Testing Polarization Measurements with Adjusted View Zenith Angles in Varying Illumination Conditions for Detecting Leaf Orientation of Wheat Canopy

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Abstract: The previous work revealed that the polarization of light reflected from heading wheat canopies allowed the detection of changes in the canopy structure, i.e., the leaf inclination angle. Accordingly, in order to improve measurement accuracy in this study we examined the effects of the solar zenith angle (=90°–solar elevation) and weather conditions at the time of polarization measurements for the light reflected from wheat canopies that were fertilized by different means. We measured polarization in the 660 nm spectral band from the heading canopies of wheat, which were grown in plots fertilized with a basal dressing and then top-dressed at the jointing and booting stages. The radiometric measurements were carried out at various solar zenith angles: 22°–41° on two proximal days, one overcast and the other clear. An empirical method for the adjustment of view zenith angle, based on the solar position at the time of measurement, was effective for the measurement of the degree of polarization (i.e., ratio of the polarized part of reflected light to the total reflected light energy) to eliminate interference due to the change in solar zenith angle. Although the mean values of polarization degree measured in overcast conditions were significantly lower than those measured under clear conditions, the plots top-dressed at the jointing stage could be detected via the polarized reflected light measured under both conditions of illumination.

Key words: Jointing-stage top-dressing, Mean tip angle, Polarization, Remote sensing, View zenith angle, Wheat.

Takahashi and Nakaseko (1993a) measured seasonal changes in the distribution of the interception of photosynthetically active radiation (PAR) in wheat canopies and showed that the PAR intercepted by the flag leaf increased from the anthesis to the milk-ripe stage as the flag leaf reclined from the erect position to a horizontal one. Then, they discussed the relationship between the varietal difference in the morphology of spring wheat canopies and its impact on crop production based on field data obtained using PAR sensors and a leaf area meter (Takahashi and Nakaseko, 1993b). These morphological characteristics (including leaf angles) are important in plant breeding as a means of selecting varieties or lines that offer high yields. Quick, non-destructive methods that can detect relative differences in the canopy structures of varieties and lines could help improve the efficiency of pedigree selection, for example. However, the procedures for collecting such field data may take considerable time and effort, even with the availability of modern machinery and computers. It is therefore preferable that the remote detection of leaf-layer structural information be available in order to facilitate the prompt examination of varietal traits for breeders.

In farm practices, the remote sensing of plant canopy structure for wider areas may assist in precision farming through the quicker diagnosis of crop nutrient conditions and dry-matter production capability. This could in turn reduce the environmental load through the proper timing and amounts of fertilizer input, which could also influence canopy structure (Inamura et al., 2004). Spectral observations of reflected solar light from crop canopies using devices ranging from hand-held radiometers on the ground to space-based image sensors may be promising, given the potential of intensively collecting the data required for wider crop fields with less effort (e.g., Asaka et al., 2006; Akiyama, 2007). However, the canopy structure is usually so complicated that few practical techniques using reflected light have been established as means to remotely assess the structure of leaf layers.

A previous study (Shibayama and Watanabe, 2007) demonstrated the relationship between the polarization of light reflected from wheat canopies at the heading stage and a plant-canopy parameter: the mean inclination angle of leaves (i.e., mean tip angle or MTA) measured using a plant canopy analyzer (LAI-2000, LI-COR, Inc., Lincoln, Nebraska, USA).
The study used the MTA to measure the mean leaf-inclination angle or the mean tilt angle of the wheat canopy, given that a previous study had shown it to be highly correlated with the results obtained using a 3-D digitizer (Shibayama and Watanabe, 2006). The lower MTA indicates that the more nearly horizontal leaf surfaces (not the nearly vertical ones) are dominant throughout the entire leaf area, which may effectively increase the polarized part in the reflected light from the canopy (Vanderbilt et al., 1985).

Simple linear regression models were introduced in the previous study so as to estimate MTA values using the measured polarized part of radiant coefficient (i.e., ratio of the polarized part of reflected light to the incident light intensity). The variable in a single visible band whose view zenith angle was adjusted to the solar zenith angle was found to be effective in predicting the MTA. However, certain discrepancies remain unsolved among the intercepts of the model equations obtained in different cropping seasons, despite the apparently common slopes among them (Shibayama and Watanabe, 2007). Naturally, relative or comparative observations for the crop canopy using reference or control canopy measurements resolve the problem, as in a breeder's line test. However, a reference or control crop canopy might not always be available near to the targeted field, for instance. Hence, parameters that are absolute so that measurements can be compared to those obtained at other occasions and sites should be preferable and applicable in the remote sensing of crops. We assumed the problems would mainly be attributable to the different physical conditions occurring during measurements, namely the solar position and weather. To reduce the uncertainty of measurements due to such physical conditions, we considered the following points.

First, the previous study compared the performance of the polarized part of the radiant coefficient (i.e., ratio of polarized part of reflected light to incident light intensity) with that of the radiant coefficient (i.e., ratio of reflected light intensity to incident light intensity), where the latter variable is roughly close to the widely used “reflectance” or “reflectance factor” in the resultant values observed in the field. However, the degree of polarization (i.e., ratio of the polarized part of reflected light to the total reflected light energy) still has not been tested thoroughly. The variable “degree of polarization” may be more robust against changes in illumination because the formula excludes the term of incident light intensity.

Secondly, the diurnal stability of the resultant polarization values has not been studied with the same plots of wheat within a time interval that would allow no significant changes in plant-canopy parameters such as MTA. Consequently, to evaluate the reliability of the technique it is necessary to measure practically the same targets under different conditions of illumination. Actually, the diurnal stability of observations is related to the changes in the solar zenith angle at the time of measurement. Moreover, the polarization measurement technique itself has to date only been examined under clear weather conditions. From a practical standpoint, the applicability of this method should also be tested under different light environments such as overcast conditions.

The objectives of this study were to test the performance of the three radiometric variables—the radiant coefficient, the polarized part of radiant coefficient and the degree of polarization with or without the adjusted view angles against the solar zenith angle—and to examine such performance on an overcast day.

To evaluate the effects of solar zenith angle and weather conditions on the method used, we first selected better radiometric variables by assessing the efficiency of discrimination for differently fertilized plots using the analysis-of-variance (ANOVA) and analysis-of-covariance (ANOCVA) tests. Subsequently, linear regression analysis was applied to test the usability of the selected variables in estimating MTA values.

A previous study found that spectral responses were rather broad in the visible wavelength range and that polarization was weak in the near-infrared range (Shibayama and Watanabe, 2007). Accordingly, the spectral band used in this study is restricted to the visible red band centered at 660 nm.

Materials and Methods

1. Radiometric variables observed

The ratio of reflected light intensity to the calculated solar irradiance at the top of the atmosphere is the radiant coefficient \( R \) (Emori and Yasuda, 1985). The value of \( R \) is comparable to the reflectance factor if atmospheric effects are ignored. In this paper the polarized part of \( R \) is expressed as \( Q \) (%). The ratio of \( Q \) to \( R \) is the degree of polarization \( P \) (no unit). \( P \) is defined as the ratio of the polarized part of reflected light to the total reflected light energy (Vanderbilt et al., 1985). In this paper, \( R \), \( Q \) and \( P \) as measured in the visible red band centered at 660 nm, are referred to as \( R_F \) (%), \( Q_F \) (%) and \( P_F \), respectively. The procedure for measuring radiometric variables was based on Ghosh et al. (1993) and Shibayama (2004). The short-wave solar radiation accumulated hourly (MJ m\(^{-2}\) hr\(^{-1}\)) was measured by an automatic meteorological observatory located in the neighborhood of the experimental wheat field on the measurement days.

2. Experimental wheat plants and the plant-canopy parameters measured

Details of the experimental site were given in the previous paper (Shibayama and Watanabe, 2007). Plots of a wheat variety \( Triticum aestivum \) L. cv., “Norin-61)” were established in the site. The wheat seeds were
sown on 10 November 2005 in east-west rows at a row width of 30 cm in a field having an area of 500 m². A basal fertilizer dressing was applied with compound fertilizers (N:P₂O₅:K₂O = 6:9:6) and ammonium sulfate at three rates (4, 6 and 8 g N m⁻²), a jointing-stage top-dressing was applied with ammonium sulfate at two rates (0 and 2 g N m⁻² on 11 March 2006), and a booting-stage top-dressing was applied at two rates (0 and 1 g N m⁻² on 21 April). Two replicates were included in the experimental design so that the entire field was divided into 24 plots of identical area (4.5×3 m) after the final top-dressing. The first heading was observed on 29 April.

On 28 April, when the second radiometric observations were carried out, a plant canopy analyzer was used on the targeted wheat stands to estimate the LAI and mean tip angle (MTA) of the canopies (Welles and Norman, 1991). Four below-the-canopy measurements were repeated at three different locations in each plot. On randomly selected three-plant hills in each plot, the plant heights (PH, cm) above ground level were manually measured and averaged. The leaf greenness (used as an indicator of leaf chlorophyll content per unit leaf area) was measured using a hand-held optical sensor (SPAD-502, Konica Minolta, Inc., Tokyo, Japan). The digital reading of the SPAD-502, commonly known as the “SPAD-value” or “SPAD,” is widely used as an indicator of the chlorophyll content of a single leaf. We used the value of “SPAD” as a direct measure of leaf greenness without converting the value into chlorophyll content. We measured and averaged the values of SPAD recorded at the middle parts of 15 randomly selected upper leaf blades in each canopy.

3. Radiometric observations

A portable spectropolarimeter (Donarec Co., Ltd., Machida, Tokyo) was used to measure the light intensity and degree of polarization in the wavelength band 660 nm (Shibayama and Akita, 2002). Radiometric observations were performed on two days: 26 and 28 April 2006. The wheat plants were at the heading stage. The weather condition on the first day was overcast, and on the second day the weather was clear. The observations on the first day were carried out between 0907 and 1107 (JST) and from 0943 to 1217 on the second day. Measurements were successively carried out twice for the site on each day.

We abbreviate the view zenith angle of the sensor and the solar zenith angle as Zv (°) and Zs (°), respectively. The Zs value during the observations ranged from 41° to 24° on 26 April, and from 34° to 22° on 28 April. The radiometric sensing unit of the spectropolarimeter was set on a 1.6m-tall tripod that stood at the north end of each plot, and observations were carried out with values for Zv of 45°, 60° and 75°. The FOV (field of view) of the radiometric system was 10°. The variation in the area of the viewing ellipse of the sensor (depending on Zv and the distance between the sensing unit and the target) was not considered. The distance between the sensing unit and the target did not affect the observed polarization when the crop canopies were well developed (Shibayama and Akita, 2002). The azimuth direction of the view of the sensing unit was always oriented toward the sun.

4. View zenith angle adjustment

The procedure used to adjust the values of Zv measured at a given Zs was proposed by Shibayama (2004) and tested by Shibayama and Watanabe (2006, 2007). The practical value of Zv ( = Zv') required for observations at a given solar zenith angle (Zs=90°–solar elevation) is calculated using the empirically introduced equation:

\[ Zv' = 35° + Zs, \quad Zs < 55° \]  \hspace{1cm} (1).

Considering the FOV of the instrument used (10°), the permissible limit of Zv' is approximately 75°, which provides for a maximum Zs value of 40°. Fortunately, the value of Zs seldom exceeds 40° during the practical measurement time (0900–1300) at the heading stage of wheat (late April) at the test site (36° 00' N, 140° 01’ E). Fig. 1 is a conceptual image of the view zenith angle relative to the solar zenith angle at the time of measurement. A hypothetical smooth plane is illustrated in the plant canopy, and theoretically it provides the largest polarization at Zv=40° and Zs=75° (the normal angles) on the assumption that the refractive index of the plane is 1.5. The observer reduces the value of Zv from 75° as much as the decreased angle of Zs ( = D°). The normal zenith angles of the sun and sensor, as well as the adjusted angles, are shown with the respective symbols (a) and (b).

![Fig. 1. Schematic of the method for adjusting the view zenith angle relative to the solar zenith angle at the time of measurement. A hypothetical smooth plane is illustrated in the plant canopy, and theoretically it provides the largest polarization at Zv=40° and Zs=75° (the normal angles) on the assumption that the refractive index of the plane is 1.5. The observer reduces the value of Zv from 75° as much as the decreased angle of Zs ( = D°). The normal zenith angles of the sun and sensor, as well as the adjusted angles, are shown with the respective symbols (a) and (b).]
radiometric variables $R_r$, $Q_r$ and $P_r$ observed at the value of $Z_v$ are referred to as $R_r(Z_v)$, $Q_r(Z_v)$ and $P_r(Z_v)$, respectively. Likewise, the radiometric variables estimated using values of $Z_v'$ calculated using equation (1) are referred to as $R_r(Z_v')$, $Q_r(Z_v')$ and $P_r(Z_v')$, respectively.

5. Analysis of data

The plant-canopy parameters and radiometric variables were investigated through analysis-of-variance (ANOVA) tests and analysis-of-covariance (ANOCVA) tests using a software package for microcomputers (JMP, version 4, SAS Institute Inc., Cary, North Carolina, USA). For the ANOVA tests the statistical model was a linear combination of the factors “basal dressing,” “jointing-stage top-dressing,” “booting-stage top-dressing,” “weather” and $Z_v$. The first four variables were ordinal predictor variables (fertilizer levels and illumination levels), and the last one was a continuous-predictor variable. The dependent variables tested were $R_r(Z_v')$, $Q_r(Z_v')$ and $P_r(Z_v')$. Moreover, $R_r(60^\circ)$, $Q_r(60^\circ)$ and $P_r(60^\circ)$, being the variables measured at the $Z_v$ value of $60^\circ$, were included in the analysis. Optionally, the $Z_v$ value of $60^\circ$ was selected as one of the typical fixed-view angles, and it was the central value of the three view zenith angles employed.

To evaluate the above-mentioned radiometric variables, linear regression models—which consisted of the MTA value and a dummy variable “weather” as the predictor variables—were employed to estimate the radiometric variables.

The total observations analyzed were 24 (=3×2×2×2) for the plant-canopy parameters. The preliminary data survey indicated that one radiometric observation should be omitted as an outlier from the data set. Thus the total observation analyzed amounted to 95 (=24 plots×2 repetitions×2 days-1) for the radiometric variables.

1. Illumination conditions during radiometric measurements

Hourly accumulated short-wave solar radiation energy (MJ m$^{-2}$ hr$^{-1}$), as measured by an automatic meteorological observatory located close to the site on each day, was plotted against the time of day in Fig. 2. The incident light intensities of 2.11-2.48 MJ m$^{-2}$ hr$^{-1}$ on the overcast day and 2.84-3.35 MJ m$^{-2}$ hr$^{-1}$ on the clear day were observed during the measurements, respectively. Data at shorter time intervals were not collected on-site. The mean short-wave solar energy during observations on the overcast day was approximately 74% relative to that of the clear day.

In the ANOCVA tests the statistical model used was a linear combination of the factors “basal dressing,” “jointing-stage top-dressing,” “booting-stage top-dressing,” “weather” and $Z_v$. The first four variables were ordinal predictor variables (fertilizer levels and illumination levels), and the last one was a continuous-predictor variable. The dependent variables tested were $R_r(Z_v')$, $Q_r(Z_v')$ and $P_r(Z_v')$. Moreover, $R_r(60^\circ)$, $Q_r(60^\circ)$ and $P_r(60^\circ)$, being the variables measured at the $Z_v$ value of $60^\circ$, were included in the analysis. Optionally, the $Z_v$ value of $60^\circ$ was selected as one of the typical fixed-view angles, and it was the central value of the three view zenith angles employed.

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The averaged values and the standard deviations of $R_r (Z_v')$, $Q_r (Z_v')$ and $P_r (Z_v')$ measured in the 660 nm band with adjusted view zenith angles ($Z_v'$) against the solar zenith angles for the targeted wheat plots at the heading stage on 26 and 28 April 2006; mean values and standard errors (SE).

| Factor                        | Amount of applied nitrogen (g N m$^{-2}$) | $R_r (Z_v')$±SE (%) | $Q_r (Z_v')$±SE (%) | $P_r (Z_v')$±SE |
|-------------------------------|------------------------------------------|--------------------|--------------------|----------------|
| Basal dressing                | 4                                        | 3.19±0.091         | 0.164±0.013        | 0.052±0.0037   |
|                               | 6                                        | 3.14±0.092         | 0.191±0.013        | 0.061±0.0038   |
|                               | 8                                        | 3.15±0.091         | 0.188±0.013        | 0.060±0.0037   |
| Jointing-stage top-dressing   | 0                                        | 3.26±0.074         | 0.151±0.010        | 0.047±0.0030   |
|                               | 2                                        | 3.06±0.075         | 0.212±0.010        | 0.069±0.0030   |
| Booting-stage top-dressing    | 0                                        | 3.22±0.074         | 0.186±0.010        | 0.058±0.0030   |
|                               | 1                                        | 3.10±0.075         | 0.177±0.010        | 0.057±0.0030   |

The different letters beside the means indicate the difference between the pair of means that was significant in the Tukey HSD test at the 5% levels. The absence of a letter indicates the lack of significance among the means.

Table 3. Summary of the analysis of covariance (ANOCVA) tests for the radiometric variables using the fertilization levels, weather conditions and solar zenith angles at the time of measurement. The radiometric variables are radiant coefficient ($R_r (60^\circ)$, %), polarized part of radiant coefficient ($Q_r (60^\circ)$, %), degree of polarization ($P_r (60^\circ)$, no unit) measured in the 660 nm band at the fixed view zenith angle of 60°, and the same ones but with adjusted view angles ($Z_v'$) against the solar zenith angles ($R_r (Z_v')$, $Q_r (Z_v')$ and $P_r (Z_v')$, respectively). The F-values obtained for the predictor variables, $R^2$ and RMSE (root mean square error) values are shown.

| Predictor variable | $R_r (60^\circ)$ | $Q_r (60^\circ)$ | $P_r (60^\circ)$ | $R_r (Z_v')$ | $Q_r (Z_v')$ | $P_r (Z_v')$ |
|-------------------|------------------|------------------|------------------|--------------|--------------|--------------|
| Basal dressing (3°) | 2.3              | 0.8              | 2.5              | 0.4          | 2.8          | 4.3*         |
| Jointing-stage top-dressing (2°) | 22.2*** | 11.4** | 30.4*** | 27.0*** | 27.9*** | 49.4*** |
| Booting-stage top-dressing (2°) | 3.9              | 1.9              | 1.0              | 3.5          | 0.8          | 0.2          |
| Weather condition (2°) | 26.9*** | 78.8*** | 75.4*** | 29.1*** | 88.5*** | 84.8*** |
| Solar zenith angle | 39.0*** | 17.4*** | 7.7*** | 268.4*** | 33.5*** | 3.8          |
| $R^2$              | 0.44             | 0.53             | 0.58             | 0.78         | 0.60         | 0.65         |
| RMSE               | 0.29             | 0.06             | 0.017            | 0.25         | 0.51         | 0.015        |

*, **, ***. Significant at the 5%, 1% and 0.1% levels, respectively. †, Number of levels for the ordinal predictor variable. ++, Continuous predictor variable (°).

The averaged values and the standard deviations of $R_r (Z_v')$ on the overcast day and the clear day were 3.28 ±0.6% (n =47) and 3.05±0.4% (n =48), respectively. Similarly, 0.14±0.07% and 0.22±0.06% were obtained for $Q_r (Z_v')$, and 0.043±0.0189 and 0.072±0.0183 were observed for $P_r (Z_v')$. Statistical F-tests for the differences in the pairs of variances indicated that the variance for $R_r (Z_v')$ on the overcast day was significantly ($p<0.05$) greater than the one obtained on the clear-sky day. However, there was no significant difference in the variances of their polarization variables--$Q_r (Z_v')$ and $Pr (Z_v')$—measured amid the two weather conditions.

2. Effects of fertilization levels on plant-canopy parameters

The booting-stage top-dressing had little effect on the four test parameters, probably due to the short duration (5 or 7 days) between its application and the measurements (Table 1). The basal fertilizer levels of 6 and 8 g N m$^{-2}$ elongated the PH about 8-9 cm over 4 g N m$^{-2}$, and the averaged LAI of those plots that received 8 g N m$^{-2}$ was 2.7, which was significantly ($p < 0.05$) greater than the others’ values, which were around 2.0. The mean MTA of the plots that received the basal dressing at 4 g N m$^{-2}$ was approximately 63° but around 60° in the other plots, while the Tukey HSD test at 5% levels indicated no significant difference among them. The jointing-stage top-dressing at the level of 2 g N m$^{-2}$ increased the SPAD values, indicating that the leaf greenness in the plots was significantly deeper than the ones that were not top-dressed. The jointing-stage top-dressing seemed to increase the mean values of PH and the LAI but decreased the mean MTA values from 62° to 59°, though no significant difference was detected.

3. Effects of fertilization levels on $R_r(Z_v')$, $Q_r(Z_v')$ and $P_r(Z_v')$

Table 2 summarizes the ANOVA tests for the combined data set of the three radiometric variables...
Regarding $R_r (Zv')$, the radiant coefficient in the 660 nm showed a slight decline in plots that received the jointing- and booting-stage top-dressings with no significant difference at the 5% levels. Moreover, $Q_r (Zv')$ and $P_r (Zv')$ showed no significant difference relative to the factors of basal and booting-stage top-dressings. However, the jointing-stage top-dressing significantly increased these polarimetric variables of the plots relative to those from the plots without fertilization.

4. Effects of view zenith angle adjustment and weather conditions on $R_r$, $Q_r$ and $P_r$ with changing $Z_s$

The ANOVA tests indicated that the view zenith angle adjustment employed could significantly improve the accuracy of detecting the plots fertilized at the jointing stage.

Table 3 shows the F-values calculated for the five predictor variables regressed to the six radiometric variables on the extreme left-hand column. The factor “jointing-stage top-dressing” most noticeably influenced the radiometric variables among the three fertilizer applications. The F-values for the factor “jointing-stage top-dressing” in the view-adjusted radiometric variables ($R_r (Zv')$, $Q_r (Zv')$ and $P_r (Zv')$), were greater than the fixed-view angle variables ($R_r (60^\circ)$, $Q_r (60^\circ)$ and $P_r (60^\circ)$), indicating that the view-angle adjustment improved the accuracy of models. Among the three radiometric variables, $R_r (Zv')$ was strongly influenced by $Z_s$, while $Q_r (Zv')$ was significantly affected by $Z_s$ (Fig. 3). On the other hand, the F-value for $Z_s$ in the $P_r (Zv')$ model was not statistically significant ($p > 0.05$), which suggests that $P_r (Zv')$ was independent of the solar position. $R_r (Zv')$ and $Q_r (Zv')$ increased along with $Z_s$, although $P_r (Zv')$ did not vary with the value of $Z_s$.

The factor “weather” (overcast or clear) was significant for all radiometric variables, and the F-values were somewhat greater for polarization variables ($Q_r (Zv')$ and $P_r (Zv')$) than those for $R_r (Zv')$ (Table 3). A significant difference was observed between the mean values of $P_r (Zv')$ collected on the clear day and overcast day.

5. Regressions of MTA and weather conditions to estimate radiometric variables

The three regression models were all statistically significant, which was also the case for the predictor variables MTA and the dummy variable “weather” (Table 4). The highest $R^2$-value of 0.48 was obtained for the model used to estimate $P_r (Zv')$, while 0.30 and 0.16 were obtained for the models of $Q_r (Zv')$ and $R_r (Zv')$, respectively.

Discussion

1. Effects of fertilizations on the plant-canopy parameters and radiometric variables

Previously (Shibayama and Watanabe, 2007), we proposed a polarimetric indicator that was sensitive to changes in the leaf orientation of the canopy brought about by the conditions of fertilization. In the experimental field, the MTA values at the heading-stage of the wheat canopy were reported less in the plots being fertilized at the jointing stage than in the plots without fertilization. On the other hand, the basal and booting-stage top-dressings were less
but the fertilization significantly affected polarization between the fertilization and the MTA, the leaf epidermis (Vanderbilt et al., 1985). Polarization is considered to be more sensitive to significant greater in the more fertilized plots. The estimated partial regression coefficients (b), their t-values (t) and probabilities (p), and the F-values obtained for the model, $R^2$ and RMSE (root mean square error) values are shown.

| Predictor variable | $R_r (Zv')$ | $Q_r (Zv')$ | $P_r (Zv')$ |
|--------------------|-------------|-------------|-------------|
| Intercept          | b           | t           | p           | b           | t           | p           | b           | t           | p           |
| MTA                | 0.034       | 3.38        | 0.001       | -0.0031     | -2.29       | 0.024       | -0.0014     | -3.97       | 0.0001     |
| Weather            | 0.12        | 2.37        | 0.02        | -0.039      | -5.84       | <0.0001     | -0.015      | -8.30       | <0.0001    |
| F-value            | 8.5         |             |             |             |             |             |             |             |             |
| $R^2$              |             |             |             |             |             |             |             |             | 0.48        |
| RMSE               |             |             |             |             |             |             |             |             | 0.017       |

effective with respect to the MTA changes at the heading stage. The MTA of a crop canopy at a given stage must be affected by various conditions, including the environment, cultivation techniques and varieties (Takahashi and Nakaseko, 1993b).

In this study, the application of jointing-stage top-dressing to the wheat canopies decreased the MTA values while it enlarged the LAI and elongated the PH (Table 1), although the statistical tests were not significant ($p=0.18-0.24$). The leaf greenness (SPAD) was significantly ($p<0.0001$) deeper in the plots to which top-dressing was applied. The PH and the LAI showed a positive correlation ($r=0.56$, $p<0.01$), while the MTA and the SPAD as well as the MTA and the PH had the negative correlations of $r=-0.48$ ($p<0.05$) and $r=-0.65$ ($p<0.01$), respectively. The higher PH and the larger LAI both lead to longer leaf blades, which might provide more nearly horizontal leaf surfaces than erect ones due to the increase in the area of drooping leaves (Takahashi and Nakaseko, 1993b). Eventually this results in a smaller MTA value. With the same MTA levels, the larger LAI possibly produces greater polarization due to the expansion of reflective surfaces for incident light.

The application of nitrogen fertilizer generally increases the leaf greenness. The deeper leaf greenness indicates an increase in chlorophyll content, which enhances the absorption of visible red light (Inada, 1963). This might be detected by decreasing the 660 nm (red) band radiant coefficient–$R_r (Zv')$–which dropped slightly (Table 2). By contrast, the polarization variables $Q_r (Zv')$ and $P_r (Zv')$ were significantly greater in the more fertilized plots. Polarization is considered to be more sensitive to leaf orientation than leaf color because the most polarization is provided by the specular reflection at the leaf epidermis (Vanderbilt et al., 1985).

The obtained results did not show a consistent relationship between the fertilization and the MTA, but the fertilization significantly affected polarization (Table 2). Therefore, in these experimental plots the variations in polarization due to fertilization could not be directly attributed to the changes in MTA. Of course, some measurement variations and/or errors due to the emerging panicles were likely in the MTA measurements using the plant canopy analyser, or the amount of fertilizer was insufficient, which might conceal the differences among the treatments.

Another interpretation is that the MTA could not be an only and the most appropriate parameter that explains the polarization although the MTA must be closely related to the polarization, as was shown in the regressions (Table 4). It is merely one of the various parameters that describe the structure of the leaf layer. Visible light sufficiently penetrates only the upper part of the leaf layer in the canopy. Because MTA is the mean inclination angle of the whole leaves that also distribute in the lower part of the leaf layer, it could not be the most appropriate indicator in explaining the responses of polarization. Actually, polarization may be affected not only by the MTA but also by other plant parameters such as the emergence of panicles above the canopy surface (Fitch et al., 1984). However, in this study there were no panicles above the canopy at the time of measurement.

Future study may reveal more precise information on leaf orientation using the polarized light reflected from plants. Although further studies are necessary in order to reach any firm conclusion, at this stage of research MTA is a convenient parameter for indicating the differences in the structural characteristics of targeted canopies.

2. Effects of the adjustment of view zenith angle

The obtained results indicated that the adjustment of the view zenith angle improved the accuracy and stability of the polarization measurements. This suggests that the optical technique could be applicable at different occasions and locations without reference canopy, which implies the possibility of airborne

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**Table 4.** Linear regression summary of the models using the mean tip angle (MTA) of the wheat canopies and a dummy variable “weather” (overcast or clear) to estimate the three radiometric variables: radiant coefficient ($R_r (Zv')$), polarized part of radiant coefficient ($Q_r (Zv')$), and degree of polarization ($P_r (Zv')$) and interpolated estimates at the adjusted view zenith angle. The estimated partial regression coefficients (b), their t-values (t) and probabilities (p), and the F-values obtained for the model, $R^2$ and RMSE (root mean square error) values are shown.
imaging polarimetry for diagnosing crop growth conditions in large areas (Homma et al., 2005).

Fig. 1 shows a hypothetical smooth plane in the canopy inclined 17.5° to the observer, which reflects the incident light in a specular manner at Zs=40° toward the direction of Zv=75°. The incident angle is equal to 57.5° (= (40°+75°)/2), which is close to the Brewster angle of 57.4° when the refractive index 1.5 is assumed for the plane. If the refractive index of the reflecting plane is 1.5, the illustrated observation geometry provides the largest degree of polarization in the reflected light. Polarization depends on the incident angle and the refractive index of the smooth plane (Collett, 2005). Vanderbilt et al. (1985) set the incident angle equal to 55° as the Brewster angle to measure the polarization characteristics of single leaves from several crop species. From Brewster’s law (n=tan iB: n: refractive index, iB: Brewster angle) and the Brewster angle 55°, the refractive index of the leaf surface is calculated as 1.43. This assumes that the refractive index 1.5 for wheat leaves is permissible for field studies.

View zenith angle adjustment, according to the decrease in solar zenith angle using equation (1), maintains the geometry needed to provide a specular reflection of the hypothetical plane, even though the incident and reflection angles are decreasing. Of course, polarization decreases as the incident angle grows farther from 55°, but it may give the greatest polarization at the Zs given. By increasing or decreasing the Zs value, the degree of polarization ought to decrease (when assuming a shiny surface that is flat and smooth) because the decrease in the incident angle reduces the degree of polarization (Collett, 2005). There is no theoretical basis for the existence of this hypothetical plane in the actual canopy. The observation geometry of Zs=40° and Zv=75° was originally introduced as a means to compensate for seasonal variations in the polarization of light reflected from growing wheat canopies due to seasonal changes in Zs (Shibayama, 2004). The hypothetical inclination angle (17.5°) of the virtual plane in the canopy (Fig. 1) is much smaller than the actually measured MTA range of 48° to 70° (Shibayama and Watanabe, 2007). However, wheat leaves have a continuous curvilinear shape, whereby at least some leaf surfaces ought to form areas with an inclination angle close to 17.5°.

The MTA is used to summarize the complexity of the canopy structure. Therefore, the possibility of forming surfaces with an inclination angle of approximately 17.5° can be related to the leaf-orientation distribution at the canopy’s upper layer. Canopies measured with relatively lower MTA values may have more near-horizontally oriented surfaces than those with higher MTA due to the near-vertically oriented foliages. However, it should be noted that the virtual plane in Fig. 1 was tentatively introduced as a means to explain the geometry for view zenith angle adjustment, so in the strict sense it is not a radiometric model of the canopy.

The aforementioned results indicate that the empirical method of view-angle adjustment probably works well for Pr, but its theoretical interpretation is still incomplete. Physically based models (e.g., Rondeaux and Herman, 1991) and empirical investigations may be required as the means to further our understanding of the information in polarization data (Vanderbilt et al., 1985).

3. Preferable radiometric variable for detecting leaf orientation of heading wheat

Regression summaries (Table 4) indicate that the model estimating Rr (Zv’) had a positive partial regression coefficient for MTA while the models of Qr (Zv’) and Pr (Zv’) had negative partial regression coefficients for MTA, which suggested that polarization decreased for higher MTA (more vertical foliage) canopies. This implies that polarization and radiant coefficient (= reflectance or reflectance factor) produced different information regarding the target.

The regression analyses using MTA for estimation of radiometric variables produced R²-values that were considerably more improved from 0.30 to 0.48 in the model for Pr (Zv’) than in the model for Qr (Zv’) (Table 4). Among the radiometric variables tested, the degree of polarization Pr (Zv’) was most promising, probably because the view zenith angle adjustments seemed to remove the effect of Zs (Fig. 3). Shibayama and Watanabe (2007) used Qr (Zv’) to estimate MTA instead of Pr (Zv’). Thus the causes of degradation in estimating the MTA between cropping seasons using Qr (Zv’) in the previous study will be partially resolved by the use of Pr (Zv’).

4. Effects of weather conditions

According to the statistical tests, the variances of the Qr (Zv’) and Pr (Zv’) values observed on the overcast day and the clear day did not differ from each other. This suggests that the illuminated sunlight intensity seemed stable enough to observe polarization (as far as the visible wavelength range was concerned) on both measurement days.

The variations in the Rr values observed on the overcast and clear days were significantly different (on the level of 5%), suggesting that the illuminated sunlight intensity on the ground seemed to vary more on the overcast day than on the clear day. Based on the solar irradiance at the top of the atmosphere, Rr (Zv’) and Qr (Zv’) must be affected by weather conditions. In other words, the changes in incident light energy should be corrected through calibration using a reference panel (Emori and Yasuda, 1985). In this experiment, the radiant coefficient was measured instead of the reflectance factor, because from the practical
aspect frequent readings for a reference panel take time and increase the total duration of observation. A significant difference was observed between the mean values of $Pr(Zv')$ collected on the clear day and the overcast day (Fig. 3). Increases in light diffusion in the overcast sky might reduce the intensity of polarization in reflected light due to the diverse directions of illuminating rays, which reduced the degree of polarization ($Pr(Zv')$). Therefore, quantitative predictions using $Pr(Zv')$ and a simple regression model in various weather conditions will cause inaccurate estimates because the correction for $Pr(Zv')$ measured in changing atmospheric conditions has not been established.

Although the levels of averaged values differed between the clear day and the overcast day, the use of $Pr(Zv')$ allowed the plots receiving the jointing-stage top-dressing to be distinguished on either day from those without it (Tables 2 and 3). This indicates that the degree of polarization of the reflected light is basically usable for the canopy’s structural assessments on both clear and overcast days. However, the results obtained under different weather conditions were only relative and comparative, not absolute. To improve the situation, atmospheric disturbances should be taken into consideration, not only in cases where observations are made from space or from very high altitudes (Nadal and Bréon, 1999) but also from ground-based platforms. To solve this problem, future studies will require simultaneous monitoring for atmospheric turbidity as well as incident solar radiation during radiometric measurements. Quantitative evaluations for the absolute values of canopy structural parameters under different atmospheric conditions may require further study in order to correct the measured radiometric variables.

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* In Japanese with English abstract.
** In Japanese with English title.
*** In Japanese. The authors of this paper translated the title.