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Relative Discrimination of Planophile and Erectophile Wheat Types using Multi-temporal Spectrum Measurements

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Abstract

Over-luxuriant winter wheat can always be seen when pre-winter accumulated temperature is high or too much fertilizer is applied before sowing. Over-luxuriant erectophile type wheat shows a similar canopy spectral feature to that of the planophile type. This special canopy spectral feature influences N fertilizer application decision making when using remote sensing technologies to detect N status. The objective of this study was to relatively discriminate erectophile type wheat from the planophile type and then further detect over-luxuriant canopy using seasonal changes in canopy spectral reference. Two groups of winter wheat cultivars with different canopy structures were investigated. The wheat leaf distribution feature was combined with the ratio of canopy spectral reflectance of 790 nm at elongation stage ($R790_e$) to that at rising stage ($R790_r$), i.e. $R790_e/R790_r$. Based on the values of both normalized $R790_e$ ($NR790_e$) and normalized $R790_e/R790_r$ ($N(R790_e/R790_r)$), a two-dimensional spectral coordinate system charactering seasonal change in canopy spectral reflectance was constructed. According to the distribution features, cultivars with $N(R790_e/R790_r) \geq 1$ were discriminated as the planophile type in which cultivars with $NR790_e \geq 1$ were normal and over-luxuriant (or dense) planophile type, and those with $NR790_e < 1$ were considered the sparse planophile type. On the contrary, cultivars with $N(R790_e/R790_r) < 1$ were grouped in the erectophile type in which cultivars with $NR790_e < 1$ were considered normal and sparse erectophile type, and those with $NR790_e \geq 1$ were attributed to the over-luxuriant erectophile type. Thus, $N(R790_e/R790_r)$ could be used to relatively discriminate wheat canopy structure, and $NR790_e$ to judge wheat canopy density. The larger the $NR790_e$ value, the higher the canopy density. The average discrimination accuracy of our method was 84.4%. Nevertheless, this method could provide the relative positions only within the investigated cultivars since both $NR790_e$ and $N(R790_e/R790_r)$ were relative ratios to their average.

Discipline: Information technology
Additional key words: canopy structure type, discriminating, multi-temporal canopy spectral data, winter wheat

Introduction

Remote sensing has been shown to be a valuable tool in mapping and quantifying within-field biophysical variations for crop management[23]. Imaging hyperspectral remote sensing combining spectral information with image-processing techniques can allow identification and quantification of scene components. Spectral responses to various biophysical parameters such as nitrogen (N) or water stress, whether imposed or naturally occurring, can be measured[11].

A number of studies have shown that spectral reflectance of plant canopies is affected by many variables such as chlorophyll content[12,13], green leaf area index (LAI)[19], biomass[3], and plant architecture[2,14,18,27,37]. Leaves assume a range of orientations, with some canopies having predominantly horizontal leaves (planophile), whilst others have predominantly vertical leaves (erectophile)[7]. It has been shown that leaves in a planophile position receive a

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greater total daily irradiance[9]. Pinter et al. (1985)[27] observed that wheat canopies with horizontal leaves exhibited higher reflectance and less sensitivity to solar zenith angle in the visible and near-infrared (NIR) regions of the spectrum than canopies with vertical leaves. However, the spectral reflectance of a sparse canopy with planophile leaf orientation is quite similar to the one of a dense erectophile canopy[1].

Typical leaf orientation varies during different growth stages for the given species, and from one species to another. Many stresses and environmental factors also induce changes in leaf inclination angles[30]. Therefore, the dense erectophile canopy may develop the aspect of a planophile one. For winter wheat with equidistant row spacing, the between-row space was covered gradually after rising stage. Under conditions of the same sowing density, the between-row space of planophile wheat type closes in a shorter period than that of the erectophile type. In China, winter wheat always faces the risk of excessive growth if it was sown early at high density or with too much fertilizer applied. It has been suggested that over-luxuriant cereal crop growth, due to marked increases in numbers of tillers and in leaf area, as well as mutual leaf shading and lodging, caused a decline in net assimilation rate and a reduction in grain weight[24,28,29]. Field measurements performed at our experimental station revealed that the spectral character of over-luxuriant (or dense) erectophile type was close to planophile type with normal population. An over-luxuriant (or dense) erectophile canopy is difficult to discriminate from the normal, even sparse, planophile canopy by using single temporal remote sensing data because both have a degree of close coverage in the horizontal plane. An incorrect N fertilizer management practice could occur if an over-luxuriant (or dense) erectophile type was treated as a planophile type with normal population. However, multi-temporal remotely sensed data could characterize the seasonal change in canopy reflectance and is expected to fulfill the above purpose. With the correct canopy structure information, an accurate decision could be made on N fertilizer management at elongation or booting stage.

The objectives of this study were to: 1) analyze the differences of canopy spectral reflectance in winter wheat between erectophile and planophile types, and 2) develop a method to relatively discriminate erectophile type from planophile type of winter wheat within the investigated cultivars and further detect over-luxuriant erectophile type using seasonal change of canopy spectrum measurements. Winter wheat cultivars with different leaf orientation value (LOV) were investigated, and the canopy spectral characteristics and spatial distribution features of the two kinds of canopy structures were compared.

Materials and methods

1. Design of the experiment

Experiments were carried out at China National Experimental Station for Precision Agriculture, located in Changping district, Beijing (40°11′ N, 116°27′ E), P. R. China, in both 2002–2003 and 2003–2004 seasons. The soil was a silt clay loam. Pre-sowing soil (0–20 cm) tests indicated organic matter at 14.2–14.8 g kg^{-1}, total N at 0.81–1.00 g kg^{-1}, available phosphorus (P) at 20.1–55.4 mg kg^{-1}, and available potassium (K) at 118–129 mg kg^{-1}. Organic matter was measured by Walkley-Black acid digestion method[35]; $K_2Cr_2O_7$ and H_2SO_4 were used to measure the oxidizable organic carbon in soil samples. Total N content was determined after digestion with H_2SO_4, NaOH and K_2SO_4 using Kjeldahl method[6]. B-339 Distillation Unit (BÜCHI Analytical Ltd, Flawil, Switzerland) was used for N analysis. Available P content was determined by the Olsen method, after extraction with 0.5 M $NaHCO_3$[25]. Available K was determined using the 1 M NH_4OAc extraction methods[5]. Soil extracts were analyzed by flame spectrometry for K content determination.

The cultivars included eight erectophile types (76-2, CA9722, Gaocheng8901 (GC8901 for short), Jing411 (J411), Jingwang10 (JW10), P7, Lumai21 (LM21), and Xiaoyan54 (XY54)) and eight planophile types (6211, 95021, 9507, 95128, Baili891 (BL981), Chaoyou69 (CY69), Jingdong8 (JD8), and Zhongmai16 (ZM16)) in the 2002–2003 season. A randomized complete block design with three replications was used. Each plot was 25.2 m long and 15 m wide. The crop was planted in the south-north direction with a 20 cm between-row space. Wheat was sown on October 18, 2002.

Twelve winter wheat cultivars, six erectophile types (I-93, J411, Laizhou3279 (LZ3279), LM21, Nongda3291 (ND3291), and P7) and six planophile types (4P3, 6211, 9428, 9507, Linkang2 (LK2), and Nongda3214 (ND3214)), were investigated in the 2003–2004 season. The same design and planting method as those in the 2002–2003 season were applied in 2003–2004. The plots were 30 m long and 7.2 m wide. Wheat was sown on October 20, 2003.

Normal fertilizer (N: 247.5 kg ha^{-1}, P_2O_5: 108.0 kg ha^{-1}, K_2O: 75.0 kg ha^{-1}) and water management were applied in both years.

2. Field and laboratory analysis

In each plot, an area (1 m^2) was selected for canopy spectral reflectance measurement and physiological and biochemical analysis[36]. Canopy spectral reflectance was measured at a height of 1.3 m above ground, under clear sky conditions between 10:00 and 14:00 using 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 350–2,500 nm spectral region with a sampling interval of 1.4 nm between 350 and 1,050 nm, 2 nm between 1,050 and 2,500 nm, and with spectral resolution of 3 nm at 700 nm and 10 nm at 1,400 nm as well as 2,100 nm. A $BaSO_4$ calibration panel (0.4 m × 0.4 m) was used for calculating the black and baseline reflectance. Vegetation reflectance measurements were taken by averaging 20 scans at optimized integration time, with a dark current correction at each spectral measurement. Calibration panel reflectance measurements were taken before and after canopy spectral measurement.

After canopy spectral measurements, total stem number and canopy structure parameters were measured. The stems in an area of 0.36 m × 0.36 m were counted to calculate the number of stems per m^2 (NSPSM).

Canopy structure parameters, including leaf length (L, cm), length from leaf base point to the zenith of the leaf (h, cm), and angle between the leaf and the stem (θ, °) were measured at elongation stage. The LOV was calculated as eq. (1) (Pepper et al., 1977)[26]:

$$LOV = \sum_{i=1}^{n} [a(h/L)_i / n] \tag{1}$$

where a is the leaf inclination angle, a=90°–θ, θ is the angle between the leaf and the stem, h is the distance from leaf base point to the zenith of the leaf, L is leaf length, and n is the leaf amount. Cultivars with LOV ≥ 45° were considered the erectophile type.

All plants on the 0.36 m × 0.36 m area were sampled immediately after the spectra and canopy structure parameters were measured. The samples were placed into plastic bags and transported to laboratory for subsequent analysis. Leaves of all the sampled plants were collected together for LAI determination. LAI was determined with a dry weight method[10,39]. Leaf segments of about 60 cm^2 were cut from the middle part of about 20–30 leaves and selected as reference leaves for LAI calculation. Both the reference leaves and the remaining ones were oven-dried at 70°C to constant weight and weighed. LAI was calculated as eq. (2):

$$LAI = \frac{S_r * W_t}{W_r * S_l} \tag{2}$$

where S_r (m^2) is the area of the reference leaves, W_t (g) is total dry weight of all the sampled leaves, S_l (m^2) is the land area of the samples, and the W_r (g) is the dry weight of the reference leaves. Before the dry weight measurement method was performed, area of all the leaves of the sampled plants was measured using a CI-203 Portable Laser Leaf Area Meter (CID Inc., USA). LAI from both methods were averaged to assess LAI values.

The planophile type always occupies more horizontal space than the erectophile type, and the stem makes a specific contribution to the canopy spectral reflectance as well. To normalize the influence of stems on canopy reflectance, the normalized crop colony index (NCCI), was developed in this study as eq. (3):

$$NCCI = \frac{B_i w_b}{B_{\max}} + \frac{LAI_i w_l}{LAI_{\max}} \tag{3}$$

where B_i is NSPSM of the investigated cultivar at a given stage, $B_{\max}$ is the maximal NSPSM in all the erectophile types (or planophile types), LAI_i is the LAI value of a cultivar at a given stage, $LAI_{\max}$ is the maximal LAI in all the erectophile types (or planophile types), and w_b and w_l are the weight of total stem number and LAI in a given canopy, respectively. In this study, the w_b and w_l were calculated according to the difference of stems and leaves to the whole canopy extracted from the digital camera picture. The w_b was assigned with 0.4, and w_l with 0.6, $w_b + w_l = 1$. High value of NCCI indicated high coverage of vegetation.

All the measurements were performed at rising (April 4, 2003 and April 1, 2004) and elongation stages (April 21, 2003 and April 15, 2004), respectively.

3. Data analysis

The wheat canopy reflectance in all wavebands was subjected to analysis of variance (ANOVA), and the most significant difference was observed at 790 ± 10 nm. Therefore, the canopy spectral reflectance at 790 nm at elongation stage ($R790_e$), which expressed the greatest difference among investigated cultivars, and at rising stage ($R790_r$), when plant canopy developed slowly, were selected to discriminate winter wheat canopy structure. Ratio of $R790_e$ to $R790_r$ ($R790_e/R790_r$) was calculated to characterize the seasonal change of wheat canopy reflectance. The method for wheat canopy structure discrimination using multi-temporal remote sensing technique was also affected by sowing date and basal seedling number, besides the growth status and soil background. The influence from the above factors must be minimized to ensure the discrimination accuracy. For this purpose, both $NR790_e$ and $N(R790_e/R790_r)$, which were calculated as eqs. (4) and (5), respectively, were used to minimize the influence of the above factors in this study:

$$NR790_e = \left(R790_e\right)_i / \overline{\left(R790_e\right)} \tag{4}$$

$$N(R790_e/\mathrm{R}790_r) = (R790_e/\mathrm{R}790_r)_i / \overline{(R790_e/\mathrm{R}790_r)} \quad (5)$$

where $NR790_e$ is normalized $R790_e$, $(R790_e)_i$ is $R790_e$ of a given cultivar and $\overline{(R790_e)}$ is the averaged $R790_e$ of all the investigated cultivars; similarly, $N(R790_e / R790_r)$ is normalized $R790_e/R790_r$, $(R790_e / R790_r)_i$ is $R790_e/R790_r$ of a given cultivar, and $\overline{(R790_e / R790_r)}$ is the averaged $R790_e/R790_r$ of all the investigated cultivars.

Both $N(R790_e/R790_r)$ and $NR790_e$ were shown on abscissa axis and ordinate axis, respectively (Fig. 1). The above values of the investigated cultivars produced two-dimensional spectral space features in the coordinate system. The spatial distribution feature based on two growth stages was expected to relatively discriminate wheat canopy structure type.

Results

1. The canopy structure characteristics of winter wheat with different canopy structures

The LOV at elongation, NSPSM, LAI, and NCCI at both rising and elongation stages are listed in Table 1. Results showed that NSPSM, LAI and NCCI of the erectophile type were 15.6%, 13.4% and –1.3% higher than those of the planophile type at rising stage, respectively. The difference of NCCI between these two canopy structure types was the smallest. With plant development, NSPSM decreased in both types, especially in erectophile type since its weak tillers died gradually. The average NSPSM and LAI of the two types were almost equivalent at elongation. Because the leaf in planophile type always stretches in the horizontal plane, the LOV of this type at elongation was smaller than that of the erectophile type.

2. Canopy spectral reflectance characteristics of winter wheat of different canopy structures

From Table 2 and Table 3, and Fig. 2 and Fig. 3, very similar canopy spectral reflectance at 790 nm between erectophile type and planophile type was observed at rising stage. At elongation, the R790 of planophile type was 19.7% higher than that of erectophile type. The canopy spectral reflectance value in 2003–2004 was higher than in 2002–2003 due to the fine winter climatic conditions in 2003–2004 growing season (data not shown).

Taking both Table 2 and Table 3 into consideration, planophile type showed higher canopy spectral reflectance at 790 nm on average than that of erectophile type. However, some erectophile types still showed higher canopy spectral reflectance in this region than that of planophile type. Table 4 revealed that $R790_r$ significantly correlated with NSPSM, LAI and NCCI; $R790_e$ significantly correlated with LOV, LAI and NCCI; $R790_e/R790_r$ significantly correlated with LOV; and $NR790_e$ significantly correlated with LOV, LAI and NCCI. These relationships provided a theoretical possibility for wheat canopy structure type discrimination.

3. Relative discrimination between erectophile and planophile wheat types and detection on over-luxuriant wheat canopy

As shown in Fig. 1, the planophile type mainly scattered in the right part of the coordinate system and the erectophile type in the left part. Cultivars with $N(R790_e/R790_r) \geq 1$ were of the planophile type, and those with $N(R790_e/R790_r) < 1$ were of the erectophile type. As has been proven in the previous section, $NR790_e$ significantly correlated with LAI and NCCI. Therefore, $NR790_e \geq 1$ indicated an over-luxuriant or potential over-

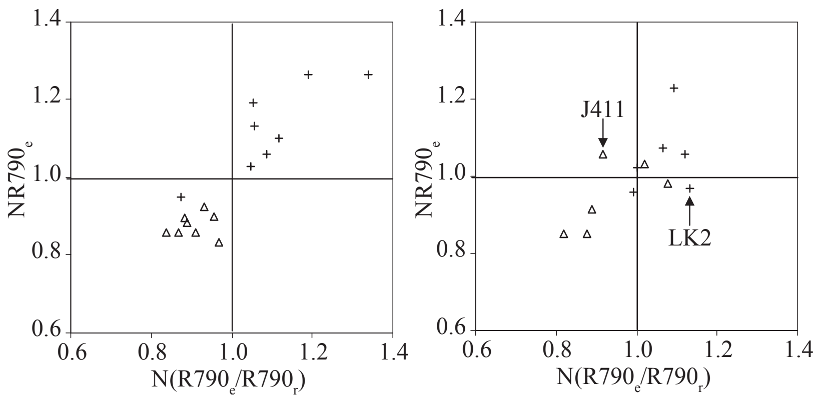

Fig. 1. Distribution features of the planophile type and erectophile type in a two-dimension spectral coordinate system in both 2003 (left) and 2004 (right)

J411 is cultivar Jing411 and LK2 is cultivar Linkang2.

△: Ereceophile-plant type; ＋: Planophile-plant type.

Table 1. Canopy structure parameters of two winter wheat plant types at different growth stages

Plant types	Cultivars	LOV(°)	Rising			Elongation		
			Number of stems per m^2 (NSPSM)	Leaf area index (LAI)	Normalized crop colony index (NCCI)	Number of stems per m^2 (NSPSM)	Leaf area index (LAI)	Normalized crop colony index (NCCI)
Erectophile type	I-93	56	1,131	0.75	0.62	775	2.13	0.52
	J411	49	1,637	1.31	1.00	1,428	4.25	1.00
	LM21	64	1,359	1.13	0.85	1,039	3.20	0.74
	LZ3279	75	1,506	0.80	0.73	1,263	2.60	0.72
	ND3291	57	1,340	0.94	0.76	1,072	2.71	0.68
	P7	61	1,209	0.64	0.59	681	1.59	0.42
	Average	60	1,363	0.93	0.76	1,043	2.75	0.68
Planophile type	4P3	39	1,240	0.77	0.75	1,284	2.79	0.82
	6211	38	1,237	1.04	0.90	934	3.06	0.75
	9428	23	1,150	0.97	0.84	968	2.48	0.67
	9507	25	1,565	1.06	1.00	1,238	4.01	0.98
	LK2	19	656	0.41	0.40	734	2.09	0.54
	ND3214	30	1,231	0.68	0.70	894	2.19	0.61
	Average	29	1,179	0.82	0.77	1,008	2.77	0.73

Data used were measured in the 2003–2004 season. J411, LM21, LZ3279, ND3291, LK2, and ND3214 are cultivars Jing411, Lumai21, Laizhou3279, Nongda3291, Linkang2, and Nongda3214, respectively. LOV was measured at elongation.

Table 2. Canopy spectral reflectance (R790) (%) at different wheat growth stages in 2002–2003

Plant types	Cultivars	Rising	Elongation	Ratio of R790 at elongation to that at rising
Erectophile type	76-2	24.0	21.9	0.91
	CA9722	23.5	22.6	0.96
	GC8901	20.4	20.4	1.00
	J411	22.3	21.0	0.94
	JW10	22.3	22.0	0.99
	LM21	24.3	21.0	0.86
	P7	23.6	21.6	0.92
	XY54	23.4	21.0	0.90
	Average	23.0	21.4	0.94
Planophile type	6211	25.7	23.2	0.90
	95021	23.3	26.9	1.15
	9507	25.2	30.9	1.23
	95128	22.4	30.9	1.38
	BL981	26.8	29.2	1.09
	CY69	23.1	25.9	1.12
	JD8	25.4	27.7	1.09
	ZM16	23.2	25.1	1.08
	Average	24.2	27.5	1.14

GC8901, J411, JW10, LM21, XY54, BL981, CY69, JD8, and ZM16 are cultivars Gaocheng8901, Jiang411, Jingwang10, Lumai21, Xiaoyan54, Baili981, Cahoyou69, Jingdong8, and Zhongmai16, respectively.

Table 3. Canopy spectral reflectance (R790) (%) at different wheat growth stages in 2003–2004

Plant types	Cultivars	Rising	Elongation	Ratio of R790 at elongation to that at rising
Erectophile type	I-93	27.1	34.0	1.26
	J411	30.3	39.3	1.30
	LM21	23.9	36.5	1.52
	LZ3279	27.3	31.6	1.16
	ND3291	26.7	38.4	1.44
	P7	25.5	31.7	1.24
	Average	26.8	35.3	1.32
Planophile type	4P3	26.5	39.9	1.51
	6211	25.4	35.7	1.41
	9428	26.8	38.0	1.42
	9507	29.6	45.7	1.54
	LK2	22.5	36.0	1.60
	ND3214	24.9	39.3	1.58
	Average	26.0	39.1	1.51

J411, LM21, LZ3279, ND3291, LK2, and ND3214 are cultivars Jing411, Lumai21, Laizhou3279, Nongda3291, Linkang2, and Nongda3214, respectively.

luxuriant canopy, otherwise, a normal or sparse canopy, in erectophile type. On the contrary, $NR790_e < 1$ in planophile type indicated a sparse canopy, otherwise, normal or potential over-luxuriant canopy, depending on the value of $NR790_e$. Thus, the four quadrants reflected four (or six) different canopy structures. Cultivars in quadrant Ⅰ were of the normal and over-luxuriant (or dense) planophile type, in quadrant Ⅱ the over-luxuriant (or dense) erectophile type, in quadrant Ⅲ the normal or sparse erectophile type, and in quadrant Ⅳ the sparse planophile type. Since the value of $NR790_e$ significantly increased with increasing NCCI (Table 4), the larger the $NR790_e$ value, the higher the possibility of an over-luxuriant canopy. So wheat canopy structure type was relatively discriminated and the potential of over-luxuriant canopy was detected with the spatial distribution feature of both $N(R790_e/R790_r)$ and $NR790_e$.

Discussion

With the development of remote sensing techniques, multi-temporal data have been applied widely in crop management. Single temporal remotely sensed data can be used to detect crop status at a given stage whereas multi-temporal data can reflect crop dynamic change, and can be applied in crop yield estimation, land-cover changes etc.[22,34]. However, the complexity of canopy structure and other external factors has limited the application of remote sensing techniques in crop management. The vegetation canopy structure parameters have been shown to be important for the construction of vegetation optical models[8,21,32,38]. To improve the estimation accuracy of the vegetation information, prior knowledge of ground-truthed information was needed. In other words, information on the spectral data and canopy structure should be obtained as much as possible when using remote sensing methods to monitor crop management.

The extraction of canopy structure information had been conducted through canopy radiation permeation ratio and multimedia image methods[4,20]. Under our experimental condition, although the planophile type showed higher canopy spectral reflectance on average at NIR region than that of erectophile type, some erectophile types still had higher canopy spectral reflectance at this region than that of the planophile type (Tables 2 and 3). Therefore, it is difficult for single temporal remotely sensed data to discriminate the difference in wheat canopy structure. Multi-temporal data could characterize the dynamics of canopy spectral feature. Based on the variety morphological and optical characteristics of wheat canopy, multi-temporal remotely sensed data were used to relatively discriminate wheat canopy structure in this study. Previous research had demonstrated that the widely used normalized difference vegetation index (NDVI) lost sensitivity at intermediate values of LAI while NIR band reflectance remained sensitive to intermediate to high veg-

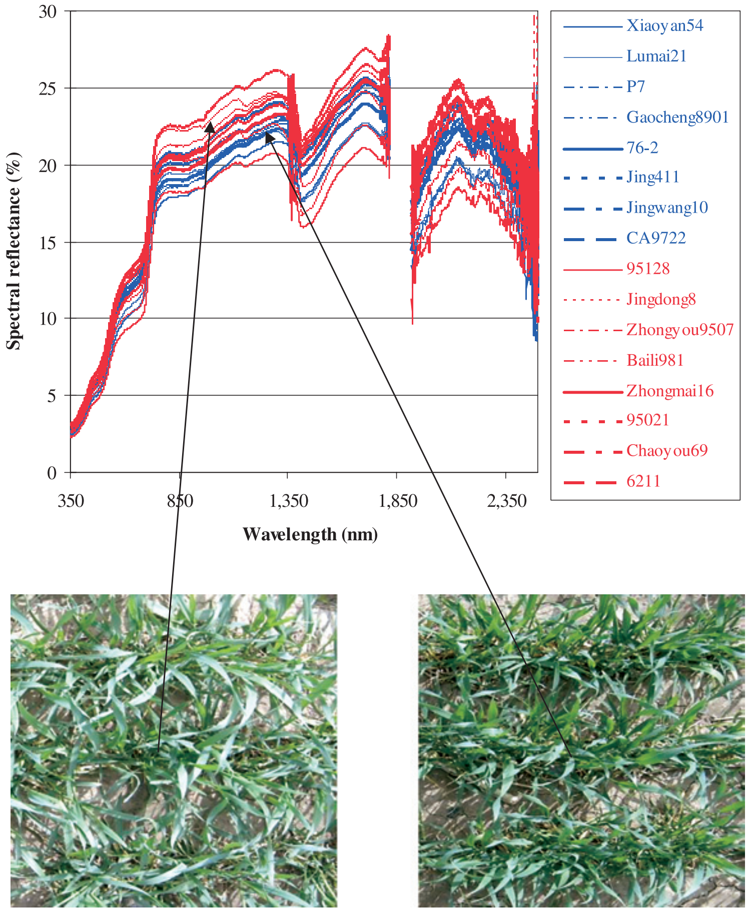

Fig. 2. Canopy spectrum features of the planophile type (Red) and erectophile type (Blue) at rising stage

Picture in left is the field profile of the planophile type, and in right is the field profile of the erectophile type.

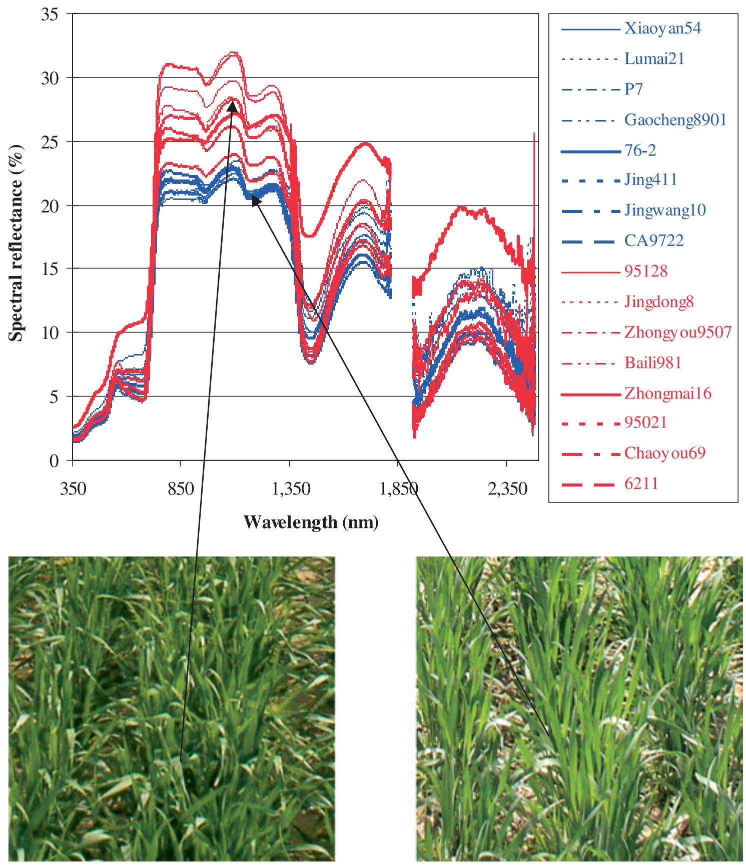

Fig. 3. Canopy spectrum features of the planophile type (Red) and erectophile type (Blue) at elongation stage

Picture in left is the field profile of the planophile type, and in right is the field profile of the erectophile type.

Table 4. Pearson's correlation coefficient between canopy structure parameters, NSPMS, LAI, and NCCI, on one hand, and $R790_r$, $R790_e$ and $R790_e/R790_r$, on the other hand

	LOV	NSPSM	LAI	NCCI
$R790_r$	–	0.784**	0.625*	0.690*
$R790_e$	–0.630*	0.465	0.638*	0.694*
$R790_e/R790_r$	–0.738**	–	–	–
$NR790_e$	–0.610*	0.479	0.655*	0.693*

$R_{0.05,12} = 0.576$, $R_{0.01,12} = 0.708$.
NSPSM is number of stems per m^2, LAI is leaf area index and NCCI is normalized crop colony index.
*, **: Significant at the 5% and 1% probability levels, respectively.

etation densities[16, 17]. So we chose canopy reference at 790 nm as a predictor for canopy structure. Taking canopy reflectance at NIR region at rising stage as basal value, the $R790_e/R790_r$ was used to characterize the seasonal change in canopy reflectance from rising to elongation stage. Our results indicated higher $R790_e/R790_r$ for the planophile type than for the erectophile type (Tables 2 and 3). In order to minimize the influence of factors other than canopy structure on the discrimination accuracy, both $R790_e/R790_r$ and $R790_e$ were normalized and were combined to reflect the seasonal change of different cultivars in a two-dimensional spectral coordinate system. From this system, cultivars with $N(R790_e/R790_r) \geq 1$ were discriminated as planophile type, and those with $N(R790_e/R790_r) < 1$ were erectophile type (Fig. 2). $NR790_e$ increased significantly with increasing NCCI at elongation (Table 4). For erectophile type, $NR790_e \geq 1$ indicated an over-luxuriant canopy, however, for planophile type a normal or over-luxuriant canopy. So the coverage of vegetation of both erectophile type and planophile type could be judged as well through the spatial distribution feature of $NR790_e$. Since the $N(R790_e/R790_r)$ value of planophile type was generally higher than that of erectophile type, so we treat $N(R790_e/R790_r) = 1$ as planophile type. For cultivars with $NR790_e = 1$ in the erectophile type group, we discriminated them as over-luxuriant, but normal ones in the planophile type group. Perhaps varieties with $N(R790_e/R790_r) = 1$, or a value very close to 1, were intermediate types, which were not included in the current study. Further study will be developed to verify this hypothesis.

In order to test the feasibility of the developed method, data from two different years were used in this study. Unfortunately, the wheat cultivars in both years did not provide consistent data. Because of this limitation, the categories of the distribution in the coordinate system were not abundant. Both the over-luxuriant (or dense) erectophile type, which had both $N(R790_e/R790_r) < 1$ and $NR790_e \geq 1$ and should be distributed in quadrant Ⅱ, and the sparse planophile type, which had both $N(R790_e/R790_r) \geq 1$ and $NR790_e < 1$ and should be distributed in the quadrant Ⅳ, were not included in the coordinate system of 2002–2003 growth season. In 2003–2004 growth season, this method discriminated one over-luxuriant erectophile type (cultivar J411) which scattered in the quadrant Ⅱ, and one sparse planophile type (cultivar LK2) located in the quadrant Ⅳ. Meanwhile, one and three cultivars were incorrectly discriminated by this method in 2002–2003 and 2003–2004, respectively. Overall, the average accuracy of this method was 84.4%.

In China, there are various wheat varieties. We found more than 5 winter wheat cultivars even in one scene of a Landsat TM image of Beijing region and Henan Province, and some over-luxuriant fields when monitoring N status in both regions. It is very difficult to detect the over-luxuriant field with a single temporal Landsat TM image. The extraction of canopy structure information through multi-temporal technique will avoid the misjudgment of wheat growth status by remote sensing techniques. Therefore, this technique will assist the application of precision decision-making on N fertilizer management. In order to avoid lodging and yield reduction, management practices on controlling wheat plant growth should be performed in over-luxuriant winter fields.

As for the appropriate time for winter wheat canopy structure type discrimination, the stage from rising to elongation was the focus in this study because both horizontal and vertical extensions in wheat canopy progressed rapidly during this stage and the soil background had less of an affect on canopy spectral reflectance. Meanwhile, it is a key stage for management application in winter wheat for the improvement of grain yield and quality.

Our current results were developed based on ground-based hyperspectral data. Application of the results on a large area should rely on satellite or airborne images, most airborne or some satellite images covering the 790 nm waveband[15,31,33]. It is possible to apply the method to airborne or satellite remote sensing. Since both $NR790_e$ and $N(R790_e/R790_r)$ were relative ratios to their average, our method could provide the relative positions only within the investigated cultivars. When judging whether a specific canopy is erectophile type or planophile type without knowing the optimum growth of each cultivar under environmental conditions, this method will lose its validity. Future study would develop such a method to solve the above problem.

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References

1. Baret, F. & Guyot, G. (1991) Potentials and limits of vegetation indices for LAI and APAR assessment. *Remote Sens. Environ.*, **35**, 161–173.
2. Barrett, E. C. & Curtis, L. F. (1992) Introduction to environmental remote sensing, 3rd ed. Chapman & Hall, London, pp. 448.
3. Behrens, T., Kraft, M. & Wiesler, F. (2004) Influence of measuring angle, nitrogen fertilization, and variety on spectral reflectance of winter oilseed rape canopies. *J. Plant Nutr. Soil Sci.*, **167**, 99–105.
4. Bonhomme, R. (1970) *In* Techniques d'Étude des Facteurs Physiques de la Biosphère. INRA, Paris, 501–505.
5. Bray, R. H. (1944) Soil–plant relations: I. The quantitative relation of exchangeable potassium to crop yield and to crop response to potash additions. *Soil Sci.*, **58**, 305–324.
6. Bremner, J. M. (1965) Total nitrogen: macro-Kjeldahl method to include nitrate. In *Methods of soil Analysis*, edited by C.A. Black. Part 2. Chemical and Microbiological properties. Agron. Monogr. 9. ASA. Madison. WI. pp. 1164.
7. Cooley, A. & Wolosin, M. (2002) Canopy structure. http://www.biology.duke.edu/bio265/msw10.
8. Disney, M., Lewis, P. & Saich, P. (2006) 3D modelling of forest canopy structure for remote sensing simulations in the optical and microwave domains. *Remote Sens. Environ.*, **100**, 114–132.
9. Duncan, W. G. (1971) Leaf angle, leaf area and canopy photosynthesis. *Crop Sci.*, **11**, 482–485.
10. Fan, L. & Hu, T. J. (1984) Research method for wheat experiment. Zhengzhou: Henan Science and Technology Press, 51–52 [In Chinese].
11. Fitzgerald, G. J. (2004) Portable hyperspectral tunable imaging system (PHyTIS) for precision agriculture. *Agron. J.*, **96**, 311–315.
12. Gitelson, A. A., Gritz, Y. & Merzlyak, M. N. (2003) Relationships between leaf chlorophyll content and spectral reflectance and algorithms for non-destructive chlorophyll assessment in higher plant leaves. *J. Plant Physiol.*, **160**, 271–282.
13. Gitelson, A. A., Kaufman, Y. J. & Merzlyak, M. N. (1996) Use of a green channel in remote sensing of global vegetation from EOS-MODIS. *Remote Sens. Environ.*, **58**, 289–298.
14. Goel, N. S. (1989) Inversion of canopy reflectance models for estimation of biophysical parameters from reflectance data. Architecture of the canopy. *In* Theory and application of optical remote sensing, ed. Asrar, G., John Wiley and Sons, New York, 205–251.
15. Hill, M. et al. (2006) MODIS spectral signals at a flux tower site: Relationships with high-resolution data, and CO_2 flux and light use efficiency measurements. *Remote Sens. Environ.*, **103**, 351–368.
16. Houborg, R. & Boegh, E. (2008). Mapping leaf chlorophyll and leaf area index using inverse and forward canopy reflectance modeling and SPOT reflectance data. *Remote Sens. Environ.*, **112**, 186–202.
17. Huete, A. et al. (2002). Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sens. Environ.*, **83**, 195−213.
18. Jackson, R. D. & Erza, C. E. (1985) Spectral response of cotton to suddenly induced water stress. *Int. J. Remote Sens.*, **6**, 177–185.
19. Lee, K. S. et al. (2004) Hyperspectral versus multispectral data for estimating leaf area index in four different biomes. *Remote Sens. Environ.*, **91**, 508–520.
20. Li, S. K. & Wang, C. T. (1997) The methods of obtaining and expressing information of crop plant shape and population structure. *J. Shihezi University (Natural Science)*, **1**, 250–256. [In Chinese with English summary].
21. Li, X. W. & Wang, J. D. (1995) Optical remote sensing models and structure parameterization for vegetation. Science Press, Beijing, 103–105.
22. Mercier, G. et al. (2005) Estimation and monitoring of bare soil/vegetation ratio with SPOT VEGETATION and HRVIR. *IEEE Trans. Geosci. Remote Sens.*, **43**, 348–354.
23. Moran, M. S., Inoue, Y. & Barnes, E. M. (1997) Opportunities and limitations for image-based remote sensing and precision crop management. *Remote Sens. Environ.*, **61**, 319–346.
24. Murata, Y. & Matsushima, S. (1975) Crop physiology. *In* Rice, ed. Evans, L. T., London, Cambridge University Press, 73–99.
25. Olsen, S. R. et al. (1954) Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circ. 939, U.S. Gov. Print. Office, Washington, DC.
26. Pepper, G. E., Pearce, R. B. & Mock, J. J. (1977) Leaf orientation and yield of maize. *Crop Sci.*, **17**, 883–886.
27. Pinter, P. J. (1985) Sun angle and canopy architecture effects on the spectral reflectance of six wheat cultivars. *Int. J. Remote Sens.*, **6**, 1813–1825.
28. Schnier, H. F. et al. (1990) Nitrogen fertilization of direct-

seeded flooded vs. transplanted rice. I. Nitrogen uptake, photosynthesis, growth and yield. *Crop Sci.*, **31**, 1276–1284.
29. Takahashi, T. et al. (2002) Relationship between dry matter production and canopy structure in wheat cultivar "Haruyutaka" bred in Hokkaido when grown in warm area of western Japan. *Jpn. J. Crop Sci.*, **71**, 481–487.
30. Tosserams, M., Magendans, E. & Rozema, J. (1997) Differential effects of elevated ultraviolet-B radiation on plant species of a dune grassland ecosystem. *Plant Ecol.*, **128,** 266–281.
31. Ungar S. et al. (2003) Overview of the Earth Observing One (EO-1) mission. *IEEE Trans. Geosci. Remote Sens.*, **41**, 1149–1159.
32. Vanderbilt, V. C. (1985) Measuring plant canopy structure. *Remote Sens. Environ.*, **18**, 281–294.
33. Vane, G. et al. (1993) The airborne visible/infrared imaging spectrometer (AVIRIS). *Remote Sens. Environ.*, **44**, 127–143.
34. Verma, K. S. et al. (1998) Gram yield estimation through SVI under variable soil and management conditions**.** *Int. J. Remote Sens.*, **19**, 2469–2476.
35. Walkley, A. & Black, I. A. (1934) An examination of Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Sci.*, **37**, 29–37.
36. Wang, Z. J. et al. (2004) Prediction of grain protein content in winter wheat using plant pigment ratio (PPR). *Field Crops Res.*, **90**, 311–321.
37. Widlowski, J. L. et al. (2004) Canopy structure parameters derived from multiangular remote sensing data for terrestrial carbon studies. *Clim. Chang.*, **67**, 403– 415.
38. Yan, G. J. et al. (2002) Spectral prior knowledge and its use in the remote sensing based inversion of vegetation structure. *J. Remote Sens.*, **6**, 1–6 [In Chinese with English summary].
39. Zhu, Y. J. et al. (1998) Study on the growth and development regularity of Wenmai6 and the crucial cultivated technique for super-high-yielding. *Acta Agron.*, **24**, 947–951 [In Chinese with English summary].