Continuous Monitoring of Visible and Near-Infrared Band Reflectance from a Rice Paddy for Determining Nitrogen Uptake Using Digital Cameras

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Abstract: A two-band digital imaging system—one band for the visible red band (RED, 630−670 nm) and the other for the near infrared band (NIR, 820−900 nm)—was devised and positioned at a height of 12 m above a rice field of 300 m² in area during the 2007 growing season. The imaging system automatically logged bird’s-eye view images at 10-min intervals from 0800−1600 every day. Radiometric corrections for the pairs of two-band images were done using solar irradiance sensors and preceding calibrations to calculate daily band-reflectance and the normalized difference vegetation index (NDVI) values for 9 plots of rice plants, with 3 levels of planting density and basal fertilization. The daily-averaged reflectance values in the RED and the NIR bands showed different but smooth seasonal changing patterns according to the growth of plants. At the maximum tiller number and the panicle formation stages, the RED and NIR reflectance values had correlation coefficients (r) of 0.79 and 0.81 with above-ground nitrogen absorption per unit land area (NA, g m⁻²), respectively, whereas the NDVI using the two band reflectance values showed r-value of -0.13. An empirically derived equation for the NA using two band reflectance values showed r-value of 0.96 and a root mean square of error (RMSE) 0.5 g m⁻² (10% of the mean observed NA) in the estimation for the original (not validated) data set acquired at the maximum tiller number and the panicle formation stages. The results indicated that reflectance observation in the RED and NIR bands using the digital imaging system was potentially effective for assessing rice growth.

Key words: Digital camera, Near-infrared, Nitrogen absorption, Red, Reflectance, Rice, SPAD.

Rising air temperature in the ripening period of rice in the warm and temperate climate regions in Japan tends to lower grain quality (Oh-e et al., 2007; Wakamatsu et al., 2007). Precise assessment and evaluation for the crop growth in situ are required to improve the crop growth diagnosis and propose better farm management and practices over an area (Yan et al., 2006). Under these circumstances, remote sensing from space-borne image sensors may help collect data over a wide area with less effort (Asaka et al., 2006; Akiyama, 2007; Ishitsuka and Yasuda, 2007). Remote sensing techniques using seasonal variations of reflected spectra from crops have been developed because high spectral and spatial resolution images can be obtained anywhere in the world on an almost daily basis since the launch of artificial satellites such as Terra/Aqua MODIS (Sakamoto et al., 2005). However, high quality images are difficult to obtain during the summer cropping season in East Asia since thick clouds frequently prohibit normal data acquisitions in the early to mid-summer rainy season (Akiyama and Kawamura, 2003). Continuous ground-based observations at a representative experimental site in the local agricultural experiment station, for instance, could help compensate for the lack of data. Because studies on physical modeling and inversion for optical remote sensing are still underway, so-called “ground truth” is required to sustain certain reliability on the remotely detected information (Kimes et al., 1998), and the relationship between the reflected spectra and the crop species, phenology, biomass, nutrient conditions and yield needs to be determined accurately for effective analysis and interpretation of data from space- or air-borne sensors (Evri et al., 2008; Tanaka et al., 2008). Even with the availability of portable spectral radiometers, the procedures for collecting field data (ground truth) may take more time and effort.

Corresponding to such requirements, an automated weatherproof spectral radiometer attached to a rotating arm has been proposed and devised for long-term continuous observations (Shibayama et al., 1999), but it will be costly to target multiple...
sites for many years. Ground-based acquisition of spectral images may partly resolve the problem since it should simultaneously collect the spatial distribution of the widespread target. For relatively simple and cost-effective ground observations, a high spatial- and spectral-resolution imaging system using line sensors has been developed for intensive surveys (Kosaka et al., 2007), but it requires a crane for scanning above the targeted object. On the other hand, handy video cameras or digital cameras have been used for assessing crop leaf nitrogen and/or chlorophyll content (Nakatani and Kawashima, 1994; Kawashima and Nakatani, 1998; Matsuda et al., 2003; Jia et al., 2004; Ku et al., 2004; Casadesus et al., 2007; Takemine et al., 2007) and for analyzing plant cover or phenology of vegetation (Purcell, 2000; Zhou and Robson, 2001; Richardson et al., 2007; Ishihara et al., 2008). Cameras with sensitivity in the near-infrared (NIR) range, which is essential for crops and plant observation due to the characteristic high reflectance from green phytomass have also been used (Omine, 2007). However, seasonally continuous spectral images as ground truth for remote sensing using digital cameras are lacking. In most studies, relative brightness has been measured in red, green, blue and/or NIR bands or their combination calculations. A band-to-band ratio-oriented calculation of reflectance or radiance such as the normalized difference vegetation index (NDVI) minimizes external factors such as the effect of sun angle changes and atmospheric interference but may lose some characteristics of the original spectra of the target such as of coniferous forest biomass (Häme et al., 1997). In non-wood canopies, the NDVI (based on the NIR/red ratio) has been effective in green biomass and/or leaf area index (LAI) estimation (Holben et al., 1980). However, the NDVI (or other vegetation indices based on the NIR/red ratio) shows an asymptotic trend for LAI greater than 3 (Shibayama and Akiyama, 1989; Baret and Guyot, 1991; Mutanga and Skidmore, 2004). Therefore, individual band reflectance values are still worthwhile to collect because of their potential applicability for detecting other canopy characteristics such as growth stages, total biomass, and nutrient conditions (Zhu et al., 2007).

The objectives of this paper were to show the performance of the two-band image collecting device using consumer-market digital cameras equipped with optical filters for observing over a rice paddy field during a cropping period from transplanting to maturation, and to assess the possibility of estimating seasonal band reflectance in the visible and NIR wavelength ranges. Obtained data demonstrated the capabilities of band reflectance and vegetation index such as the NDVI in the detection of a plant growth parameter: above-ground nitrogen absorption per unit land area (NA, g m⁻²), during the before-heading growth period.

Materials and Methods

1. Instruments

A portable dual-band camera system (PDC, Kimura OyoKogei Inc., Saitama, Japan) which contained two digital camera boards, one for visible red (RED) and
another for near-infrared (NIR) light bands, built in a water-proof housing, was used for measurement (Figs. 1 and 2). The digital cameras were originally manufactured by Orite Technology Co., Ltd (Taipei, Taiwan), and the V2210 model (2.1×10^6 pixels, focal length 9.05 mm) was used for the RED band, and the V3210 model (3.1×10^6 pixels, focal length 8.47 mm) was used for the NIR band. It was difficult to control two cameras of the same model using a computer because of software conflict between the driver programs for the cameras. We replaced the original NIR-cut filters with band-pass filters, which we attached anew to the CMOS image sensors. Generally, these sensors have sensitivity in the NIR range up to 950 nm. The center wavelengths and the bandwidths of the filters were, respectively, 650 nm and 40 nm for the RED band, and 860 nm and 80 nm for the NIR band. These wavelength bands were adjusted to approximately Band-1 (620−670 nm) and Band-2 (841-876 nm) used by the currently operative artificial satellite Terra/Aqua MODIS (http://modis.gsfc.nasa.gov/about/specifications.php). The cameras were brought into focus by adjusting the position of the lenses. We switched off the automatic white balancing and exposure speed control functions built into the cameras to avoid the interference from the targeted object.

We installed the PDC, attached on a motorized platform for tilt angle adjustment on the top of a 12 m-high duralumin telescopic pole (FSP-712X, Fuji Industry, Co. Ltd., Chiba, Japan). A computer (OS: Windows 2000) controlled the PDC and received the 640 ×480 pixel images through a USB interface and cable. The PDC was programmed to set exposure speed and triggered shooting images. A 400 GB hard disk data storage system saved the images as bitmap format (BMP) files. The solar irradiance sensor (SIS) monitored the two bands during the measurement using a pair of silicon photocells covered by cosine diffusers and the same-spec band-pass filters for the PDC. The computer saved the spectral solar irradiance values that were averaged for the one-minute period preceding the camera exposures into a subsidiary file provided separately with the corresponding image file.

2. Experimental paddy field

We established plots of a rice variety (Oryza sativa L. ssp. japonica, cv. ‘Koshihikari’) in a 15 m×56 m paddy field on the campus of the Toyama Prefectural Agricultural, Forestry and Fisheries Research Center in Toyama City (36° 37′ 37″ N and 137° 14′ 3″ E, 50 m above sea level). The seedlings were transplanted on 14 May 2007 in north-south rows with a row width of 30 cm. Fig. 3 depicts the experimental field. The experimental design included 3 planting densities of 18.8, 21.4 and 24.2 hills m\(^{-2}\) and 3 basal fertilization levels of 3, 4 and 5 g N m\(^{-2}\) applied with compound fertilizers (N-P\(_2\)O\(_5\)-K\(_2\)O=6-9-6). Topdressing applications were with the compound fertilizers at a rate of 1.5 g N m\(^{-2}\) on 23 and 31 July for all the plots. We divided the entire field into 18 plots of equal area (3.6 m×6 m) with margins of 2 m width on the east and west sides of the field. There was a 15×17 m marginal area at the south end of the field, in which the PDC system was set up in the end of May, about two weeks after the transplanting. About half of the panicles in each hill started emerging on 8 August (heading stage). We measured the number of tillers (NT, tillers m\(^{-2}\)), plant length (PL, cm), eye-observed leaf color index (LCI, from 1 to 7 at 0.5 intervals scaled corresponding from light green to dark green) using the FHK Leaf Color Scale for Paddy Rice (Fujihira Industry, Tokyo, Japan). The survey was conducted at the following five major growth stages: the last productive-tiller emergence (LP, 12 June), maximum tiller number (MX, 3 July), panicle formation (PF, 12 July), heading (HD, 8 August) and dough-ripe stage (DR, 29 August). We found a difference of less than a day on the growth stages of the plots. LCI was not surveyed on the last date. On the northern 9 plots, which were not observed by the PDC, we surveyed the
above-ground dry biomass (DW, g m\(^{-2}\)) and the leaf greenness. We also measured the nitrogen content of the plant (g N g\(^{-1}\)DW) at each stage by the Kjeldahl method. 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). We did not measure LAI in this study. The DW and SPAD values in the southern 9 plots observed by the PDC were not surveyed directly but were estimated using the NT, PL and LCI and the corresponding DW and SPAD values surveyed in the northern 9 plots that were not viewed by the PDC using regression equations. The procedure provided the estimates only for the before-heading stages due to the lack of a strong relationship between the variables in the heading and ripening stages.

3. Radiometric calibration

We calibrated the solar irradiance sensors (SIS) in the laboratory using a certified standard electric bulb to obtain the coefficients for converting the output voltages into the incident spectral irradiance in the band b: \(L_b\) (\(\mu W cm^{-2} nm^{-1}\)). We calibrated the PDC in the field on a clear day in May 2007. We placed a white drafting paper pasted on a 1 m \times 1 m polystyrene foam plate horizontally on the ground and the PDC observed it at a zenith angle of 20º from about 1 m above the target. The view direction was perpendicular to the sun to avoid the shadow of the PDC and tripod. The SIS monitored the solar irradiance during the calibration. We temporarily placed some neutral density filters in front of the PDC to lower the intensity of light coming into the PDC. Laboratory measurement using a spectrophotometer (V-570, JASCO Corp., Tokyo, Japan) provided the spectral reflectance of the white drafting paper in the bands.

The calibration procedure assumed that the drafting paper was optically uniform at all points on the plane and the bidirectional reflectance characteristics were negligible. Advanced camera calibration techniques for geometric correction (Kunii and Murai, 2008) were not applied in this experiment. For each band and each camera exposure speed, we converted the camera’s output digital count (\(D\)) at the center and 24 off-center points of 10 \times 10 pixel to a ratio relative to the \(D\) value at the center (=1.0). Then a quadratic regression equation estimated the relative sensitivity (\(S_{be}\)) of each pixel on the image to that of the center:

\[
S_{be}(x, y) = f(x, y, x^2, y^2), \quad x = 0 - 479, y = 0 - 639, \quad (1)
\]

where \(x\) and \(y\) are the coordinates in the image, and suffix \(b\) indicates the band and suffix \(e\) indicates the exposure speed. In the calibration for practically observed images, each pixel of coordinate \(x\) and \(y\) in the image was divided by \(S_{be}(x, y)\) to compensate for variations in sensitivity due to the traits of the lenses, image sensors, filters and so on.

To convert the \(D\) values obtained for exposure speed \(e\) (\(D_e\)) into the spectral irradiance \(I_b\) (\(\mu W cm^{-2} nm^{-1}\)), we used the following equations:

\[
I_b = \beta_0 + \beta_1 \times D_e/100 + \beta_2 \times 10^{D_e/100} + \beta_3 \times \log_10(1 - 10^{-D_e/100}) \quad (2),
\]

\[
I_b = L_b \times R_b \times T \quad (3).
\]

Regression calculations provided the regression coefficients in Eq. (2) to estimate the camera’s detected light intensity in band \(b\): \(I_b\), from the corresponding \(D_e\) using the averaged value of the central 100 \times 100 pixels of the images of the sunlit white drafting paper. The form of Eq. (2) is based on the equation for predicting light intensity from exposed film density (Honeycutt and Chaldu, 1970). Eq. (3) estimated the \(I_b\) by multiplying the solar irradiance in the band \(b\) (\(L_b\)), the reflectance of the drafting paper (\(R_b\)), and the transparency provided by the neutral density filters (\(T\)). The calibration performance using Eq. (2) was acceptable if the \(D_e\) values were within certain ranges (Fig. 4). The appropriate \(D_e\)-value ranges of Eq. (2) varied depending on the band and exposure speed so that each equation was accompanied with the upper and lower limit values of \(D_e\).

4. Seasonal measurement for the targeted rice plots

The PDC took the images from 0800–1600 (JST) daily from 30 May to the end of the season (25 October) at 10-min intervals. The computer program employed exposure speeds of 0, 10, 20, 30, 40, 50, 60, 70 and 80 in that order, for both bands in each measurement period. The larger number of the exposure speed indicates a higher camera sensitivity. However, there is no released information on the
relationship between these exposure speeds and the actual sensitivity. The computer saved all the images regardless of the image quality: some images were too dark or too bright because the built-in automatic exposure speed control was inactive. The PDC was able to take images of the southern 9 plots (3×3) in the experimental paddy (Fig. 3). At the time of setting-up, the view tilt angle was adjusted remotely using the motorized platform for locating the central plot in the second row from the south end at the center of the camera’s sight. The view angle of depression was approximately 35º.

5. Reflectance calculation procedure

The averaged $D_e$ value of the central 100×100 pixels of a given image was compared with the upper and lower limits accompanied with Eq. (2) for the band and the exposure speed (e) concerned. When the $D_e$ value was within the limits, each $D_e$ value from in the plant plot was corrected using Eq. (1) as provided for each band and exposure speed, and then converted to the irradiance using Eq. (2). The averaged irradiance value in the plot was divided by the solar irradiance to derive the reflectance. The coordinates of the sampled points in the nine plots were determined manually by observing the imprints of unit area sampled for the yield survey. However, the coordinates had to be slightly adjusted on the day in mid July when a strong windstorm shifted the viewing direction of the PDC. The size of the sampled area in the images was constantly 20×20 pixels for all the plots without regard to the distance between the PDC and the targeted plots (Fig. 5).

6. Analysis of data

The plant canopy parameters (NT, PL and LCI) and radiometric variables were investigated through ANOVA (analysis of variance) tests and linear regressions using a software package for desktop computers (JMP, version 4, SAS Institute Inc., Cary, North Carolina, USA). For the ANOVA tests the statistical model used for the plant canopy parameters was a linear combination of the factors “basal dressing (BD),” “planting density (PD),” “growth stage (GS)” and their interacting terms (BD×PD, BD×GS, PD×GS, and BD×PD×GS). The model for the radiometric variables as the dependent variables consisted of the factors BD, PD, GS and “distance from the PDC (DIS).” Since no repetition was made because the PDC observed only 9 of the entire 18 plots, the interaction terms included in the model were BD×GS, PD×GS and DIS×GS. The radiometric variables were the reflectance values in the RED, NIR and normalized difference vegetation index (NDVI), where the NDVI was calculated using the following equation:

$$NDVI=\frac{\text{reflectance in NIR} - \text{reflectance in RED}}{\text{reflectance in NIR} + \text{reflectance in RED}} \quad (4).$$

In addition to the NDVI, the ratio vegetation index (RVI) and the difference vegetation index (DVI) were also tested.

$$RVI=\frac{\text{reflectance in NIR}}{\text{reflectance in RED}} \quad (5),$$

$$DVI=\text{reflectance in NIR} - \text{reflectance in RED} \quad (6).$$

The reflectance values were averaged for each day and the indices in Eqs. (4), (5) and (6) were derived from the averaged reflectance values. NDVI values obtained using two-band light intensities measured at the same time, instead of the daily-averaged band reflectance, were also calculated and are shown by ‘instNDVI’ (instantaneous NDVI). The radiometric variables analyzed were the means of daily averaged values measured on 5 d including the 2 d before and after the day the plants reached the corresponding growth stage. Radiometric variables observed at the milk-ripe (MR, 20 August) instead of dough-ripe (DR, 29 August) stage were analyzed because of the trouble in the system at the end of August.

To evaluate the measured band reflectance values, we calculated the correlation coefficients between the above-ground nitrogen absorption (NA, g m⁻²) observed at the MX and PF stages and the corresponding radiometric variables. Since the NA values were not directly measured in the plots observed by PDC, they were derived using the actually surveyed PL, NT and LCI by using the relations between those variables and DW and SPAD, and then NA and DW and SPAD. Next, linear regression models—consisting of the reflectance values and dummy variables of “distance of the plot from the PDC” (DIS: near, middle and far), and “growth stage” (GS: MX and PF) as the predictor variables—were employed to estimate the NA values.

Fig. 5. The observed southern 9 rice plots and the 20×20-pixel sampled areas for reflectance calculations. The background image is the RED band image taken at 1230 on 30 May 2007.
Results

1. Collection of spectral images for the paddy field
   The device started the measurement on 30 May. Trouble in the program caused measurement interruptions on 3 and 4 June. The hard disk drive in the computer crashed on 3 July, probably due to overheating. The system recovered the day after repair. From 23 August to 13 September, the system suspended measurement because the driver software that controlled the digital cameras stopped for unknown reasons. There was another 10-d interruption from 25 September to 5 October until the withdrawal on 25 October. This study mainly examined the data from 30 May to 18 September because the imprints caused by the unit area sampling made on 19 September might have prevented the device from taking proper reflectance of the plots. During this period, the previously mentioned intermission of measurement unfortunately occurred for three weeks in the ripening period. However, the successful observations from 30 May to 22 August almost continuously covered the entire way through from the initial tillering stage to the milk-ripe stage. Hence, the observation duration included most of the important growth stages when the number of productive tillers and number of grains per panicle were established and the final yields were partially determined. In the morning of 20 July, the local meteorological observatory recorded a maximum momentary wind speed of 16 m s\(^{-1}\). The PDC turned slightly on the pole and changed its view fractionally. All the plots were still in the camera view, so different coordinates for the sampled points in each plant plot were used in the former and the latter measurement periods, without adjusting the camera view.

2. Growth parameters of the experimental plants
   ANOVA tests were performed to determine the significance of the mean values for the NT, PL and LCI for the 18 rice plots. The interaction term between “basal dressing” and “planting density” (BD × PD) was insignificant in the tests for NT, PL and LCI. The mean NT increased from 377 tillers m\(^{-2}\) at the last productive tiller emergence stage to 658 tillers m\(^{-2}\) at...
the maximum tiller number stages, and then declined to around 360 tiller m\(^{-2}\) at the heading stage. The higher BD and PD increased the NT significantly but the interaction term “basal dressing” and “growth stage” (BD × GS) was also significant at 5% level. The root mean square of error (RMSE) was 35.5 tillers m\(^{-2}\) or about 5% of the maximum NT. The mean PL values increased steadily from 29.9 cm at the last productive-tiller emergence stage to 97.0 cm at the heading stage and declined to 83.1 cm at the dough-ripe stage. The BD of 5 g N m\(^{-2}\) might extend the mean PL 2 cm against the others but the PD did not significantly affect the PL. In the case of PL, the interaction terms including “growth stage” (BD × GS, PD × GS and BD × PD × GS) were insignificant. The RMSE value was 1.8 cm. The LCI declined (leaf greenness faded) until the panicle formation stage and recovered somewhat at the heading stage. The higher BD darkened the LCI and the highest PD plots showed lower (faded) LCI values. The brown rice yields distributed from 473 to 542 g m\(^{-2}\) and slight lodgings were observed only in the plots of BD of 5 g N m\(^{-2}\). Thus, the experimental site could be considered as a normally growing rice field and it was adequate for the trial study of seasonal reflectance estimations.

The plant growth parameters: NT, PL and LCI, observed in the PDC-observed area (southern 9 plots) were plotted against the corresponding values measured in the plots of the non-observed area (northern 9 plots: plot No. 10−18) in Fig. 6A, B and C, respectively. The correlations were significant and there was no evident bias from the 1:1 lines. Fig. 7 shows the relationships between the DW and PL×NT, and the SPAD and the LCI measured in the northern 9 plots. The DW and the SPAD in the PDC’s observation area were estimated through the medium of the 3 growth parameters of NT, PL and LCI. The following regression equations were then derived by the data set:

\[
\text{PL} \times \text{NT} = 5290.1 + 171.3 \times \text{DW}, \\
n = 18, r^2 = 0.97, \\
\text{stages: LP (12 June) and MX (3 July)}
\]  

(7),

\[
\text{PL} \times \text{NT} = 10920.2 + 89.8 \times \text{DW}, \\
n = 9, r^2 = 0.54, \text{stage: PF (12 July)}
\]  

(8),

\[
\text{LCI} = -0.604 + 0.121 \times \text{SPAD}, \\
n = 27, r^2 = 0.82, \text{stages: LP, MX and PF}
\]  

(9).

Using the transformed equations from Eqs. (7), (8) and (9), we estimated the DW and SPAD values in the southern PDC 9 observing plots (plot No. 1−9) in which the DW and SPAD values were not primarily surveyed. To see the usefulness of the DW and SPAD...
values in evaluating the nutrient condition of rice plants, the values of DW × SPAD were plotted against the total aboveground nitrogen absorption of the plant (NA, g m\(^{-2}\)) in Fig. 8. The relationships seemed to be linear at the stages of MX and PF. Although the evaluation was performed only for the northern 9 plots that were actually out of the PDC view area, it was assumed that a similar relationship might have existed in the PDC viewing plots. Transformed equations from the following linear regression models estimated the NA values in the 9 plots in the PDC viewing area:

\[
DW \times SPAD = 1254.0 + 1535.5 \times NA, \\
\text{r}^2 = 0.90
\]

\[
DW \times SPAD = 3619.6 + 1832.9 \times NA, \\
\text{r}^2 = 0.95
\]

Fig. 9. Diurnal changes of incident solar irradiance in the RED (SI-RED, ●) and NIR (SI-NIR, ○), and the solar elevation (º, ■) on 30 May, 12 June and 8 August, which were sunny and partly cloudy days.

3. Diurnal variations of estimated reflectance of a plant plot in the observed images

Fig. 9 shows typical three diurnal changing patterns of the solar elevation and the incident spectral irradiance (µW cm\(^{-2}\) nm\(^{-1}\)) in the RED and NIR bands recorded during the measurement campaign. The estimated reflectance values for the central plot (plot No. 5) on these days are plotted against the time of day in Fig. 10. Although the incident solar irradiance and solar elevation changed drastically, the estimated reflectance values were almost stable on the sampled days in the hours of late morning and early afternoon. However, a few reflectance values in the NIR band were lower than the majority on 8 August, for an unknown reason. The chart for solar irradiance sensor (SIS) outputs on 8 August shows that there were several sharp drops in the incident spectral irradiance in the NIR band during the observation hours (Fig. 9). The recorded SIS outputs were the one-minute averages preceding the camera exposure. Therefore, a sudden change in solar irradiance due to haze or clouds may have influenced the reflectance estimations.

The employed camera exposure speed was only 20’ for both bands. The other exposure speeds were tested, but only to show an insufficient stability in day-to-day and time-to-time variations. Even with the exposure speed at 20, the estimated reflectance values varied considerably in the early morning and late afternoon probably due to the lack of incident light energy. Therefore, for the estimation of daily
reflectance values, we hereafter fixed the observation period of each day from 0900–1400. Symmetrical time partitioning centered at noon (1200) such as 0900-1500 was not employed because the sun crossed the meridian before twelve noon, JST, in the site and eye-observations for the calculated diurnal reflectance values on several days indicated that the data variation was considerably larger in the 1400–1600 period. In addition, the incident irradiance range should be taken into account to obtain stable reflectance. Incident solar irradiance less than 20 μW cm⁻² nm⁻¹ gave unreliable estimates of reflectance values in both bands. On the other hand, conditions of more than 70 μW cm⁻² nm⁻¹ in irradiance frequently caused saturation in the NIR band, especially during the latter growing period. Hence, the threshold values of 20 and 70 μW cm⁻² nm⁻¹ were tentatively set for further calculation.

Besides the two conditions above, we did not take weather conditions such as cloud cover, rainfall, haze, mists or winds into consideration in the reflectance calculations.

4. Seasonal signatures of the RED- and NIR-band reflectance and the NDVI

Reflectance values in the two bands were calculated with the rules described in the previous section. The daily-averaged RED and NIR reflectance values and NDVI for the central parts of the 9 plots are plotted against the day of year in Fig. 11A, B, C respectively. The seasonal reflectance in the RED band decreased from the beginning of the measurement to the maximum tiller number stage and then slightly increased until the heading stage. It may have increased rapidly during the ripening period, although
the data were missing due to instrument trouble. The NIR daily-averaged reflectance steeply increased from the early growth stages to the panicle formation stage and asymptotically approached saturation, which might correspond with the pattern of the growth of green biomass and expansion of leaf area. The seasonal signatures of the band reflectance values seemed smooth and reasonable. The asymptotically reached reflectance values in the middle and late growth period were approximately 0.02 in the RED, and 0.95 (or more) in the NIR. The values of 0.02 in the RED and 0.95 in the NIR seemed rather low and high as the reflectance from rice plants, respectively (Shibayama and Akiyama, 1989). Since no on-the-site inspection of absolute values of reflectance was available during the measurement period, we used the obtained results for further analyses as they were. The seasonal NDVI values for the 9 plots increased steeply from the beginning to the panicle formation stage and then reached a plateau. The seasonally changing pattern was similar to that of the NIR but the variations among the plots and stages were less obvious.

ANOVA tests indicated that the factor of growth stage (GS) was highly significant (P<0.0001) for reflectance in the RED and NIR, and the NDVI and instNDVI. Table 1 presents the mean radiometric values and results of the statistical comparison tests. The basal dressing (BD) affected the reflectance in the RED (P=0.0002) and the NIR (P=0.01), and the NDVI (P=0.04) but did not in the instNDVI (P=0.416). The NDVI derived using the daily-averaged-two-band reflectance was superior to the instNDVI calculated using the detected light intensity in the bands without reflectance estimation.

The planting density (PD) affected none of the 4 radiometric variables (P=0.42−0.91). The reflectance values in the RED and NIR were sensitive to the distance (DIS) (P < 0.001) but it was not the case in the NDVI and instNDVI. Almost all the interaction terms were not significant except in the GS×BD (P = 0.024) and GS×DIS (P = 0.041) for the NIR reflectance.

5. Estimations for NA using two-band reflectance
Correlation coefficients between the radiometric variables and the NA indicated that the NIR band reflectance was the most high-correlated radiometric variable with the NA among the tested variables in each and combined stages of the MX and PF (Table 2). The DVI and RED reflectance were the next best and the NDVI, instNDVI and RVI were not only effective but also insignificant for the MX and the combined stages. Regression analyses for the models estimating the NA using the two-band reflectance values and the dummy variables of GS and DIS resulted that the
Table 2. Correlation coefficients between the above-ground nitrogen absorption (NA, g m\(^{-2}\)) and the observed radiometric variables measured for paddy rice plots.

| Growth stage | Number of observations | Reflectance in RED | Reflectance in NIR | NDVI | instNDVI | RVI | DVI |
|--------------|------------------------|--------------------|--------------------|------|----------|-----|-----|
| MX (3 July)  | 8                      | 0.79*              | 0.97***            | -0.18| -0.28    | -0.24| 0.96***|
| PF (12 July) | 9                      | 0.90***            | 0.90***            | -0.78*| -0.76*   | -0.75*| 0.87**|
| MX + PF      | 17                     | 0.79***            | 0.81***            | -0.13| -0.16    | -0.22| 0.80***|

The growth stages were the five-d periods centered at the maximum tiller number (MX, 3 July) and panicle formation (PF, 12 July). *, **, *** Significant at 5, 1, and 0.1% probability levels, respectively.

Table 3. ANOVA summaries of 4 multiple linear regressions estimating rice aboveground nitrogen absorption (NA, g m\(^{-2}\)) using the RED and NIR reflectance values with and without the dummy variables of growth stage (GS) and the distance between the plot and the sensors (DIS).

| Model identifier | Predictor variable | Degrees of freedom | Sum of squares | F    | P       | R\(^2\) | R*\(^2\) | Standard error |
|------------------|--------------------|--------------------|----------------|------|---------|---------|---------|----------------|
| I                | Growth stage (GS)  | 1                  | 2.9            | 309.5| <0.0001| >0.99   | >0.99   | 0.097          |
| I                | Distance (DIS)     | 2                  | 0.01           | 0.6  | 0.56    |         |         |                |
| I                | Reflectance in RED (RED) | 1                | 2.3            | 241.7| <0.0001|         |         |                |
| I                | Reflectance in NIR (NIR) | 1                | 10.5           | 1105.6| <0.0001|         |         |                |
| II               | GS                 | 1                  | 4.2            | 473.7| <0.0001| >0.99   | >0.99   | 0.094          |
| II               | RED                | 1                  | 6.3            | 704.2| <0.0001|         |         |                |
| II               | NIR                | 1                  | 14.3           | 1613.0| <0.0001|         |         |                |
| III              | DIS                | 2                  | 1.3            | 2.6  | 0.12    | 0.95    | 0.90    | 0.50           |
| III              | RED                | 1                  | 2.1            | 8.3  | 0.014   |         |         |                |
| III              | NIR                | 1                  | 17.7           | 70.2 | <0.0001|         |         |                |
| IV               | RED                | 1                  | 16.0           | 51.9 | <0.0001| 0.93    | 0.92    | 0.56           |
| IV               | NIR                | 1                  | 18.3           | 59.2 | <0.0001|         |         |                |

The criterion variable NA was obtained using the values of SPAD and DW, which were also estimated by actually surveyed PL, NT and LCI. Data observed in two before-heading stages (MX and PF) were analyzed. The number of observations was 17 due to excluding one negative observed NA value as an extreme. R*, multiple correlation coefficient adjusted by degrees of freedom.

The predictor variable of DIS in the regression models I and III was not significant (Table 3). Model II, that used the GS and the two-band reflectance estimated NA values, had the best accuracy among the models. Model VI, excluding the dummy variable of GS, provided a test to evaluate the performance of the sole reflectance values. Looking on the NA-SPAD×DW relations (Fig. 8), the parameters in Eq. (10) for the stage MX and Eq. (11) for the PF were different each other. Therefore, the radiometric estimation model VI without the GS parameter might have performed insufficiently. However, the R\(^2\) value of 0.93 and the standard error of 0.56 g m\(^{-2}\) indicate a considerably high performance of the model even for combined stages with no dummy variables. The obtained model equation (VI) is as follows:

\[
NA = -14.1 + 404.2 \times (\text{reflectance in RED}) + 13.5 \times (\text{reflectance in NIR})
\]  

(12)

The NA values derived with Eq. (12) using the reflectance values were plotted against the estimated NA values from the measured NT×PL and LCI in Fig. 12. Since this test used the same data set to build Eq. (12), they were not validating the model in a strict sense. However, it gives an approximate overview of the performance of the methodology. A linear relationship with the root mean squared error (RMSE) 0.5 g m\(^{-2}\) (10% of the mean observed NA) was gained. The estimates of both two stages seemed to line up on and around the common 1:1 line and do not require separate models for each stage.
1. Reflectance estimations using the observed images

Generally, ground reflectance observations have been performed at the nadir or near-nadir viewing directions (Richardson et al., 1982; Asrar et al., 1985; Patel et al., 1985). However, nadir observations using a camera tend to limit the viewing area when the camera elevation is finite due to the constraint of installing a tall pole 10 m or higher in a paddy field. A restricted view area caused by nadir viewing would limit the variability in plant growth conditions and resultant growing parameters, which might restrict the validity of the measurement. To simplify the measuring system and cut the cost, we did not use mobilization of the PDC view angle and/or position. Off-nadir or bird’s eye observations introduce bidirectional reflectance characteristics of targeted plant canopies into the measuring system (Kimes, 1983). This study has not solved the view angle effects but has partly evaluated it with statistical analyses. The distance (DIS) from the PDC to the targeted plots might be one of the possible sources of error because we made no view angle corrections in this study. However, the statistical tests for the data taken at the MX and PF stages indicated that the DIS was an insignificant predictor variable (Table 3). On the other hand, it was significant when all stages were included (Table 1). In earlier growing stages, reflectance values might be relatively insensitive to the effect of DIS (view angle) due to the smaller soil and water coverage with green leaves.

The reflectance values in the NIR band in the middle and latter growth period seemed to be higher than the corresponding data that has appeared in previous works (Patel et al., 1985; Martin and Heilman, 1986). On the other hand, the reflectance values in the RED band seemed to be lower than the previous results. The view zenith angles for the sampled points in the images varied from 43° for the nearest central plot to 55° for the center plot and 62° for the far central plot. Theoretical and experimental results indicate that backscattering at the larger view zenith angles produces a larger reflectance in relation to the value observed in the nadir direction (Shibayama and Wiegand, 1985). This fact might at least partly explain the high reflectance values in the NIR band observed in this experiment. In the visible wavelength, the soil coverage affects the reflectance. In the images of the off-nadir viewing, the soil coverage increased more rapidly than in the case of nadir viewing because rice plants have by nature a vertical leaf orientation.

This study made no field demonstration for the absolute values of reflectance during the measurement period. To collect reliable ground truth data for remote sensing, future study needs to improve the calibration technique and to include the field verification in the operational period for revealing the accuracy of the estimated reflectance values. However, the seasonal nature of reflectance changing in the two bands seemed principally reasonable, at least in their relative shapes, so that the optical and electrical functions and specifications seemed constant during the observation period.

The measurement trouble was mostly caused by breakdown of the hard-disk storage system, which was sensitive to high ambient air temperature, and subsequent software malfunction. These problems may be solved by using robust hardware and adding to the computer program multiple recovery functions for such emergencies.

2. Band reflectance versus NDVI

The NDVI saturated rapidly in the early growth period (Fig. 11), although the RED and NIR band reflectance values of 4 of the 5 tested stages differed significantly (Table 1). In addition, the obtained results indicated that the discrete band-reflectance was able to estimate the nitrogen absorption per unit land area more effectively in comparison with the daily-averaged NDVI and instNDVI (Table 2). Because it requires no solar irradiance monitors or calibration to derive vegetation indices such as NDVI, field spectroscopic observations could be greatly simplified. Instead of converting light intensity into reflectance, 2- or multi-band vegetation indices can be directly derived from the sensed light intensity in each band. The present work, however, showed that reflectance estimations were usable in seasonal monitoring for the nutrient conditions of rice plants. Naturally, further retests are necessary to draw any firm conclusions but the results showed a typical example of how band-reflectance measurements are superior than the NDVI that have
previously been widely applied for field radiometry.

3. Estimating nitrogen uptake

Regression summaries and evaluations (Table 3 and Fig. 12) indicated that the nitrogen absorption estimating model could be used for future practical application for rice plant diagnosis. Using the original before-heading data set, the performance of the model for nitrogen absorption prediction with the variation (relative RMSE to the mean nitrogen absorption of 10%) was acceptable because of non-destructive measurements. Major technical limitations on the measurement, however, are supposed to be the restriction for the growth stages of rice plants, and the distance of the target plots from the PDC. Asymptotic nature of the seasonal reflectance signatures (Fig. 11) may lower the performance after the panicle formation stage. The height of the pole practically restricts the applicability for distant plots. The experiment indicated that the PDC on the top of a 12 m-high pole could measure plots within at least 30 m from the base of the pole. In this condition, the variation in the view angle had no apparent effect on the measurement.

Chlorophyll or nitrogen content per unit leaf area or leaf DW (LNC) has been used as the targeted variable for field spectrometry (Zhu et al., 2007; Tanaka et al., 2008). Nakatani and Kawashima (1994) extracted green leaves from the background in red, green and blue video images to estimate the chlorophyll content per unit leaf area in wheat, barley and rye. Matsuda et al. (2003) showed maps of LNC of rice leaves in a paddy field of 10 to 15 d before heading using close-up digital camera images taken at very low angles, where there were actually no mixed pixels of soil and water that might have interfered with the estimation procedure. These works required a rather fine spatial resolution in the images to separate the leaves or hills from the background soil and water. To estimate band reflectance values from the whole plant canopy, we primarily averaged D values of 20×20 pixels from each plant plot image recorded by the PDC. In addition, the original spatial resolution of the PDC was too coarse to detect single leaf greenness from its position of 12 m above the ground. Therefore, we did not target LNC or the chlorophyll content of individual leaves in this study. Cameras with a higher resolution and more advanced techniques are needed to extract reflectance from individual leaves in the observed image. However, because nitrogen absorption is the total nitrogen amount absorbed by plants per unit land area, the radiometric variables taken for the whole canopy should be able to detect it more easily than LNC (Shibayama and Akiyama, 1986). Moreover, considering the impact of farming practices on the environment, nitrogen absorption, which is partly related to the nitrogen use efficiency is a valuable parameter (Yagi and Minami, 2005).

LAI during the vegetative period is another important parameter for determining the canopy productivity, but has not been measured at local agricultural experiment stations because it requires intensive labor and/or expensive instruments. The low-cost PDC system can also be applied to automatically observe the radiometric variables for estimating LAI, and warrants further study.

Conclusions

This study indicated that 2-band reflectance image observation could be useful for assessing above-ground nitrogen absorption during the period before heading regardless of the weather conditions on each measurement day. It will not in principle require labor and time for surveying once the regression model and its coefficients are initially fixed. The results suggested that this low-cost digital camera system could be as effective as more elaborate field spectroradiometers for collecting seasonally continuous spectral data for crop canopies, and warrants further investigation. By applying this technique, it will become possible to automatically collect ground truth data and/or compensate for the lack of satellite images due to cloud cover, and enable cropping management on a wider scale using satellite sensors.

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