A Multiband Polarimetric Imager for Field Crop Survey
—Instrumentation and Preliminary Observations of Heading-stage Wheat Canopies—

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Abstract: A spectral and polarization image observation technique for detecting multiband polarimetric characteristics of reflected light from field-growing plants under daylight conditions was developed and the potential application of the method to in-situ assessments of wheat-leaf orientation at the heading stage was assessed. The developed digital imaging system corresponded to wavelength bands centered at 470, 550, and 647 nm, each with bandwidths of 10 nm. The instrument was fitted with a glass polarizer, which rotated from 0 to 360° in 15° steps, and polarized images of 1360 ×1024 pixels were captured at heading in wheat plots subjected to different fertilizer regimes at the jointing stage. Degree of polarization (DP) and mean brightness (MB) of the three bands were calculated from images of several pairs of top-dressed and non-top-dressed (non-dressed) plots, with a camera depression angle of 15–20° on two clear days. The relative azimuth angles between the view and insolation were approximately 135° (oblique front) and 180° (right in front), respectively. The mean DP for each plot area in the images varied between 0.3 and 1.4%. Although most of the top-dressed plots had significantly higher DPs than the non-dressed plots in the 550 nm band, few of the MB images in any band showed a clear difference between the top-dressed and non-dressed plots.

Key words: Digital image, Leaf inclination, Multiband, Polarization, Wheat.
use of polarization for field crop measurements is relatively uncommon (Herman and Vanderbilt, 1997). Previous studies have reported that the amount of partially polarized light reflected from crop canopies varies between canopies of different leaf orientations, such as legumes and grasses (Shibayama, 2003), and differently fertilized wheat plots (Shibayama and Watanabe, 2006). Panicles emerging above wheat canopies have been shown to reduce the polarization of reflected light (Fitch et al., 1984; Ghosh et al., 1993), and the geometry between the directions of viewing, illumination and reflection have all been demonstrated to have a marked effect on observed polarization (Rondeaux and Herman, 1991). For instance, the actually observed degree of polarization (DP) for wheat canopies at the stages from the tillering through dough-ripe was less than a few percent of the total reflected light energy, which may complicate the acquisition of quality data (Ghosh et al., 1993). Indeed, these problems have hindered the practical application of polarization measurements in field studies to date. Moreover, since most polarization studies have employed non-imaging, unified-field-of-view radiometers (Manjul and Verma, 1993; Shibayama and Akita, 2002), effective simultaneous comparisons of targeted areas, plots and organs under common optical conditions have not previously been possible. We propose that the use of imagery may resolve at least some of the aforesaid problems, and may facilitate the application of the technique to more pragmatic uses. Extensive research and development has been undertaken in the area of spectral and polarimetric imaging camera systems (e.g., Shingu et al., 2002), and commercial models of polarization imagers have recently become available at production prices (e.g., http://www.bossanovatech.com/; http://www.photonic-instruments.com/). Effective, multi-band polarimetric imager for conducting field experiments has been demonstrated to have a marked effect on observed polarization (Rondeaux and Herman, 1991). For instance, steps in viewing, illumination and reflection have all been demonstrated to have a marked effect on observed polarization (Rondeaux and Herman, 1991).

2. Experimental wheat field

The experimental site is located on the campus of the National Institute for Agro-Environmental Sciences (36°01′28″N and 140°06′29″E; 25 m a.s.1). Four equal-area plots (8 × 10 m) of a wheat variety (Triticum aestivum L., cv. Norin-61) were established in a 10 × 50 m concrete-framed field. The seeds were drilled on 11 November 2008 in a northeast-southwest rows with a row width of 60 cm. The experimental design included a single basal fertilization level of 4 g N m⁻² applied with compound fertilizers (N-P₂O₅-K₂O = 10-10-10). Top-dressing was applied at the jointing stage with compound fertilizers (N-P₂O₅-K₂O = 10-10-10) at a rate of 2 g N m⁻² for two of the four plots on 5 March 2009. Heading was observed on 16 April. For agronomic surveys, each plot was divided into two subplots of 8 × 5 m, with one located closer to the MBPI observation position than the other. A plant canopy analyzer (LAI-2000, LI-COR, Inc., Lincoln, Nebraska, USA) was used on the targeted wheat stands to estimate the leaf area index (LAI) and mean tip angle (MTA) of the canopies (Welles and Norman, 1991). Four below-canopy measurements were repeated at three different points for each subplot. On randomly selected three-plant hills in each subplot, the plant heights (PH, cm) and plant lengths (PL, cm) above ground level were manually measured and averaged. In this experiment, measurements of PH and PL included...
leaves but emerged panicles were neglected. The difference between PL and PH was derived from these values, and is hereafter denoted as PL-PH (cm). MTA indicates the average leaf inclination for an entire plant canopy. On the other hand, PL-PH may indicate the relative degree of drooping in the flag leaves. 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 means of these SPAD readings, which taken from the uppermost (flag) leaves on five consecutive hills, were averaged for three locations within each subplot. The agronomic surveys were conducted together with the corresponding MBPI observations on 23 and 30 April. Analysis of variance (ANOVA) tests employing the factors “date” (23 and 30 April), “top-dressing” (0 and 2 g N m\(^{-2}\)) and “subplot” (near and far from the MBPI), were used to compare the obtained data.

3. Polarimetric image observations for wheat plots

The spectral polarization images of the wheat plots were acquired from 1130 to 1210 (JST) on 23 April 2009, and from 0950 to 1030 on 30 April. Weather conditions were clear and calm during the observations. A diagram of the wheat plots shows the observation positions, directions of viewing and solar insolation as well as the fertilization regime (Fig. 1). The observation position was located at the border of adjacent sets of paired plots. Three scenes covering four plots were observed on each date. Each scene included two adjacent wheat plots, one was top-dressed and the other was non-top-dressed (non-dressed). The two adjacent plots, one top-dressed and the other not, were simultaneously observed to compare their radiometric responses. View direction was always perpendicular to planting rows and approximately from the northwest to the southeast. Since the observations were conducted on different days, the sun azimuth and elevation angles were different. On 30 April, the azimuthal angle of MBPI almost faced the sun, while on 23 April the direction of view and solar insolation were approximately 135°. The angles of depression used for viewing were 15° on the first observation date and 20° on the second date. The optics head was attached to a tilting platform mounted on a steel-pipe horse that was supported on the back of a flatbed truck (Fig. 2). The optics head was positioned 2.2 m above the targets, and the distance between MBPI and the edge of the wheat plots was 1.6 m on the first date and 2.3 m on the second date. The soil surface was 0.35 m below the paved levee which ran alongside the field and along which the vehicle could move parallel to the planting rows.

The polarizer of MBPI rotated from 0° to 360° at steps of 15°. At each polarizer angle, band-pass filters were switched from 470 nm to 550 nm and 647 nm in sequence. In addition, spectrally broad-ranging observations from approximately 450 to 950 nm in wavelength were made without any band-pass filters, with each exposure taking approximately 100 or 150 ms for each band and 2 ms for the no-filter observation. The total time required for each scene required about 10 min.

Results

1. Calculation of polarization and brightness

Assuming most polarized light would be linearly polarized, we utilized the definition of Ghosh et al. (1993) for degree of polarization (DP, %) and mean brightness
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The equations for calculating the degree of polarization (DP) and mean brightness (MB) are as follows:

\[ DP_{\text{max-min}} = \frac{(DN_{\text{max}} - DN_{\text{min}})}{(DN_{\text{max}} + DN_{\text{min}})} \times 100 \, \% \tag{1} \]

\[ MB = \frac{(DN_{\text{max}} + DN_{\text{min}})}{2} \tag{2} \]

where DN refers to the camera's digital number (0-255). Because the camera was not calibrated for physical quantities such as radiance, MB was used as a relative measure of the brightness of the targeted object. The suffixes max and min indicate the maximum and minimum camera outputs obtained by polarizer rotation. DP_{\text{max-min}} is the DP value obtained using the detected DN_{\text{max}} and DN_{\text{min}}. Variation in the intensity of the light that passes through the rotating polarizer increases as the amount of observed light is polarized. The disadvantages associated with using DP_{\text{max-min}} are that the angular step used when rotating the polarizer either needs to be continuous or very small so as to accurately detect the peak DN values; however, this drastically prolongs the measurement time. Furthermore, precise measurement of the DN_{\text{max}} and DN_{\text{min}} values under the fluctuating insolation conditions encountered in an open field is often not practical.

On the other hand, DP can also be simply estimated using Stokes parameters, S₀, S₁, S₂, and S₃, and the following equation (Manjul and Verma, 1993):

\[ DP_{\text{Stokes}} = \sqrt{\frac{S₁² + S₂² + S₃²}{S₀}} \tag{3} \]

where, \( S₀ = \frac{(DN_{0º} + DN_{45º} + DN_{90º} + DN_{135º})}{4} \), \( S₁ = DN_{90º} - DN_{0º} \), \( S₂ = DN_{45º} - DN_{135º} \), and \( S₃ \) is the intensity of circularly polarized light that is neglected in this study (Talmage and Curran, 1986). As shown by Eq. (3), the DP_{\text{Stokes}} of light can be estimated using only four DN images taken at fixed polarizer angles of 0º, 45º, 90º and 135º. This reduces the time required for measurement and may simplify the observation system and calculation procedure. However, due to the wide range of reflected light intensities from plants and the insufficient dynamic range of CCD cameras, DN values are frequently saturated when light is totally reflected on near-horizontal leaf surfaces and the polarizer angle is approximately 90º or 270º (the transmissive axis of the polarizer is horizontal in the optics of the MBPI). The
As indicated by Eq. (5), the intensity variation can be generally described by a phase-shifted trigonometric curve based on the function cos^2θ; the curves of both functions are shown in Fig. 5. Assuming the DN variation caused by θ follows this trigonometric function, we fitted the observed DN values to the equation

\[ I = I_0 + I_0 B^2 + C^2 \cos(2\theta - \varphi), \]

(6)

The phase-shift angle \( \varphi/2 \) was derived using the following procedure:

\[ \sigma \sin = (1/n) \sum \text{DN}_i \times \sin(2\theta_i), \]

(7)

camera sensitivity should be significantly lowered to avoid saturation of any pixels in the image, which means decreasing the average image intensity to obtain reliable DP values for the majority of pixels in the image.

Prior to conducting observations of wheat, we captured polarized images of several crop species. The sweet potato, which is generally considered to be a planophyll-type species, may sometimes exhibit large variations in DN values in images captured at different polarizer angles. Fig. 3 shows the DP of a sweet potato field in the 550 nm band captured by MBPI using the alternative procedure described below (Eqs. (7)–(13)). Images were taken at polarizer angles (θ) from 0° to 360° at 15° intervals. Here, the polarizer angle of 360° is equal to 0°. The sampled DN values of several sets of pixels from these images (indicated by open circles in Fig. 3) are plotted against \( \theta \) in Fig. 4. Due to the contribution of fluctuation in the insolation and reflected light intensity caused by unstable plants in the open-air plot, simply selecting DNmax and DNmin from the obtained data points and applying these to Eq. (1) in order to determine DP max-min was considered unsuitable. For example, two markedly different curves plotted in Fig. 4 are presented in Fig. 5. Since several of the DN values of one of the curves ("solid triangles") shown in Fig. 5 are saturated, application of Eq. (3) for estimating DP_{stokes} is not suitable. Meanwhile, according to the Jones vector for describing elliptically polarized light, two orthogonal components can be described as \( A_x \exp(i \delta_x) \) and \( A_y \exp(i \delta_y) \), and when transmitted through a rotating polarizer, the observed light intensity \( I(\theta) \) is given by the equation (Tsuruta, 1990)

\[ I(\theta) = I_o \left( 1 + \cos^2 \alpha \cos^2 \theta + \sin^2 \alpha \cos \delta \sin^2 \theta \right), \]

(4)

where, \( \tan \alpha = A_y / A_x \), and the phase difference \( \delta = \delta_y - \delta_x \). Assuming no change in \( \alpha \) and \( \delta \) during a single measurement, we fixed the parameters cos2\( \alpha \) and sin2\( \alpha \) in Eq. (4) as constants, and expressed them as B and C, respectively. Thus, Eq. (4) is converted to

\[ I(\theta) = I_o \left( 1 + B \cos^2 \theta + C \sin^2 \theta \right). \]

(5)

As indicated by Eq. (5), the intensity variation can be generally described by a phase-shifted trigonometric curve based on the function cos2\( \theta \); the curves of both functions are shown in Fig. 5. Assuming the DN variation caused by θ follows this trigonometric function, we fitted the observed DN values to the equation

\[ I = I_o \left( 1 + \sqrt{B^2 + C^2} \cos(2\theta - \varphi) \right), \]

(6)

The phase-shift angle \( \varphi/2 \) was derived using the following procedure:

\[ \sigma \sin = (1/n) \sum \text{DN}_i \times \sin(2\theta_i). \]

(7)
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\( \sigma \cos = \frac{1}{n} \sum \text{DN}_i \times \cos^2 \theta_i \) \hspace{2cm} (8)

\[ \arctan = \tan^{-1} \left( \frac{\sigma \sin}{\sigma \cos} \right) \] \hspace{2cm} (9)

\[ \phi / 2 = -90^\circ + \frac{\arctan}{2}, (\arctan \geq 0) \] \hspace{2cm} (10)

\[ \phi / 2 = \frac{\arctan}{2}, (\arctan < 0). \] \hspace{2cm} (11)

Here, \( n \) is the number of \( \theta \)s employed for a single observation, and \( \theta_i \) is the given polarizer angle. The following simple linear regression model can then be obtained using the observed data:

\[ \text{DN} = b_0 + b_1 \times \cos^2 (\theta - \phi / 2) \] \hspace{2cm} (12)

As shown in Fig. 6, saturated DN values were omitted from the regression analysis. In addition, \( \text{DN}_{\text{max}} \) and \( \text{DN}_{\text{min}} \) were estimated by substituting 1 and \(-1\), respectively, for \( \cos^2 (\theta - \phi / 2) \) in Eq. (12). Using the estimated regression coefficient \( b_1 \) and intercept \( b_0 \) and Eq. (1), \( \text{DP}_{\text{max-min}} \) can be derived as follows:

\[ \text{DP}_{\text{max-min}} = \left( b_0 + b_1 - (b_0 - b_1) \right) / \left( (b_0 + b_1) + (b_0 - b_1) \right) \times 100 \% \]

\[ = \frac{(b_0 + b_1) - (b_0 - b_1)}{(b_0 + b_1) + (b_0 - b_1)} \times 100 \% \] \hspace{2cm} (13)

Similarly, using Eq. (2), mean brightness (MB) can be calculated as follows:

\[ \text{MB} = \frac{(b_0 + b_1) + (b_0 - b_1)}{2} \]

\[ = b_0. \] \hspace{2cm} (14)

In the present study, Eqs. (7)–(13) were used exclusively for the polarization calculations and applied to all pixels without any preprocessing, such as smoothing, filtering and/or grouping. Hereafter, the denotation ‘DP value’ is taken to indicate the modified \( \text{DP}_{\text{max-min}} \) derived using Eq. (13).

2. Agronomic variables of observed wheat plants

During the field study, the observed LAI of wheat plants varied between 1.04 and 2.5, and PH ranged from 67 to 88 cm. ANOVA tests indicated that two-day measurements repeated at one-week intervals did not significantly affect any of the variables except the SPAD values, which decreased from 27.1 to 25.3 on average (Table 1). LAI, PH and PL at near subplots (closer to the position of MBPI) were significantly greater than those at the far-end of the subplots, although the PL-PH values of the far subplots were significantly higher, and there were no significant differences in the MTA and SPAD values. There may have been some unevenness in soil fertility between the near side of the field and the far side, probably due to a previous experiment on paddy rice in the same field. Among the three factors analyzed, only ‘top-dressing’ had a significant effect on all variables. Top-dressing at the jointing stage increased the LAI, PH, PL and SPAD values. MTA decreased in top-dressed plots. The leaves of fertilized plants hung more horizontally than the leaves of unfertilized plants, although the difference in average MTA values between the two plot-types was less than 4°. The average PL-PH value of top-dressed plots was 5.2 cm, which was almost twice that of non-fertilized plots.

3. Degree of polarization (DP) and mean brightness (MB) in wheat plots

In each processed image, we demarcated a rectangular area of 8×10 m in each wheat plot that included the subplots both near and far from the MBPI (Fig. 7). Within the marked rectangular area, ten squares of 100×100 pixels were randomly selected and the arithmetic means of the MB and DP values were obtained for each band and each time of observation. The difference in these values between the different fertilization treatments were then statistically compared (Table 2). The two central plots were each recorded on two consecutive occasions, but the position of the plot in the images was shifted from right to left by the time of the second recording.

Table 1. Summary of analysis of variance tests for agronomic variables of observed wheat plots on 23 and 30 April. The mean values together with the probability (\( p \)) that the null hypothesis (there is no difference between the pair of means above) is correct are presented in each column. The fertilization levels are indicated as the amount of nitrogen per square meter applied at the jointing stage. The positions ‘near’ and ‘far’ indicate the 5-m wide strips of paddy field that were close to, and distant from, the observer.

| Factor | Variable         | Mean tip angle (º) | Leaf area index | Plant height (cm) | Plant length (cm) | Plant length - Plant height (cm) | SPAD value |
|--------|------------------|--------------------|-----------------|-------------------|------------------|---------------------------------|------------|
| Fertilizer | 0 g N m$^{-2}$ | 55.75              | 1.54            | 75.25             | 77.79            | 2.54                            | 23.97      |
|         | 2 g N m$^{-2}$  | 52.13              | 2.11            | 82.58             | 87.79            | 5.21                            | 28.50      |
| p      |                  | 0.0042             | 0.0001          | 0.0013            | 0.0001           | 0.036                           | 0.0001     |
| Position | far              | 53.25              | 1.64            | 74.13             | 79.42            | 5.29                            | 25.59      |
|         | near             | 54.63              | 2.01            | 83.71             | 86.17            | 2.46                            | 26.67      |
| p      |                  | 0.286              | 0.0016          | 0.0022            | 0.0024           | 0.027                           | 0.091      |
| Date   | 23 April         | 54.88              | 1.83            | 77.08             | 81.33            | 4.25                            | 27.14      |
|         | 30 April         | 53.00              | 1.82            | 80.75             | 84.25            | 3.50                            | 25.33      |
| p      |                  | 0.093              | 0.07            | 0.06              | 0.124             | 0.519                           | 0.023      |
Table 2. Means of mean brightness (MB) and degree of polarization (DP, %) calculated for ten averaged values in 100×100 pixel randomly selected areas in the wheat plots for observations employing three spectral bands and no-filter. Results of statistical comparisons for the values obtained in the fertilized and non-fertilized plots are indicated after each pair of means. The plot IDs, ‘a’, ‘b’, ‘c’ and ‘d’ are shown in Fig.1.

| Central wavelength of spectral band (nm) | 470 | 550 | 647 | Thru (no filter) |
|----------------------------------------|-----|-----|-----|-----------------|
| Date / time | Plot ID | Variables | 0  | 2  | 0  | 2  | 0  | 2  | 0  | 2  |
| 23 Apr./ 11:33 | a + b | MB | 198.95 | 209.94 ns | 166.81 | 161.5 ns | 157.64 | 157.87 ns | 78.24 | 93.29* |
| | | DP (%) | 0.267 | 1.01*** | 0.53 | 0.925*** | 0.588 | 1.37*** | 1.08 | 1.12 ns |
| 23 Apr./ 11:46 | b + c | MB | 210.33 | 199.96 ns | 170.21 | 159.5 ns | 162.57 | 151.26* | 90.03 | 76.94* |
| | | DP (%) | 0.289 | 0.300 ns | 0.624 | 0.710** | 0.847 | 0.773 ns | 0.997 | 0.999 ns |
| 23 Apr./ 11:58 | c + d | MB | 214.81 | 209.24 ns | 150.82 | 169.15** | 150.26 | 154.8 ns | 82.09 | 93.94* |
| | | DP (%) | 0.398 | 0.501* | 0.518 | 0.654*** | 0.517 | 0.473 ns | 0.813 | 1.12*** |
| 30 Apr./ 09:57 | a + b | MB | 175.46 | 179.24 ns | 215.79 | 204.51 ns | 218.15 | 201.53** | 106.19 | 107.13 ns |
| | | DP (%) | 0.014 | 0.187*** | 0.261 | 0.453*** | 0.09 | 0.042*** | 0.090 | 1.01 ns |
| 30 Apr./ 10:10 | b + c | MB | 182.86 | 180.89 ns | 222.1 | 192.93*** | 212.52 | 202.50ns | 103.26 | 97.26 |
| | | DP (%) | 0.186 | 0.227* | 0.294 | 0.259 ns | 0.190 | 0.084*** | 0.870 | 0.838 ns |
| 30 Apr./ 10:22 | c + d | MB | 185.39 | 185.36 ns | 215.74 | 209.18 ns | 214.94 | 206.6 ns | 97.73 | 108.54 ns |
| | | DP (%) | 0.313 | 0.356 ns | 0.410 | 0.863*** | 0.12 | 0.177 ns | 0.681 | 0.722 ns |

*, **, *** and ns: Significance levels of 0.05, 0.01, 0.001 and non-significant, respectively.

Fig. 8. Mean degrees of polarization for each wheat plot versus the measured agronomic variables: (a) the difference between the plant length (PL, cm) and the plant height (PH, cm), (b) the mean tip angle (MTA), (c) the leaf area index (LAI), and (d) the leaf greenness (SPAD value). The data points separated with dashed lines were of the same observation (the second observation on 30 April) in the four datasets (a) through (d), and not used in the regressions.
left. In the 470 nm band, DP values varied between 0.014 and 1.01%, and DP values from top-dressed plots were significantly higher than those from non-dressed plots in four out of six observations. In the 647 nm band, DP values ranged from 0.084 to 1.37% and DP values were significantly larger in two out of six top-dressed plots. The DP value of a non-dressed plot was larger in the second observation on 30 April. The 550 nm band DP values ranged between 0.26 and 0.925%, and DP values for top-dressed plots were significantly larger in five out of six observations. The difference between DP values for top-dressed and non-dressed plots was significant for all observations except those of the second observation conducted on 30 April. While it is possible that there may have been some problems with the second observation conducted on 30 April, the DP values in the 470 nm band were signifi cantly larger in the top-dressed plot; no MBPI malfunctions have been experienced to date and there were no marked changes in weather conditions on the day the observations were conducted. Spectrally broad range observations without a band-pass fi lter produced relatively poor results for DP value comparisons between fertilization regimes. Most of the MB values from top-dressed and non-dressed plots showed no signifi cant differences, and the magnitude relation was indefi nite in all spectral bands and also in the broad spectral range observations. Taken together, these fi ndings indicated that mono-band MB images were not suitable for clarifying fertilization effects on plant canopies. However, the poor sensitivity of mono-band MB in this analysis does not exclude the possibility of detecting color differences in plant leaves using the spectral combination technique of the three-band MB images, although we did not explored such an approach in the present study.

4. Band DP values versus the morphological characteristics of wheat plants

A relatively consistent relationship was observed in the 550 nm band mean DP values for top-dressed and non-dressed plots. Fertilized plant canopies generated a greater polarized portion of refl ected light. The next step, therefore, was to identify the main agronomic variables of the plants that likely affected the polarization. The relationships between the 550 nm band DP values and the morphological characteristics of the wheat canopies are presented in Table 3.

### Table 3. Simple correlation coefficients calculated for observed agronomic and radiometric variables in the wheat plots. The values at the upper right of the table show correlations obtained for all 12 observations, while those at lower left are derived from 11 observations, excluding the observations of the fertilized plot (plot ID = c) at the time of the second observation on 30 April.

|               | MTA | LAI | PH | PL | PL-PH | SPAD | MB (470 nm) | DP (470 nm) | MB (550 nm) | DP (550 nm) | MB (647 nm) | DP (647 nm) | MB (thru) | DP (thru) |
|---------------|-----|-----|----|----|-------|------|-------------|-------------|-------------|-------------|-------------|-------------|-----------|-----------|
| MTA           | 0.20| 0.14| -0.18| -0.52| -0.16| -0.35| 0.20        | -0.14       | -0.52       | 0.44        | 0.21        | -0.36       | 0.17       | -0.36      |
| LAI           | -0.76| 0.70| 0.19| 0.53| -0.54| 0.73| -0.36       | -0.52       | -0.54       | 0.73        | -0.36       | 0.17        | -0.36      | 0.17       |
| PH            | -0.61| 0.39| 0.38| 0.55| 0.54| -0.49| 0.35        | 0.41        | 0.54        | 0.99        | 0.54        | 0.64        | 0.28       | 0.37       |
| PL            | -0.68| 0.86| 0.42| 0.88| 0.54| 0.30| 0.78        | -0.73       | -0.54       | 0.64        | 0.71        | -0.85       | 0.62       | 0.36       |
| PL-PH         | -0.50| 0.80| 0.59| 0.35| 0.78| 0.55| 0.80        | -0.53       | 0.80        | 0.54        | 0.73        | 0.47        | 0.70       | 0.62       |
| SPAD          | -0.66| 0.91| 0.62| 0.78| 0.41| 0.60| 0.43        | 0.17        | 0.44        | 0.57        | 0.48        | 0.44        | 0.37       | 0.44       |
| MB (470 nm)   | 0.20| 0.39| 0.38| 0.55| 0.54| -0.49| 0.35        | 0.41        | 0.54        | 0.99        | 0.54        | 0.64        | 0.28       | 0.37       |
| DP (470 nm)   | -0.14| 0.39| 0.13| 0.55| 0.54| -0.53| 0.76        | -0.54       | 0.54        | 0.73        | -0.54       | 0.64        | 0.28       | 0.37       |
| MB (550 nm)   | -0.18| -0.16| 0.19| 0.40| -0.49| -0.62| 0.99        | -0.54       | 0.73        | 0.47        | 0.70        | 0.62        | 0.36       | 0.17       |
| DP (550 nm)   | -0.52| 0.69| 0.42| 0.88| 0.54| 0.66| 0.73        | -0.73       | -0.54       | -0.47       | 0.70        | 0.64        | 0.36       | 0.17       |
| MB (647 nm)   | -0.16| -0.22| 0.14| 0.44| -0.53| -0.92| 0.99        | 0.54        | 0.73        | 0.47        | 0.70        | 0.64        | 0.36       | 0.17       |
| DP (647 nm)   | 0.17| 0.36| 0.17| 0.58| 0.54| 0.66| 0.73        | -0.73       | -0.54       | 0.70        | 0.64        | 0.36        | 0.17       | 0.17       |
| MB (thru)     | -0.35| 0.08| 0.57| 0.43| -0.21| 0.48| 0.43        | 0.44        | 0.37        | 0.28        | -0.62       | 0.70        | -0.36      | -0.36      |
| DP (thru)     | 0.21| 0.43| 0.25| 0.36| 0.45| 0.48| 0.43        | 0.44        | 0.37        | 0.28        | 0.44        | 0.70        | -0.36      | -0.36      |

*p|>|0.602|=0.05, p|>|0.735|=0.01, p|>|0.847|=0.001, n=11.
*p|>|0.576|=0.05, p|>|0.708|=0.01, p|>|0.823|=0.001, n=12.
MB (wavelength): Mean brightness observed in the band centered at the wavelength.
DP (wavelength): Degree of polarization (%) observed in the band centered at the wavelength.
thru: Denotes that the observation was made with no band-pass filter.
MTA: Mean tip angle (º).
LAI: Leaf area index.
PH: Plant height (cm).
PL: Plant length (cm).
PL-PH: Difference between PL and PH (cm).

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surveyed agronomic variables are shown in Fig. 8. Of the four agronomic variables, PL-PH was considered most likely to influence variations of the DP values. The data from the second observation conducted on 30 April were plotted as outliers in each graph and omitted from the correlation analysis. The concerned observations showed rather different DP agronomic variable responses from the majority. Although we have not yet determined the causes that the corresponding data collected for the same plot on the two sample days were markedly different. LAI showed a positive correlation with DP values, and leaf greenness (SPAD), PH and PL were all positively correlated with DP values (Table 3).

Among the three wavelength bands, 550 nm band DP values were most strongly correlated with PL-PH (Fig. 8a). Generally, increased PL-PH values corresponded to higher DP values in all bands. In the 470 and 647 nm bands, however, fluctuations in the DP values against PL-PH were larger, especially on the date of the second observation (30 April). Interestingly, as opposed to the time of the first sampling (23 April), most of the panicles at the time of the second sampling (30 April) were located above the flag leaf layers.

Discussion

Due to the narrow dynamic range and limited resolution of the camera, combined with the relatively long measurement time, care should be taken when analyzing the obtained DP values. However, the estimated DP values generally agreed with results obtained in previous studies using portable spectropolarimeters (Fitch et al., 1984; Ghosh et al., 1993; Shibayama and Watanabe, 2007). Mean DP values observed from erectophyll plant canopies, such as wheat, are expected to be relatively smaller than those obtained from planophyll plants, like the sweet potato, even if the directions of viewing and insolation are opposing (looking toward the sun). Mean DP values sampled from plots of a certain size depend on the polarization properties of the leaf surface itself and the probability of the existence of leaves that have geometrically adequate orientation for producing larger polarization. If the reflected surface is a pane of glass with a refractive index of 1.5, then polarization is maximum (~100%) when the incident angle to the reflected surface is at the Brewster angle (~57.4°) (Collett, 2005). The refractive index of leaf epidermis is close to 1.5 and vegetation can reflect largely polarized light depending on factors such as view and illumination geometry (Grant et al., 1993). Obtained results showed that of the three visible wavelength bands tested, the 550 nm band DP values appeared to be most sensitive to changes in the leaf orientation. We did not expect that the characteristics of the DP fertilization relationship would vary among wavelength bands in the visible spectrum because the refractive index of a leaf surface is considered to be constant in the range of visible wavelengths (Vanderbilt et al., 1985). While previous studies employing spectropolarimeters also reported differences in absolute DP values among spectral bands, the relationships between the agronomic and polarimetric variables were basically parallel among different visible wavelength bands (Shibayama and Akita, 2002; Shibayama, 2003). Since the 550 nm band is located between both chlorophyll absorption bands (430 and 660 nm), the reflected light intensity of the 550 nm band is relatively larger than that observed for the 470 and 647 nm bands using the MBPI. This increased reflected light intensity may account for the relatively higher signal to noise ratio obtained for the 550 nm band. In addition, compared to observations conducted using a unified-field-of-view radiometer (e.g., Fitch et al., 1984; Ghosh et al., 1993; Shibayama and Watanabe, 2007), the pixel-by-pixel estimations of DP values employed in this study for the image data may produce DP values with slightly different arithmetic means; however, this is just speculation and further research is required in order to clarify the contribution of differences in the morphological and physiological status on the spectral characteristics of DP values of crop and/or vegetation canopies. Consequently, due to the limited number of observations in this study, care should be taken when interpreting the results.

Greater PL-PH values may indicate that the flag leaves were longer and drooped more, which implies that the more horizontally oriented leaf surfaces were relatively more abundant in canopies with larger PL-PH values. The larger PL-PH values corresponded to higher DP values (Fig. 8a). Larger MTA, which typically indicate that there are more relatively erect leaves rather than horizontal leaves, corresponded to lower DP values (Fig. 8b). Both PL-PH and MTA seemed to affect the observed DP values. However, because the canopy analyzer measured the light transmitted through all leaf layers above the soil, the obtained MTA data represents the entire canopy including the lower leaves. On the other hand, PL-PH values can be used to infer the morphological inclination of leaves in the upper layer in the canopy only. Due to the shallow angle of depression used for MBPI, we consider that the detected solar light may have been reflected and polarized mostly at the top or upper leaf layers in this experiment. During the reproductive growth period of wheat, flag leaves mainly provide dry-matter. Therefore, the leaf angular orientation as well as the leaf area and nutrient condition, affects the photosynthetic capacity of the canopy through the light use efficiency (e.g., Murata et al., 1976). Nondestructive remote sensing may be useful for collecting critical parameters for crop growth modeling, yield prediction and fertilization management.

Compared to the method used for calculating DP values in the present study, obtaining DP values using Stokes
parameters (DP_{max-min}) would drastically reduce measurement time and may also simplify the observation system and DP calculation procedure (Walraven, 1981; Fitch et al., 1984). However, due to the wide range of light intensities reflected by plants and the insufficient dynamic range of the CCD camera, DN values may frequently be saturated when light is completely reflected by near-horizontal leaf surfaces and the polarizer angle is approximately 90° or 270° (the transmissive axis of the polarizer is horizontal). To avoid saturation and/or under-exposure of any pixels in the image, we employed a time-consuming procedure to measure reflected light intensities using polarizer angles ranging from 0° to 360° at 15° intervals with 25 angular steps in total. Presumably, narrower angular steps would be required to directly estimate DP_{max-min} by detecting the maximum and minimum DN values. The modified DP calculation method employed in the present study may therefore have achieved a good balance between the accuracy and measurement duration because it uses more than 20 observations in each regression analysis to estimate the parameters while excluding saturated DN values and eliminating random errors. Nonetheless, the number of angular steps and the appropriate interval need to be investigated further in order to optimize both measurement time and accuracy. When glinting or specular reflection from very small portions of leaves is negligible, such as when the target and the observer are far apart and highly reflective small areas of the target become inconspicuous relative to the pixel size, DP calculations using Eq. (3) will be effective. MBPI can also be configured for application of Eq. (3) to estimate DP_{max-min} values.

Although further experiments are required to verify the results, polarization measurements and imaging are considered to be useful methods for performing macroscopic comparisons of morphological characteristics in multiple targets observed under the same conditions. The present study showed the potential application of field polarization image measurements for identifying heading-stage wheat plants subjected to different fertilization regimes. Further studies are required to testify the possibility of diagnostic measurements at different growth stages as well as for different crop species. In addition to spectral information, polarization detects morphological characteristics of vegetation and improves the prospects of refining field radiometric methodologies. The equipment could also be applied to develop future airborne optical remote sensing techniques used for discriminating between crop and plant species by detecting differences in their morphological characters.

Acknowledgments

We thank Hiroyuki Iino and Terushi Kamada from the National Institute for Agro-Environmental Sciences for their technical support in the field experiments.

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