Remote Assessment of Wheat Canopies under Various Cultivation Conditions Using Polarized Reflectance

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Abstract: The polarization of light reflected from crop canopies gives information on the canopy structure, such as the distribution of leaf inclinations. In order to verify those findings and to put the technique to practical use, we conducted two experiments in wheat fields. In the first experiment, the reflectance and polarized reflectance at 660 nm in the canopies of wheat plants, sown in both narrow and wide rows, and at two levels of topdressing, were measured periodically with a spectropolarimeter. We also probed the leaf orientation geometry of the plants using a 3-D digitizer and a plant canopy analyzer (LAI-2000). In the second experiment, we observed the polarization of light reflected from wheat planted in plots fertilized with basal dressing, and topdressing at the jointing and booting stages. Polarization showed a seasonal change with an upward convex clearly indicating the heading time. This pattern was not found by conventional band reflectance. Using polarization, it was possible to detect the differences in row width and fertilization conditions during the booting stage. The mean leaf inclination angle (MLI) detected with the 3-D digitizer and the mean tip angle (MTA) detected with the LAI-2000 were relatively closely correlated with the polarization than the reflectance at 660 nm and normalized difference vegetation index (NDVI) that was derived from the reflectance at 660 nm and 830 nm. Topdressing at the jointing stage was well detected by polarization obtained at the heading stage. Polarization measurements are useful in practical terms for remote detection of changes in stand geometry induced by cultivation management such as topdressing.

Key words: Booting stage, Jointing stage, Leaf inclination angle, Solar zenith angle.

The stand geometry of wheat changes markedly during the growth period (Udagawa, 1980). Information on the stand geometry of wheat is important not only because the photosynthetic ability of the wheat is closely related to its canopy structure (Wall and Kanemasu, 1990), but also because it is related to its growth stage (Chhina and Kler, 1997). The nutritional state of plants at specific stages of development has been investigated to predict their yield and the quality of wheat grain harvested, especially the protein content (Hoshino et al., 1992; Sato et al., 1992a; Ogiuchi and Sakuyama, 2005). Information on canopy structure is useful in predicting the growth stages and nutrient conditions, which may provide better cultivation and fertilization techniques such as topdressing at the time suitable for producing high yield and high quality grain. Optical remote sensing of the greenness of leaves and fresh biomass using spectral reflectance measurement is a promising technique both for hand-held surveys (e.g., Matsuda et al., 2003; Huang et al., 2004) and surveys from the air or from space (e.g., Asaka and Shiga, 2003; Kanemoto et al., 2004). Methods for sensing the stand geometry of crop canopies remotely remain to be developed.

Theoretical and practical research revealed that it is possible to use the polarization of the reflected light from canopies to detect the leaf inclination geometry of vegetation canopies (Egan, 1970; Curran, 1981; Fitch et al., 1984; Rondeaux and Herman, 1991; Nadal and Bréon, 1999; Shibayama, 2003; Shibayama, 2004). Previously, we reported the preliminary results of polarization measurement of crop canopies using a portable spectropolarimeter designed for field use (Shibayama and Akita, 2002).

In experimental studies, methods have been developed for reducing the effects of a change in the angle of incidence of sunlight on polarization (Shibayama, 2004). To examine the seasonal degree of observed light, we need to consider the influence of the geometry of illumination and observation on polarization because the elevation of the sun in the sky changes during the cropping season. Polarized reflectance estimated by regression equations employing the solar zenith angle as an independent variable increased toward the time of heading, and decreased thereafter, supposing that the solar zenith angle is hypothetically fixed at a normal angle, for instance at 40°. However, these regression equations were derived from the data obtained by measurements in situ over the whole day each day, because the solar
zenith angle varies greatly so that the regression is possible, and it also includes the normal solar zenith angle on each day. A simpler method for analyzing the seasonal change of polarization was suggested in the study to replace this time-consuming procedure. However, the technique proposed was empirical and remains to be verified for different crops, cultivation conditions, at other locations and in other seasons.

This paper demonstrates the seasonal change in the polarization of light reflected from wheat canopies in various cultivation conditions, and investigates the relationship between the polarization of reflected light and the structural changes in the leaf layers of the canopy.

The reflectance ($R\%$) is the ratio of the reflected light intensity to the incident light intensity, and the polarized reflectance ($Q\%$) is the term for the polarized part of $R$. In this paper, $R$ and $Q$ measured in a band centered at $x$ nm are referred to as $R_x$ (%) and $Q_x$ (%), respectively. The zenith angle of the viewpoint of the sensor and the solar zenith angle are abbreviated to $Z_v$ and $Z_s$, respectively. In this study, the band is centered at a wavelength of 660 nm when analyzing reflectance ($R_{660}$) and polarized reflectance ($Q_{660}$). This is because there is little variation in polarization among the visible wavelength bands because of the spectral homogeneity in the inflection coefficient of the light reflected from the cuticle of leaf epidermis (Vanderbilt et al., 1985).

**Materials and Methods**

1. **Instruments used**

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 with values for the fields of view (FOV) of the optical system of 10° and 14° (Shibayama and Akita, 2002). For polarimetric measurements, only an FOV of 10° was used. However, an FOV of 14° was chosen to measure subordinate reflectance to obtain a normalized difference vegetation index (NDVI) (Rouse et al., 1973):

$$\text{NDVI} = \frac{(R_{830} - R_{660})}{(R_{830} + R_{660})}$$

The procedure for measuring reflectance and polarization was carried out with reference to Shibayama (2004).

2. **Experiment 1**

(1) **Experimental wheat plants, and stand geometry and other measurements**

The plant canopies measured in the experiment were grown in a field of Andosol located on the campus of National Institute for Agro-Environmental Sciences, Tsukuba (36° 01 ' N, 140° 06 ' E). Wheat (*Triticum aestivum* L. cv. ’Norin-61’) seeds were drilled in a row in a north-south direction at row widths of 20 cm and 40 cm in both of two 17-m×11-m fields on 14 November 2003. A basal dressing of N-P-K at 3-4.5-3 gm⁻² was applied to all four fields. N-P-K at 6-9-6 gm⁻² was applied to two of the four fields on 24 February 2004. The heading was observed in the fields with a row width of 20 cm on 19 April, and in the fields with a row width of 40 cm on 22 April. 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 taken using a Polhemus 3Space Isotrak II tracking system (Polhemus Inc., Colchester, VT, 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 these six segments. The area of each leaf segment, and the zenith angle of the line perpendicular to the center of each triangular segment were calculated (Shibayama, 2001). The mean of the angles for the sample plants, weighed by their area, was calculated to estimate the mean leaf inclination angle (MLI) of the canopy from which the sampled plants came from. A plant canopy analyzer (LAI-2000, LI-COR, Inc., Lincoln, NE, USA) was also used in the
field to estimate the LAI and mean tip angle (MTA) of the wheat stands (Welles and Norman, 1991). MLI and MTA were measured differently, but the definition is identical. For each sampled plant, the plant height was scaled, and the leaf greenness index was read using a hand-held optical sensor (SPAD-502, Konica Minolta Holdings, Inc., Tokyo, Japan) that detects the chlorophyll content of a single leaf.

(2) **Radiometric observations**

Observations were made on six clear-sky days between 6 April and 25 May 2004. No atmospheric corrections were made, but radiometric observations were made only on clear-sky days. The observation on each day was carried out between 9:45 and 12:40 (JST). The optical sensing unit of the spectropolarimeter was set on a 1.6 m-high tripod that stood at the north side of the field, and observed with values for $Z_v$ of $15^\circ$, $30^\circ$, $45^\circ$, $60^\circ$, and $75^\circ$. The variation in the area of the viewing ellipse of the sensor depending on $Z_v$ was ignored. The azimuth direction of the view was always towards the sun. Over the entire period of the experiment, $Z_s$ decreased from $39^\circ$ on the first day to $16^\circ$ on the last day. Measurements were carried out three times for each value of $Z_v$. Spectral reflectance measurements (with no polarization) were made on 18 clear-sky days between 19 February and 4 June. The same equipment was used, but FOV was $14^\circ$ and $Z_v = 0^\circ$ (a nadir viewing angle).

(3) **Adjustment of $Z_v$ in radiometric measurements for various values of $Z_s$**

The adjustment procedure for $Z_v$ used in this study was one of the two methods suggested by Shibayama (2004). The normal observation geometry was empirically $Z_v = 75^\circ$ for $Z_s = 40^\circ$. The $Z_v$ required for observation at a given $Z_s$ was derived using the following equation:

$$Z_v = 35^\circ + Z_s$$

Linear interpolation was utilized to estimate the optical variables at the calculated $Z_v$ from Eq. (2) using the two values observed at the nearest two values of $Z_v$. A schema of the observation geometry is shown in Fig. 1. The polarized reflectance is referred to as $Q_{660}$ adjusted for $Z_v$, and the reflectance derived from this procedure is referred to as $R_{660}$ adjusted for $Z_v$.

(4) **Analysis of variance tests**

The procedure for adjusting the $Z_v$ according to the value of $Z_s$ at the time of observation was evaluated using an analysis of variance test for a three-factor factorial experiment with no repetition. Three consecutively measured optical variables for each plot were averaged in advance. The statistical model was a linear combination of the factors “day of measurement,” “row width,” and “topdressing” ($6 \times 2 \times 2$). The independent variables tested were $R_{660}$ adjusted for $Z_v$, $Q_{660}$ adjusted for $Z_v$, and the unadjusted values for $R_{660}$ and $Q_{660}$ observed

### Table 1a. F-values (F-obs) obtained by the analyses of variance of the whole data of polarized reflectance ($Q_{660}$) adjusted for $Z_v$ and each $Z_v$.

| Factor (number of levels) | Adjusted for $Z_v$ | $Z_v 75^\circ$ | $Z_v 60^\circ$ | $Z_v 45^\circ$ | $Z_v 30^\circ$ | $Z_v 15^\circ$ |
|--------------------------|--------------------|----------------|----------------|----------------|----------------|----------------|
| Date (6)                 | 92.80**            | 33.61**        | 62.60**        | 34.85**        | 11.49*         | 20.12*         |
| Row width (2)            | 22.34*             | 5.00           | 16.95*         | 25.08*         | 1.87           | 2.74           |
| Topdressing (2)          | 3.94               | 0.69           | 0.76           | 0.66           | 0.00           | 0.03           |
| Date × Row width         | 4.15               | 0.79           | 3.96           | 3.42           | 0.58           | 0.83           |
| Row width × Topdressing  | 1.12               | 0.84           | 3.01           | 0.49           | 0.00           | 0.00           |
| Date × Topdressing       | 0.69               | 0.27           | 0.23           | 0.19           | 0.44           | 0.40           |

**, *: Significant at 0.1% and 1% level, respectively.

### Table 1b. F-values (F-obs) obtained by the analyses of variance of the whole data of reflectance ($R_{660}$) adjusted for $Z_v$ and each $Z_v$, and NDVI (Normalized Difference Vegetation Index) measured from the nadir.

| Factor (number of levels) | Adjusted for $Z_v$ | $Z_v 75^\circ$ | $Z_v 60^\circ$ | $Z_v 45^\circ$ | $Z_v 30^\circ$ | $Z_v 15^\circ$ | NDVI |
|--------------------------|--------------------|----------------|----------------|----------------|----------------|----------------|------|
| Date (6)                 | 241.00**           | 42.78**        | 44.82**        | 17.78*         | 22.18*         | 51.67**        | 5.79 |
| Row width (2)            | 0.35               | 1.96           | 1.10           | 11.14          | 2.06           | 19.48*         | 0.53 |
| Topdressing (2)          | 24.53*             | 8.23           | 16.19          | 6.62           | 14.65          | 5.45           | 0.09 |
| Date × Row width         | 9.87               | 0.59           | 2.53           | 2.98           | 9.12           | 1.91           | 0.47 |
| Row width × Topdressing  | 3.92               | 1.91           | 0.73           | 2.68           | 0.25           | 0.66           | 3.06 |
| Date × Topdressing       | 0.68               | 0.23           | 0.35           | 0.36           | 0.84           | 2.60           | 0.05 |

**, *: Significant at 0.1% and 1% level, respectively.
at values of $Z_v$ from 15° to 75° at 15° intervals. In addition, the NDVI measured with an FOV of 14° at a nadir view angle ($Z_v = 0°$) was included in the analysis for reference.

In addition, an analysis of variance test was applied to the optical data for each day, containing $R_{660}$ adjusted for $Z_v$, $Q_{660}$ adjusted for $Z_v$, and NDVI to investigate the effects of “row width” and “topdressing.”

3. Experiment 2

1) Plants used for experiment

The experimental site was located in the study field that had been established for the Program of Field Management for High Quality Wheat Production conducted by National Institute of Crop Science, Ibaraki, Japan (36°00’ N, 140°01’ E). Wheat (Triticum aestivum L. cv. ‘Norin-61’) seeds were drilled in east-west rows at a row width of 30 cm in a 10-a field on 28 November 2003. Basal dressing was applied at three levels (4.8, 6.8, and 8.8 gN m$^{-2}$), jointing-stage topdressing at two levels (0 and 2 gN m$^{-2}$ on 15 March), and booting-stage topdressing at two levels (0 and 2 gN m$^{-2}$ on 12 April) four times. The whole field was divided into 48 plots of equal area (4 m × 5 m) after the final topdressing. The heading was observed on 21 April 2004. A yield survey was conducted in all plots after the harvest.

2) Radiometric observations

The reflectance and polarized reflectance of the wheat plots were observed on 21 April 2004. It was a sunny, clear-sky day. The measurement started at 9:50 and ended at 12:20. An observation method similar to that in Experiment 1 was employed, using the same apparatus with an FOV of 10°, except that only values of 30°, 45° and 60° were used for $Z_v$. First, all 48 plots were measured consecutively with $Z_v = 45^\circ$, and then the same was done for $Z_v = 30^\circ$, and $Z_v = 60^\circ$, successively. The value of $Z_v$ varied from about 34° during the observation with $Z_v = 45°$, to about 24° for the observation with $Z_v = 60^\circ$. The observation geometry for $Z_v = 60^\circ$ and $Z_s = 24^\circ$ approximately satisfied Eq. (2).

3) Analysis of variance tests

Analysis of variance tests for the surveyed yield components and the observed optical variables were conducted, treating the experiments as completely randomized three-factor factorial experiments carried out four times.

Results and Discussion

1. Experiment 1

1) Wheat plant growth traced by NDVI

Fig. 2 shows the values of NDVI observed for the wheat canopies and the bare soil surfaces during the growing period, and indicates the dates of heading, application of topdressing and polarimetric measurements. The NDVI of the wheat appeared to increase every day at first, although one expects to see saturation occurring between days 100 and 130. The NDVI of the canopies in rows with a width of 40 cm was smaller than that of the rows with a width of 20 cm in the earlier stages (DOY 50-80). This means that sparsely sown canopies had smaller leaf areas and less green biomass than densely sown ones. However, the difference between sparsely sown plants and densely sown plants disappeared in the booting and heading stages. During the period about 20 days before and after heading, the NDVIs taken from the differently treated plots appeared to be very close.

2) The effect of adjusting for $Z_v$ on reflectance and polarized reflectance

Table 1a and 1b show the ratios between variances due to factors and error variance (F-obs) for the factors “day of measurement,” “row width,” and “topdressing,” and their interaction terms, obtained from the analysis of variance for the optical parameters. The factor “day of measurement” seemed significant at a 0.1% level for most of the variables at a majority of values of $Z_v$, except for the case of NDVI. To avoid possible type II errors in repeated statistical tests, it may be best to use 0.1% as the level of significance. The largest F-obs was obtained for the factor “day of measurement” for $R_{660}$ adjusted for $Z_v$ (F-obs = 241.0), and the second largest one was given by $Q_{660}$ adjusted for $Z_v$ (F-obs = 92.8). Even the unadjusted values for $R_{660}$ and $Q_{660}$ gave the largest F-obs (= 24.5) for the factor “topdressing,” and
the value of $Q_{660}$ adjusted for $Z_v$ gave the second largest $F$-obs ($= 22.3$) for "row width." Adjusting for $Z_v$ is thought to improve the accuracy of measurement, not only for $Q_{660}$ but also for $R_{660}$. Usually, spectral reflectance is measured avoiding the geometrical situation where the sensor is looking towards the sun, because a large disturbance due to specular reflection and complex patterns in the bi-directional reflectance distribution are expected (Kimes, 1983). $Q_{660}$ is the polarized part of $R_{660}$, which means that the two optical variables are always obtained together, because a radiometer equipped with a rotating polarizer detects the intensity and the degree of polarization of incident light simultaneously (Shibayama and Akita, 2002). If the two variables provide different kinds of information about the subject, it is desirable to use both of them together. From this point of view, it seemed hopeful that $R_{660}$ could detect "topdressing," while $Q_{660}$ could detect "row width." The results of the analysis demonstrate that the process of adjusting for $Z_v$ is useful in improving the accuracy of polarization measurements, and also suggest that reflectance as well as polarization can be used to assess the state of crops.

(3) **Seasonal variations in polarized reflectance adjusted for $Z_v$**

In this study, the seasonal $Z_s$ decreased monotonically, because the radiometric measurements were made during an almost constant time period on each day (Fig. 3). Figs. 4a, 4b, and 4c show the means with the 95% confidence interval of $Q_{660}$ adjusted for $Z_v$, $R_{660}$ adjusted for $Z_v$, and NDVI observed at a nadir-viewing angle, respectively. The value of $Q_{660}$ adjusted for $Z_v$ increased from the start until heading time, and then steeply decreased (Fig. 4a), while $Z_s$ decreased monotonically during the whole period of the experiment (Fig. 3). Because the value of $Q_{660}$ adjusted for $Z_v$ at heading time was significantly larger than the value obtained 10 days before heading, changes in the geometry of the canopy stand are believed to have influenced the polarization. It is unclear whether the decrease was caused directly by the panicles emerging, or whether it should be

![Fig. 4](image-url) Seasonal profiles of radiometric variables. a: $Q_{660}$ adjusted for $Z_v$, b: $R_{660}$ adjusted for $Z_v$, and c: NDVI.

| Optical parameter | Factor       | 97  | 103  | 113  | 128  | 132  | 146  |
|-------------------|--------------|-----|------|------|------|------|------|
|                   | Day of year (2004) |     |      |      |      |      |      |
| $Q_{660}$ adjusted for $Z_v$ | Row width | 3.64 | 45.60** | 2.79 | 0.16 | 1.89 | 0.41 |
|                   | Topdressing  | 97.79** | 389.98** | 2.99 | 1.10 | 0.46 | 0.83 |
|                   | Interaction  | 0.68 | 22.75* | 3.49 | 0.10 | 2.29 | 0.00 |
| $R_{660}$ adjusted for $Z_v$ | Row width | 4.28 | 5.62 | 2.38 | 14.52* | 6.29 | 1.72 |
|                   | Topdressing  | 10.70 | 10.14 | 0.76 | 0.08 | 23.62* | 5.05 |
|                   | Interaction  | 5.51 | 0.11 | 0.59 | 7.11 | 1.03 | 0.06 |
| NDVI              | Row width | 0.16 | 1.87 | 8.63* | 1.54 | 11.83* | 0.48 |
|                   | Topdressing  | 0.44 | 0.34 | 0.00 | 12.70* | 0.77 | 28.05** |
|                   | Interaction  | 0.78 | 4.15 | 1.72 | 17.01* | 54.35** | 73.66** |

**, *: Significant at 0.1% and 1% level, respectively.
attributed to another factor, such as the distribution of leaf inclination. On the other hand, the value of $R_{660}$ adjusted for $Z_v$ was relatively constant before heading, and decreased after heading to reach its minimum in the middle of the maturing period (Fig. 4b). The NDVI observed vertically was almost constant during the whole measurement period, which indicates that the green leaf area changed little in this period (Fig. 4c). This is why NDVI is commonly used as an index for assessing the green leaf area of vegetation.

These results show that polarization is usable to detect the heading time of wheat crops, even though vegetation indices such as NDVI are not able to distinguish headed canopies from those still booting. Although the reflectance adjusted for $Z_v$ in the red band also decreased after heading, the values obtained at around heading time (DOYs 103 and 113) and afterwards during the maturing period (DOY 146), were too close to be distinguished clearly (Fig. 4b).

(4) Cultivation conditions affecting polarized reflectance

Table 2 shows the F-obs values calculated from the analysis of variance of the data for each day. Of the parameters tested for whole days, the values of $Q_{660}$ observed on 12 April (DOY 103) and 6 April (DOY 97) adjusted for $Z_v$ gave the largest and second largest F-obs values, respectively, for the factor “topdressing.” The value for $Q_{660}$ observed for the canopies with a row width of 40 cm and adjusted for $Z_v$ was significantly greater than that for the canopies with a row width of 20 cm (Fig. 5). Although the application of topdressing increased the value of $Q_{660}$ adjusted for $Z_v$, the effect was more significant for the canopies with a row width of 20 cm. This interaction was indicated by the significantly larger F-obs of the interactive term ($= 22.8$). Polarized reflectance was an effective indicator for detecting the nutritional state and the row width at approximately 10-16 days before heading time. During this period, ordinary reflectance and NDVI are not helpful in determining cultivation conditions (Fig. 5).

(5) Plant canopy parameters and polarization at the booting stage

The unadjusted value of $Q_{660}$ observed for values of $Z_v$ from 15° to 75° on 12 April (the booting stage, DOY 103) demonstrated that $Q_{660}$ at larger values of $Z_v$ could be used to determine the canopy conditions more clearly (Fig. 6). When $Z_v$ was 60° or 75°, with the value for $Q_{660}$ observed for the plot noted in the form (row width, topdressing), was lowest in the form (20 cm, no topdressing), and increased in (20 cm, topdressing applied), (40 cm, no topdressing) and (40 cm, topdressing applied) in this order. This means that wider row widths and the application of topdressing increased the degree of polarization in the reflected light. Photographs of the uprooted plants show the typical appearance of the plants (Fig. 7). Topdressing increased the number of leaves and the length of each leaf, and it is thought that it enlarged the horizontal areas of the leaves. Plant hills from the plot with row widths of 40 cm had a larger biomass than those from the plot with row widths of 20 cm. To identify the causes of the phenomena observed, the canopy parameters, including information on the stand geometry, need to be related to the polarization. The following canopy parameters were obtained for the four wheat plots during the booting stage (Table 3a): the mean leaf inclination angle (MLI) estimated using the 3-D digitizer, the LAI and the mean tip angle (MTA) measured by the plant canopy analyzer LAI-2000, leaf greenness measured by the SPAD-502, and the plant height. The MLI and the MTA are highly correlated with each other ($r > 0.99, n = 4$) but they do not show a one-to-one match, and the following relation is obtained:

$$M_{TA} = -63.2 + 1.8 \times M_{LI}$$

(3)

It is not evident which of the MTA and MLI is more reliable. The high correlation between the MTA and
the MLI suggests that both of them may reflect the nature of the leaf angles of a plot to some extent, even though their absolute values were not very reliable (Table 3b). A negative correlation between $Q_{660}$ adjusted for $Z_v$ and MTA indicated that erectus (vertical) leaf surfaces reduced polarization (Table 3c). The height of plants showed a positive correlation with $Q_{660}$ adjusted for $Z_v$. The more planophyll (horizontal) leaves in the plots with a wider row width and the more fertilized plots increased the degree of polarization in the reflected light in the observation geometry employed. The results observed agreed with those observed by Rondeaux and Herman (1991) and Ghosh et al. (1993).

### 2. Experiment 2

#### (1) Yield components of wheat in differently dressed plots

The aboveground fresh weight and number of ears per area significantly increased in plots that were given a heavy basal dressing and topdressing at the booting stage. An analysis of variance test indicated that the grain weight increased significantly at the 1% level due to the two factors of basal dressing and jointing-stage topdressing. Booting-stage topdressing tended to increase grain yield, although the probability level was at 5%. As shown in Fig. 8, the grain yield apparently increased with the amount of fertilizer applied. Since the plots fertilized heavily produced more than 560 kg/10a in grain yield with 10.0% protein content, the tested experimental sites accomplished the expected standard yield levels (Sato et al., 1992b). Hence, they were entirely appropriate for the remote sensing

![Fig. 6. The view zenith angle and $Q_{660}$ measured for the four wheat canopies under different cultivation conditions. Measurements were made at the booting stage (DOY 103).](image)

![Fig. 7. Plants uprooted for 3-D digitizing at the booting stage (12-16 April).](image)
Table 3a. Parameters of the wheat plant canopies surveyed during the booting stage.

| Topdressing (gN\textsuperscript{m\textsuperscript{-2}}) | 0   | 2   | 0   | 2   |
|-------------------------|-----|-----|-----|-----|
| MLI (3SPACE Isotrak-II)\(\textsuperscript{1)}\) (°) | 68.9| 66.4| 66.3| 65.9|
| LAI (LAI-2000)\(\textsuperscript{2)}\) (m\textsuperscript{2}m\textsuperscript{-2}) | 3.7 | 4.4 | 4.7 | 5.9 |
| MTA (LAI-2000)\(\textsuperscript{2)}\) (°) | 61  | 57  | 56  | 52  |
| Leaf greenness (SPAD-502 reading)\(\textsuperscript{3)}\) (unit less) | 40.4| 45.0| 43.7| 47.4|
| Plant height\(\textsuperscript{3)}\) (cm) | 50.2| 50.7| 56.3| 55.9|

Dates of measurement. \(\textsuperscript{1)}\): DOY103-107, \(\textsuperscript{2)}\): DOY113, \(\textsuperscript{3)}\): DOY103.

MLI: mean leaf inclination angle measured using a 3-D digitizer.
LAI: leaf area index measured by a plant canopy analyzer.
MTA: mean tip angle measured by a plant canopy analyzer. (≈ MLI)
Leaf greenness: mean of the optical sensor (SPAD-502) readings to detect chlorophyll content of each leaf.

Table 3b. Correlation coefficients among the canopy data shown in Table 3a.

| MLI (3SPACE Isotrak-II)\(\textsuperscript{1)}\) | 1 |
| MLI (3SPACE Isotrak-II)\(\textsuperscript{1)}\) | 1 |
| LAI (LAI-2000)\(\textsuperscript{2)}\) | −0.225 | 1 |
| MTA (LAI-2000)\(\textsuperscript{2)}\) | 0.996\(\textsuperscript{*}\) | −0.231 | 1 |
| Leaf greenness (SPAD-502)\(\textsuperscript{3)}\) | −0.977\(\textsuperscript{*}\) | 0.250 | −0.954\(\textsuperscript{*}\) | 1 |
| Plant height\(\textsuperscript{3)}\) | −0.723 | 0.376 | −0.781 | 0.577 | 1 |

Dates of measurement. \(\textsuperscript{1)}\): DOY103-107, \(\textsuperscript{2)}\): DOY113, \(\textsuperscript{3)}\): DOY103.

\(\textsuperscript{*}\): Significant at 5\% level. Number of observations (n)=4.

Table 3c. Correlation coefficients between the radiometric variables and plant canopy parameters.

| Q\textsubscript{660} \textsuperscript{adjusted for } Z\textsubscript{v} | R\textsubscript{660} \textsuperscript{adjusted for } Z\textsubscript{v} | NDVI |
|-------------------------|-------------------------|-------------------------|
| MLI (3SPACE Isotrak-II)\(\textsuperscript{1)}\) | −0.887 | −0.163 | −0.554 |
| LAI (LAI-2000)\(\textsuperscript{2)}\) | 0.490 | 0.171 | 0.833 |
| MTA (LAI-2000)\(\textsuperscript{2)}\) | −0.917\(\textsuperscript{*}\) | −0.252 | −0.519 |
| Leaf greenness (SPAD-502)\(\textsuperscript{3)}\) | 0.802 | −0.041 | 0.648 |
| Plant height\(\textsuperscript{3)}\) | 0.938\(\textsuperscript{*}\) | 0.788 | 0.294 |

Dates of measurement. \(\textsuperscript{1)}\): DOY103-107, \(\textsuperscript{2)}\): DOY113, \(\textsuperscript{3)}\): DOY103.

\(\textsuperscript{*}\): Significant at 10\% level. \(\textsuperscript{\dagger}\): \(\textsuperscript{\ddagger}\): Number of observations (n)=4.
(2) Radiometric observations on heading stage

Table 4 shows the values of F-obs obtained from the analysis of variance test of the radiometric data. Among the tested radiometric variables, the value of NDVI observed at $Z_{v}=45^\circ$ gave the largest F-obs value ($=23.11$) for the factor of basal dressing. Fig. 9a graphically demonstrates the effects of fertilization on the value of NDVI observed at $Z_{v}=45^\circ$. This result might be due to the sensitivity of NDVI for the green leaf area that should be increased depending on the amount of basal dressing. The NDVI observed at values of $45^\circ$ also gave the largest F-obs value ($=7.41$) for the factor of booting-stage topdressing. This might be due to the changes in the red band reflectance $R_{660}$ used for calculating NDVI. The booting-stage topdressing applied 10 days before heading might decrease the $R_{660}$, probably due to the increase in leaf chlorophyll content. In fact, the value of $R_{660}$ observed at $Z_{v}=60^\circ$ for the plots given the booting-stage topdressing was lower than that of the other plots (Fig. 9b).

Although the F-obs ($=4.83$) was greater than $F_{0.05}$, it might not be sufficient to make confident statistical decisions due to the fact that multiple statistical tests are used.

Jointing-stage topdressing increased grain yield significantly (Fig. 8). However, the influence of the topdressing on the plant canopies was hardly recognized by either field survey and/or eye-observation. Assuming that a larger F-obs value indicates a better parameter for that factor, the value of $Q_{660}$ observed at $Z_{v}=60^\circ$ was the most effective indicator for jointing-stage topdressing among all the optical parameters tested (F-obs = 72.15). The values of $Q_{660}$ observed at $Z_{v}=60^\circ$ measured for those plots that received the jointing-stage topdressing were shown to be clearly larger than those without it (Fig. 9c). We speculate that the jointing-stage topdressing, which significantly increases the grain yield, raised the polarized reflectance by causing changes in the leaf inclination angle. The geometry of the view used

### Table 4. F-values (F-obs) derived from the analyses of variance of the radiometric data measured on the heading stage.

| Factor               | Q660  | R660   | NDVI   |
|----------------------|-------|--------|--------|
|  | $Z_v = 30^\circ$ | $Z_v = 45^\circ$ | $Z_v = 60^\circ$ | $Z_v = 30^\circ$ | $Z_v = 45^\circ$ | $Z_v = 60^\circ$ | $Z_v = 30^\circ$ | $Z_v = 45^\circ$ | $Z_v = 60^\circ$ |
| Basal dressing (BD)  | 1.80  | 0.43   | 10.12* | 0.70   | 3.91* | 0.22   | 13.11** | 23.11** | 4.70*   |
| Jointing-stage topdressing (JT) | 2.49  | 18.24** | 72.15** | 2.50   | 7.32* | 0.28   | 10.98*  | 49.69** | 6.92*  |
| Booting-stage topdressing (BT)  | 0.99  | 0.38   | 0.00   | 0.84   | 2.79  | 4.83* | 3.43   | 7.41*   | 5.34*   |
| BD × JT              | 0.28  | 1.60   | 0.92   | 0.59   | 0.54  | 0.63   | 3.61*  | 2.36    | 0.79    |
| BD × BT              | 1.81  | 0.06   | 0.16   | 0.17   | 0.61  | 0.10   | 0.04   | 0.89    | 0.36    |
| JT × BT              | 0.77  | 0.17   | 0.50   | 0.00   | 1.84  | 0.40   | 0.06   | 3.05    | 0.14    |
| BD × JT × BT         | 0.82  | 0.84   | 2.96   | 0.99   | 0.16  | 0.63   | 2.21   | 2.63    | 0.04    |

**, *: Significant at 0.1 and 1% level, respectively.

*: Larger than $F_{0.05}$, but not enough to conclude it to be significant. See text.

![Fig. 9. Radiometric variables measured at the heading stage, and plotted against fertilization conditions. a: NDVI, b: $R_{660}$ adjusted for $Z_v$, and c: $Q_{660}$ adjusted for $Z_v$.](image-url)
for observation and the relationship with the angle of the sun almost satisfied Eq. (2). Accordingly, the values for $\Omega_{660}$ observed at $Z_v = 60^\circ$ in this experiment can be considered to be adjusted for $Z_v$. This might help improve the accuracy of attempts to distinguish between plots with and without the jointing-stage topdressing.

Conclusions

The polarization of reflected light acquired at specific view angles corresponding to the solar elevation clearly detected the heading stage, which is a practically important stage in wheat cultivation. Simply adjusting the viewing angle according to the elevation of the sun at the time of measurement worked well, not only for polarization but also for reflectance, and increased the reliability of measurements. Polarization distinguished cultivation conditions such as the width of rows and jointing-stage topdressing, which eventually affects grain yield. Polarization is closely related to the leaf inclination angle, which was obtained using a 3-D digitizer and a plant canopy analyzer. These findings imply that polarization data acquired at specific view angles are useful to obtain canopy structural information. However, this information has not been thoroughly processed. There is a need for further study into methods of estimating geometrical parameters for canopies using polarization. In future studies, the leaf inclination angle (MTA or MLI) should be measured at the same time as radiometry measurements are performed, to identify the relationship between fertilization and the stand geometry of the canopies. The results also indicate that the combined use of polarization and reflectance (including NDVI) with adjusted viewing angles is a promising method for inclusive assessing of wheat canopies.

For future utilization of polarimetry from air-, and/or space-borne optical sensors, the Japan Aerospace Exploration Agency (JAXA) has already developed imaging spectropolarimeters for polarimetric analysis of solar rays reflected from the Earth’s surface (Shingu et al., 2002), and efforts are currently underway to realize the practical application of the sensors for monitoring crop situation and identifying grass species (Homma et al., 2005). This new technique provides us with a reliable tool for diagnosing growth in a practical way by detecting changes in productive structure.

Acknowledgements

The authors acknowledge Dr. S. Goto at NIAES for the loan of the LAI-2000 used in this research. We also thank Messrs F. Suzuki, T. Suzuki, T. Ara and Mrs. M. Sakai at NIAES, and Mr. H. Ino at NARO/NICS for their help in collecting field data. Professor T. Akiyama of Gifu University provided extremely helpful comments on the manuscript. The submission of SAS was performed with the assistance of the Computer Center for Agriculture, Forestry and Fisheries Research, MAFF, Japan. This work was partly supported by the research program “Methodology Development for Prediction of Food Balance According to Global Environmental Changes” funded by MAFF.

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