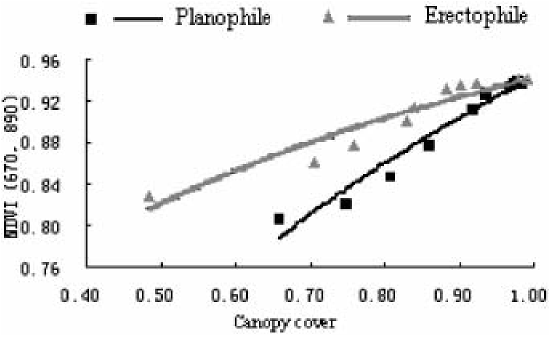

Figure 1. Changes in normal difference vegetation index of different wheat canopy covers in planophile and erectophile varieties.

planophile varieties increased more from jointing to booting stage as did varieties with low LAI. Compared vertically in the scatter plot, groups A and D can be differentiated but not groups B and C. Compared horizontally, B and C can be differentiated clearly. This indicates that varieties with different LADs can be differentiated using R890 and ΔR890 whether their LAI is equal or not.

Discriminant Analysis

Discriminant Analysis Results for Training and Validating Data Using NDVI and Canopy Cover

To prove the reliability of identifying wheat varieties with different LADs using this method, the other 12 varieties from the validation test plots were considered. Bayes discriminant analysis method, in SAS 7.0 (SAS Institute, Inc., USA), was used to test the method. Varieties in the training plots were used as calibration to establish a linear discriminant function. The training plot data were resubstituted and classified using the linear discriminant function. All varieties were classified into the group that had the higher posterior probability. The result indicated error count estimates for G were zero; there were no errors in classification. The posterior probability for proper classification was more than 80% (Table4). This result indicated that the discriminant function using NDVI and canopy cover was feasible. When the validation test plot data were considered using the discriminant

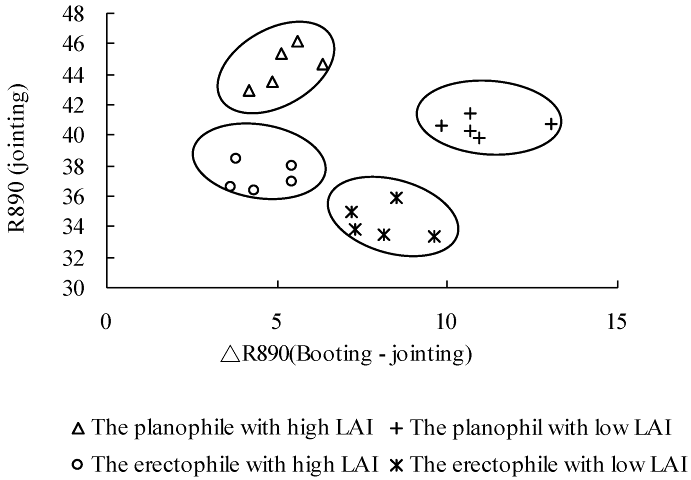

Figure 2. Classification of 20 observations based on R890 at jointing stage and the increment from jointing to booting stage (△R890) in wheat.

function, only one variety (ND3214) was classified in error. The misclassification rate was 8.333%, which indicated that the method of differentiating leaf orientations using NDVI and cover was valid. However, this method was not feasible for the planophile varieties with low LAI and the erectophile varieties with high LAI.

Discriminant Analysis Results for Training and Validating Data Using R890 and ΔR890

Similarly, Bayes discriminant analysis was used to test the method to identify wheat varieties using R890 and ΔR890. The results (Table 5) indicate that there were no errors in classification. The posterior probabilities for proper classification were more than 70% in training data and 60% in validating data. There were no misclassifications in either data set. This result indicated that the discriminant function produced by R890 and ΔR890 was feasible. This method made it not only faster but also more convenient to differentiate leaf orientations than calculating LOV, a more laborious and time-consuming method (Daughtry 1990). Further study will focus on validating the method in different growing environments and differentiating LADs quantitatively.

CONCLUSIONS

LAD is one of the key parameters to simulate radiative transfer and energy and mass balance of vegetative canopies (Mauro et al. 2001;

Table 4. Classification results for training and validating data using NDVI and canopy cover

Obs.	Training data		Validating data	
	Name	Posterior probability in correct group	Name	Posterior probability in correct group
1	CA9901	0.9978	CA0015	0.7845
2	P29	1.0000	CA0045	0.6687
3	P0185	0.9997	H3276	0.6685
4	CY66	0.9784	P7	0.6789
5	J411	1.0000	ND3214	0.4322
6	J9428	0.9986	J411	0.6572
7	JD8	1.0000	JD8	0.6799
8	ZY9507	0.9997	ZY9507	0.7644
9	CA9554	0.9814	ZY9844	0.8735
10	DF9817	0.8189	J9428	0.8898
11			GC9801	0.7299
12			ZM9	0.7845

Table 5. Classification results for training and validating data using R890 and ΔR890

Obs.	Training data		Validating data	
	Name	Posterior probability in correct group	Name	Posterior probability in correct group
1	JD8-2	0.9978	CA0015	0.8781
2	ZY9501-2	0.9997	CA0045	0.8975
3	ZY9844-2	0.9785	H3276	0.8075
4	JD8-1	0.9986	P7	0.7851
5	ZY9501-1	1.0000	ND3214	0.6551
6	ZY9844-1	0.9997	J411	0.7912
7	DF9801-2	0.9814	JD8	0.7959
8	J411-2	0.8189	ZY9507	0.7652
9	P29-2	0.9890	ZY9844	0.6811
10	DF9801-1	0.7005	J9428	0.9236
11	J411-1	0.9949	GC9801	0.7478
12	P29-1	0.9823	ZM9	0.8721

Wang, Li, and Su 2007). Wheat varieties with different LADs produced different influences on canopy spectral reflectance. Previous work has suggested that LOV or LAD can be measured to check effectiveness of visual ratings of leaf orientation (Pepper, Pearce, and Mock 1977). In this study, the potential for using imaging and spectral reflectance technology to identify canopy structural type in wheat was analyzed. The LOV indicated differences between the planophile and the erectophile varieties, and the classification agreed with visual observation ratings. Different canopy leaf distribution status resulted in different cover, spectral reflectance, and NDVI in wheat. The visually observed difference is most obvious at the jointing stage compared to the subsequent growth stages. The correlation between NDVI and canopy cover in two varieties indicated that the erectophile plants produced higher NDVI than the planophile when the vegetative coverage was similar. A further conclusion was made that NDVI and canopy cover measured simultaneously can differentiate wheat varieties with different leaf distributions. The jointing stage is the best growth stage for this identification. However, NDVI and cover cannot differentiate the planophile varieties with low LAI and the erectophile varieties with high LAI. The reflectance difference between the jointing and booting stages (ΔR890) reflects the potential of population explosion, which can differentiate the planophile with low LAI from the erectophile with high LAI when R890 is quantified. This study may contribute to improving accuracy in estimating canopy physical and chemical parameters by remote sensing.

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