Seasonal Profiles of Polarized Reflectance and Leaf Inclination Distribution of Wheat Canopies

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Abstract: Reflectance and polarized reflectance in the visible red band were measured for wheat canopies in a wide range of solar zenith angles to explore the relations among reflectance and polarization, view and illumination geometry, and crop canopy development. The reflected sunlight in a 10° field of view was measured with a radiometer at approximately 1.6 m in height. The view zenith angles were set from 0° to 75° at 15° intervals, and the observation azimuth was towards the sun. The relation between the polarization and solar zenith angle depended both on the view zenith angle and the growth stage. Multiple regressions were applied to estimate the polarization and reflectance at solar zenith 40°. Seasonal profiles of LAI, leaf inclination distribution, reflectance, and polarized reflectance indicate that polarization includes information for canopy structure such as leaf inclination distribution. Observations at solar zenith angles of more or less than 40° may also give similar results when the view zenith angle is appropriately set, corresponding to the solar zenith angle at the time of measurement.

Key words: LAI, Leaf inclination angle, Polarized reflectance, Reflectance, Solar zenith angle.

The quality of wheat grain depends on the weather, harvesting time and the plants’ nutrient condition during the heading and maturing stages (Hoshino et al., 1992; Sato et al., 1992). Remote sensing of the growth stage as well as of the biomass, leaf color and leaf area index (LAI) level may provide valuable information for wheat cultivation. Reflectance and reflectance-based vegetation indices such as NDVI, which is the ratio of the difference to the sum of red and near-infrared band reflectance (Rouse et al, 1973), have been widely used for LAI and/or green biomass surveys for agricultural and natural vegetation (SzeliFda, 1988). In the vegetative growth stage, differences in the increasing rate of LAI due to nutrient conditions and/or cultivars are detectable by current reflectance-based indices such as NDVI. However, after the complete closure of foliage over the canopy, NDVI may show limited sensitivity in dense vegetation (Boyd and Ripple, 1997). On the other hand, the wheat canopy structure changes conspicuously during the growth period from stem elongation to emergence of panicles and the maturing stages (Udagawa, 1980). Information on wheat canopy productive structure is important not only because the photosynthetic ability is closely related to the canopy structure (Wall and Kanemasu, 1990), but also because it is connected to the growth stage (Chhina and Kler, 1997). Canopy structural information may be useful in predicting crop growth stages and may provide better cultivation and fertilization techniques such as timely topdressing for high yielding and high quality grain production. However, there is so far no appropriate method for remotely assessing canopy structure. One possible technique is to utilize the polarization of reflected light because leaf inclination as well as the geometry of illumination and observation angle may influence the degree of polarization (Egan, 1970; Curran, 1981; Fitch, et al., 1984; Nadal and Bréon, 1999). Although Rondeaux and Herman (1991) built a mathematical model that accurately describes the degree of polarization using angular leaf information, there are few studies on practical applications using the relation between canopy structure and polarization.

Previously, we described the specifications of a portable spectropolarimeter, which was specially designed for field use, and reported the preliminary results of polarization measurement for crop canopies (Shibayama and Akita, 2002). The study using the equipment revealed that polarization information was effective for predicting the ratio of legumes in a mixed seeding pasture of clover and tall fescue by detecting the planophil leaf area from the erectophil leaf area in a canopy (Shibayama, 2003). It is also necessary that wheat canopies be studied to investigate the relation between the polarization of reflected light and the structural changes in the leaf layers in the canopy caused by the seasonal progress of vegetative growth, heading, maturing and senescence. Although illumination and observation geometry influence the polarization remarkably to deal with the seasonal characteristics of observed light, the sun changes...
its elevation in the sky during the cropping season. Therefore, experimental studies are needed to develop methods of correcting the effects of solar incidence angle on polarization.

This study therefore compares seasonal variability in reflectance, polarization, and canopy structural properties by reducing the effect of the solar zenith angle.

Materials and Methods

1. Instrumentation and measurements

A portable spectropolarimeter (Donarec Co. Ltd., Machida, Tokyo) was used to measure the light intensity and the degree of polarization in wavelength bands centered at 490, 560, 660, 830, 1150, 1250, 1650, and 2200 nm. The sensing unit is equipped with devices to monitor the sensor’s view zenith angle (Zv) and the azimuth direction. The field of view of the optical system is 10° (Shibayama and Akita, 2002).

Reflectance (R%) is the ratio of reflected light intensity to the incident light intensity. Instead of measuring a standard reference panel for calibrating the radiometer to the incident light intensity, R was obtained by normalizing the reflected light intensity from the target by the solar irradiance at the top of the atmosphere (Itoa, W cm⁻² sr⁻¹ nm⁻¹), which was also corrected by the cosine of the solar zenith angle (Zs) (Bréon et al., 1995). The radiometer was calibrated in the laboratory to give the light intensity (I, W cm⁻² sr⁻¹ nm⁻¹) at each given angle of the polarizer transmission axis of 1° intervals by measuring the intensity of light emerging from the polarizer (I', W cm⁻² sr⁻¹ nm⁻¹). In each band, I at 5° intervals of angular orientation of the polarizer filter that rotated in front of the radiometer was measured to estimate the minimum signal (Imin, W cm⁻² sr⁻¹ nm⁻¹) and the maximum signal (Imax, W cm⁻² sr⁻¹ nm⁻¹) (Fig. 1). R and polarized reflectance (Q%) were calculated as follows (Gosh et al., 1993):

\[
R = 0.5 \times \left( \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{toa}} \times \cos Z_s} \right) \times 100\% \quad (1),
\]

\[
Q = 0.5 \times \left( \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{toa}} \times \cos Z_s} \right) \times 100\% \quad (2).
\]

Q is the term for the polarized part in R, and the degree of polarization (P, no unit) is the ratio of Q to R:

\[
P = Q / R \quad (3).
\]

In this paper, R and Q measured in a band centered at x nm are referred to as Rx (%) and Qx (%), respectively.

2. Radiometric observations

Radiometric observations were made on six clear-sky days between 20 March and 15 May 2002. The coordinate system used in this study is shown in Fig. 1. The period of observation on each day was from 10 a.m. to 4 p.m. (JST). The optical sensing unit of the spectropolarimeter was set on a tripod that stood at the north side of the field, and observed at the view zenith angles (Zv) of 0, 15, 30, 45, 60, and 75°. The repetition number of measurements at each Zv was 3. The height of the tripod was 1.6 m. The greater diameter of the sensor’s viewing ellipse varied about 0.3 m to 5 m depending on the Zv. The view azimuth direction was always towards the sun. The solar zenith angle (Zs) during the whole experiment varied between 18° and 67°.

No atmospheric corrections were made, but radiometric observations were made only on clear-sky days.

3. Experimental wheat plants and 3-D measurement

The plant canopies measured in the experiment were grown in a field of Andosol located on the campus of NIAES, Tsukuba (36° 01' N, 140° 06' E). Wheat (Triticum aestivum L. cv. ‘Norin-61’) was drilled in north-south row directions at a row width of 30 cm in a 17-m×22-m field on 5 November 2001. The heading was observed on 15 April. The maximum LAI...
averaged for the canopies was 5.1, which was observed about 10 days before heading. The minimum LAI observed during the radiometric experiment was 2.9.

A hill of plants was uprooted from the field, placed in a 15-cm-diameter plastic pot, and taken to a laboratory where three-dimensional (3-D) canopy geometry measurements were carried out using a Polhemus 3Space Isotrak II tracking system (Polhemus Inc., Colchester, VT, USA) in no more than two days from each corresponding radiometric observation. The apparatus consists of a system electronics unit, a stylus receiver, and a transmitter (emitter). The device uses electromagnetic waves to determine the position of a remote object with a static accuracy of 0.24 cm rms (root mean square) for the X, Y, and Z receiver positions when the receiver is located within a hemisphere with a radius of 10.2-71.1 cm from the transmitter (Shibayama, 2001). Eight points were digitized, starting from the bottom to the top of each leaf. Some leaves were sampled after digitizing, and the areas were measured using a laser area meter (CI-203, CID, Inc., WA, USA).

Each leaf was treated as an aggregation of six triangular segments inferred from the eight digitized points around it. The area of a leaf was calculated by adding the areas of the six segments.

The size of the zenith angle of a line perpendicular to the center of each triangular segment was calculated together with the area for each leaf segment. Tests to measure the angle and area using a small 8-cm² plastic triangle in an area held from 20 cm to 80 cm above the electromagnetic source indicated that the accuracy was appropriate for the 3-D measurement of plants of less than 80 cm in height (Figs. 2 and 3).

Results and Discussion

1. **R660 and Q660 at various solar zenith angles**

The degree of polarization in the visible region is more conspicuous than in the longer wavelength region (Shibayama and Akita, 2002). However, there is little variation in polarization among the visible wavelength bands because of the spectral homogeneity.
in the inflection coefficient of the cuticle of the leaf epidermis (Vanderbilt et al., 1985). Therefore, in this study we considered the band whose center wavelength was 660 nm in the analyses of reflectance ($R_{660}$) and polarized reflectance ($Q_{660}$) because the band is located in the absorption band of chlorophyll, and is used widely in remote sensing application for vegetation. Polarized reflectance ($Q_{660}$), instead of the degree of polarization ($P_{660}$), was tested here because the degree of polarization may vary with the reflectance even though the polarized part of the reflected light is constant (Eq. (3)).

$R_{660}$ and $Q_{660}$ against $Z_s$ at each $Z_v$ before and after the heading time were plotted in Figs. 4 and 5. $R_{660}$ increased along with $Z_s$ in the case of $Z_v$ $60^\circ$–$75^\circ$, but the growth stage did not seem to affect the angular responses (Fig. 4). On the other hand, $Q_{660}$ decreased as $Z_s$ increased at all $Z_v$ before heading, but it increased as $Z_s$ increased at $Z_v$ $0^\circ$–$45^\circ$ after the heading stage (Fig. 5). The contrasting responses of $R$ and $Q$ in the two growth stages concretely indicate that $R$ and $Q$ have different information on the canopies, which was suggested by Herman and Vanderbilt (1997) for practical proof.

These results show that the polarization may distinguish between headed and pre-heading canopies if several observations at various solar zenith angles are made at appropriately selected view angles, although the reflectance may not be as efficient. However, it is unclear whether the emerged panicles directly caused the phenomenon, or whether the cause is attributable to another factor such as leaf inclination distribution. Observation at various $Z_s$s takes time and requires stable weather conditions. As the sun changes its position day by day during the wheat-maturing season in Japan (March, April and May), radiometric observations at a constant $Z_s$ are ideal for investigating the relation between crop growth development and polarization data.

2. **Multiple regressions to estimate radiometric variables**

Seasonal evaluations for radiometric variables such as polarized reflectance require measurement data taken at a common $Z_s$ throughout the cropping
season because $Z_s$ influences the results. However, certain weather conditions prohibit arbitrary $Z_s$ at a given time of day, which happens to equal the predetermined common $Z_s$. Several measurements from morning to afternoon in a day at a wide $Z_s$ range may increase the possibility that the resultant $Z_s$ range includes the common $Z_s$. Multiple regression models were therefore introduced as a method of estimating $\bar{R}_{660}$ and $\bar{Q}_{660}$ at the common $Z_s$ and the given $Z_v$ on the day of measurement. It was assumed that the structure of the wheat canopy would not alter much over one measurement day. The models include $Z_v$, $Z_s$, $Z_v^2$ and dummy variables for the date. The cosines of $Z_s$ and $Z_v$ were also tested instead of simple $Z_s$ and $Z_v$, but this resulted in slightly less $R^2$ than the simple degree values of angle. The models are both highly significant, and explain 68% of the variation in $\bar{R}_{660}$, and 48% of the variation in $\bar{Q}_{660}$. All of the independent variables are significant at 5% by Student’s $t$-test, and the lower $R^2$ for $\bar{Q}_{660}$ may indicate that other factors such as canopy structural parameters, in addition to geometric

Regression models estimated the radiometric variables at the common $Z_s$ 40°, which was covered on five days of the total of six measurement days. The data of 1 measurement day on which the weather conditions prohibited observation at $Z_s$ more than 40° were not used in the following analyses to avoid errors due to extrapolation.

Estimates for $\bar{R}_{660}$ and $\bar{Q}_{660}$ at $Z_s$ 40° and various $Z_v$s on the measurement days are plotted against the day of the year in Fig. 6. $R_{660}$ decreased between heading and early maturing time, and then increased later when the $Z_v$ was between 0° and 45°. The seasonal changes for $\bar{Q}_{660}$ show distinctive patterns depending on the $Z_v$. It is interesting that the values of $\bar{Q}_{660}$ measured at various $Z_v$s were very similar on the first and last days, and they varied most conspicuously just before and during heading. Changes in variation in polarized reflectance with $Z_v$ may be used to predict heading time if seasonal observations are carried out at a constant $Z_s$ of 40°.

Fig. 6. Seasonal estimates of 660-nm band reflectance ($\bar{R}_{660}$) (above) and polarized reflectance ($\bar{Q}_{660}$) (below) of wheat canopies at various view zenith angles ($Z_v$) of the radiometer. The solar zenith angle substituted into the multiple regression models is 40°.

Fig. 7. Leaf areas of wheat plants measured intact using the 3-D digitizer (Y) versus the corresponding leaves cut from the stems and measured using a laser area meter (X).
(Kharuk and Yegorov, 1990). The polarized reflectance decreased after heading when the $Z_v$ was more than 45°, but remained almost constant or slightly increased when the $Z_v$ was less than 45°. Larger $Z_v$ makes the proportion of panicles in the sensor FOV larger because panicles are like oblong rods above the canopy surface. The smaller $Z_v$, namely, when the observation angle approaches a more nadiral direction, may reduce the effect of panicles on polarization and, as a result, the sensor could detect leaf surface orientation.

3. Leaf inclination angle distributions

Leaf area estimated using a 3-D digitizer was relatively smaller than the area measured using the area meter (Fig. 7). This may have been due to the method used for modeling leaf shape with only six triangles. The narrowness of leaves, crooked leaves, and lack of rigidity of the leaves of wheat may also have caused variation in the estimation. The shape of each leaf of the uprooted plants might differ from the original shapes when the plants are in the field. Although the accuracy of the absolute values of leaf area may be insufficient, leaf inclination angle distributions (LID) are based on each segment area relative to the whole leaf area of the plants. Therefore, the obtained LIDs could be used for further analysis. Although the method is one of the best current direct measuring techniques for canopy structural information, these difficulties remain, and the method needs to be refined.

The inclination angle of a leaf segment is defined as the zenith angle of the line perpendicular to the center of the segment. The accumulated areas of leaf segments attributed to angular classes at 5° intervals provided a histogram that represents the LID. The 3-D measurements provided a histogram of wheat LID on each day, and Fig. 8 shows some of the results obtained before heading, during heading and in the maturing stages. Goel and Strebel (1984) showed that a two-parameter beta distribution accurately represents leaf angle distribution for various types of vegetation canopy including wheat. Beta distribution
functions fit well to most of the histograms in this study, but discrepancy between the measured and fitted values in the maturing stage remained (Fig. 8). Further investigation may be needed to apply beta distribution functions for summarizing LID characteristics in the whole cropping season. To deal with canopy structure, Anten (1997) divided rice canopies into 3 leaf angle classes each within a 30˚ range. This study also adapted the proportions of the leaf area in specific angular classes to the total leaf area to characterize seasonal changes in canopy structure. Instead of 3 classes within the 30˚ range, the proportions of the leaf area in angular classes 0˚–50˚, 50˚–70˚ and 70˚–90˚ were calculated for the histograms acquired from 3-D measurement (Fig. 9). The angle range between 0˚ and 50˚ was larger than the other two ranges simply because the leaf area in the lower angle range was small, and the boundary angles divided the distribution into three classes of leaf area of no less than 20% during the season.

4. Seasonal profiles of radiometric and canopy parameters

Seasonal profiles of LAI, LID and radiometric values were obtained using a normalizing procedure in which each value was subtracted by the average and divided by the standard deviation (Fig. 10). The procedure cancels out the difference in the level of each parameter so that the seasonal patterns of several variables can be easily compared.

The $R_{660}$ profiles measured at different $Zv$s varied very little and showed the minimum values after the heading (early maturing) time. On the other hand, the $Q_{660}$ profiles measured at $Zv$ 0˚–15˚ resembled the profiles of the proportion in the 0˚–50˚ class of the LID, and those at $Zv$ 60˚–75˚ were similar to the 70˚–90˚ class of the LID. However, the maximum in the LID profile in the 70˚–90˚ class was observed 10 days earlier than the maximum in the $Q_{660}$ profiles measured at $Zv$ 60˚–75˚. Not only the proportion of leaf area, but also the actual leaf area in the 70˚–90˚ class may influence polarization in the pre-heading stage in which the LAI reached the maximum. The profile of LAI was similar to the profile of LID in the 70˚–90˚ class, mainly because half of the leaf area belonged to this class.

A multidimensional scaling method provided by SAS (Version 6.1.1, SAS Institute Inc., Cary, NC, USA) was used for the graphical analysis of the profile signatures. The profile scores were calculated based on distance $O_{ij}$ between the $i$th and $j$th profiles acquired on $k$th day, as defined by the following equation:

$$O_{ij} = \sqrt{\sum_{k=1}^{p} (y_{ik} - y_{jk})^2}$$  \hspace{1cm} (4),

where $p$ is the total number of measurement days (Maekawa, 1997).

The signatures of the two profiles qualitatively
resemble each other if the locations of the points on the two-dimensional scatter diagram are close to each other. The scattered points show that polarized reflectance patterns differ from reflectance except in the case of $Z_v 0^\circ$, which again indicates that polarization generally reflects different information with reflectance (Fig. 11). The resemblance between $Q_{660}$ at $Z_v 15^\circ$ and LID in the $0^\circ$–$50^\circ$ range, and $Q_{660}$ at $Z_v 75^\circ$ and LID in the $70^\circ$–$90^\circ$ range was verified by the fact that these points are close together in the scatter diagram. The seasonal profile for LID in the $50^\circ$–$70^\circ$ class is close to that of the $R_{660}$ at a view zenith angle between $60^\circ$ and $75^\circ$. Scatter diagram analysis confirmed the results of comparison by visual observation of the seasonal profiles (Fig. 10).

5. Possibility of polarimetric measurements at optional solar zenith angles

The results demonstrate the possibility of assessing seasonal change in LID in specific angular classes detected by polarization. However, several observations at solar zenith angles of and around $40^\circ$ were required to build a regression model in situ. It would be more convenient if a single optional solar position were permeable. When the solar zenith angle was fixed at $40^\circ$, $Q_{660}$ measured at $Z_v 15^\circ$ and $Z_v 75^\circ$ showed unique seasonal responses. The divergence between $Z_v$ and $Z_s$ was therefore $-25^\circ$ (= $15^\circ$–$40^\circ$), and $35^\circ$ (= $75^\circ$–$40^\circ$). Hence, estimations were made for the values of $Q_{660}$ measured at $Z_s$ in which the differences in $Z_v$ and $Z_s$ were equal to $-25^\circ$ and $35^\circ$, respectively (Fig. 12). The averages and standard deviations were then calculated for each measurement day. The estimates of $Q_{660}$ at a provided $Z_s$ of more or less than $40^\circ$ were calculated simply by linear interpolation using the two closest neighboring $Z_s$s that were set from $0^\circ$ to $75^\circ$ at $15^\circ$ intervals in the observation experiment. The seasonal patterns of $Q_{660}$ at the fixed $Z_s$ of $40^\circ$ and different angles were close to each other in the tested cases (Fig. 13). This phenomenon can be explained by the virtual leaf area specularly reflecting the incident light because the view zenith angles were adjusted to be specularly reflecting geometry relative to the $Z_s$. These results suggest that seasonal polarization measurement is possible for detecting the changes in the LID of...
wheat canopies at least partly free from the solar position at the time of measurement.

Conclusion

Polarization measurement may refine growth-stage detection of wheat canopies, for instance, when the canopy alters its structure independently of the LAI. After the complete development of foliage, polarization information may be usable for detecting the phenological stages. These findings have implications for the use of polarization data acquired at specific view angles for deriving canopy structural information. Currently however, the results are restricted, and further study is required at many other study sites and for different types of crop before firm conclusions can be drawn.

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