Estimating Paddy Rice Leaf Area Index with Fixed Point Continuous Observation of Near Infrared Reflectance Using a Calibrated Digital Camera

Michio Shibayama, Toshihiro Sakamoto, Eiji Takada, Akihiro Inoue, Kazuhiro Morita, Wataru Takahashi and Akihiko Kimura

1National Institute for Agro-Environmental Sciences, 3-1-3 Kannondai, Tsukuba, Ibaraki 305-8604, Japan;
2Toyama National College of Technology, 13 Hongo-machi, Toyama, Toyama 939-8630, Japan;
3Toyama Prefectural Agricultural, Forestry and Fisheries Research Center, 1124-1 Yoshioka, Toyama, Toyama 939-8153, Japan;
4Toyama Prefectural Office, Agriculture, Forestry and Fisheries Department, 1-7 Shin-sogawa, Toyama, Toyama 930-8501, Japan;
5Kimura OyoKogei Inc., 292-4 Takagi, Saitama, Saitama 331-0071, Japan

Abstract: A two-band digital imaging system—one band for visible red (RED, 630–670 nm) and the other for near infrared (NIR, 820–900 nm)—was positioned 12 m above a 600-m² rice field. The imaging system automatically logged bird’s-eye-view images at 10-min intervals from 0700 to 1700 JST daily during the 2008 paddy rice season. Radiometric corrections and midterm field validations for the pairs of two-band images utilized solar irradiance sensors and prior calibrations to calculate 0900–1500 JST daily-averaged reflectance factor (DARF). The DARF values in the RED and the NIR bands agreed with observations made with a portable spectroradiometer and showed smooth seasonal changes in terms of plant growth. During the before-heading period, NIR DARF values had a correlation coefficient (r) of 0.91 with the leaf area index (LAI). An empirically derived equation for LAI using NIR DARF values and the cosines of angles between the view and the planting row directions, and the view and the meridian directions, showed R² values of 0.93, in estimations of LAI from the dataset (number of observations = 52) acquired at four sample points centrally located within the viewing field. Validation indicated that the equation also worked well for the other six observation points spread across the viewing field, the data of which were not used in deriving the equation parameters. The DARF values observed in the NIR band calibrated with solar spectral irradiance sensors were useful for assessing rice LAI during the before-heading periods.

Key words: Digital camera, Leaf area index, Near infrared, Red, Reflectance factor, Rice.

Prompt assessment of the ecological and physiological status of crop plants in a field area, which may range from a narrow experimental plot to crops on a regional scale (Akiyama, 2007; Muraoka and Koizumi, 2008), is emerging as a key technology in an agricultural industry that must consider both stable and high-quality production, and environmentally protective practices (Yagi and Minami, 2005). Precise and timely diagnosis of crop nutrient conditions in a region is essential, for example, in planning appropriate fertilization that could improve sustainability and economization (Moran et al., 1997). A technique known as “remote sensing” from air- or spacecraft has been extensively tested for practical use in Japan during crop production to collect crop status information (Asaka et al., 2006; Sakaiya et al., 2008; Tanaka et al., 2008). However, clear skies are not frequent enough during the summer cropping season in Japan to guarantee cloud-free remote sensing images every season (Akiyama and Kawamura, 2003). Furthermore, annual fluctuations in air temperature and the amount of insolation, for instance, may affect the crop yield and quality of harvest (Lee and Akita, 2000; Morita, 2000). On the other hand, air- and space-borne remote sensing usually require a link between remotely sensed data and variables related to crop status in order to build and subsequently validate the methods (Delécolle et al., 1992). Radiometric measurement with hand-held or

Received 30 October 2009. Accepted 25 May 2010. Corresponding author: M. Shibayama (shibayama@niaes.affrc.go.jp, fax +81-29-838-8199). This work was financially supported by Grants-in-Aid for Science Research (C) (Nos. 19580305 and 21580320) from the Ministry of Education, Culture, Sports, Science and Technology of Japan and the Japan Society for the Promotion of Science.

Abbreviations: DARF, daily-averaged reflectance factor; LAI, leaf area index; NIR, near infrared; RED, visible red; RF, reflectance factor.
ground-based equipment has provided valuable information in effective wavelength bands, basic model structures and model parameters for estimating agronomic information (Milton et al., 2009). Reflectance measurement in the visible and near infrared wavelengths using the sun as the light source has been widely studied to assess chlorophyll, nitrogen, leaf area, and biomass of various major crops including soy, sorghum, wheat, corn and paddy rice (e.g., Holben et al., 1980; Richardson et al., 1982; Asrar et al., 1985; Baret and Guyot, 1991; Daughtry et al., 2000; Takahashi et al., 2000; Zhu et al., 2007). Several researchers have been measuring reflectance spectra on the ground to use the detected crop status directly for farm management (Horio et al., 2004). Takahashi et al. (2003) devised a method of field diagnosis using portable spectroradiometer measurements to advise local farmers on appropriate top-dressing. However, because the methodology principally depends on sunlight for measurement, the unstable nature of solar illumination in an open field due to clouds, haze and change in the sun’s position has been a major problem in practical applications (Kunii and Murai, 2008). In fact, several authors have reported accuracy and stability. Recently, the feasibility of using single-lens reflex digital cameras for mapping was reported (Kunii and Murai, 2008). Various studies have been conducted to resolve this problem by correcting effects on reflectance due to changes in illumination with time of day, weather conditions, season, soil type, and site location (Kimes, 1983; Shibayama and Wiegand, 1985; Jackson et al., 1992; Vincini et al., 2008). However, the reliability and accuracy remain poor, and there are few automated reflectance monitoring techniques to measure the status of field crops at intervals of one day or less.

The present study aims to obtain accurate agronomic growth parameters of field crops non-destructively using spectral imaging techniques based on automated long-term and continuous monitoring, with solar irradiance as the light source. To overcome the instability of solar irradiance, we devised a two-band digital camera enclosed in a waterproof housing, combined with solar irradiance sensors, for collecting as many images as possible during the daytime regardless of the time and weather conditions. An imaging device such as a digital camera, instead of a non-imaging, unified-field-of-view radiometer, allows instantaneous and multiple-site observations without mechanical movement of the sensor (Kharuk et al., 1992; Shibayama et al., 1999). To reduce equipment costs, we used lowprice pocket cameras converted into a two-band imaging device. Low-cost pocket cameras are designed and manufactured mainly for taking snapshots easily, and manufacturers do not usually recommend them for measurement or survey use that requires a high degree of accuracy and stability. Recently, the feasibility of using single-lens reflex digital cameras for mapping was reported (Kunii and Murai, 2008). In fact, several authors have shown favorable results using color video or still digital cameras, or multiband cameras equipped with a near infrared band-pass filter for assessing crop coverage or leaf greenness (e.g., Kawashima and Nakatani, 1998; Adamsen et al., 1999; Purcell, 2000; Zhou and Robson, 2001; Matsuda et al., 2003; Jia et al., 2004; Ku et al., 2004; Casadesus et al., 2007; Omine, 2007; Takemine et al., 2007; Crimmins and Crimmins, 2008; Okada and Ikeba, 2008; Takada et al., 2009; Sakamoto et al., 2010).

In the present study, visible red and near infrared band images were collected at 10-min intervals along with solar irradiance data during a complete paddy rice season. The large number of observations, advanced radiometric calibration, midterm validation and statistical analysis of the dataset enabled the extraction of substantial radiometric information that was then utilized for assessing agronomic variables.

Previously, we described the devices and methodology employed in the present study, and shows preliminary results and a method for estimating nitrogen uptake in rice plants (Shibayama et al., 2009). However, validation for the obtained radiometric values was insufficient, and one of the major agronomic variables, leaf area index (LAI), was beyond the scope of that study. The objectives of the present study were to examine the reliability of estimated spectral imagery employing a calibration procedure, and to develop an empirical equation for estimating LAI of paddy rice using the measured radiometric data. In this attempt, we proposed to include the planting row direction, the azimuth direction of the camera’s view and the approximate mean solar azimuth direction as well as the radiometric values.

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, 630–670 nm) and another for near-infrared (NIR, 820–900 nm), built into a waterproof housing, was used to take measurements. The PDC was installed atop a 12-m-high duralumin telescopic pole (FSP-712X, Fuji Industry Co., Ltd., Chiba, Japan). The detailed specifications of the system have been described (Shibayama et al., 2009).

2. Radiometric calibrations

A radiometric calibration for the PDC was carried out before the study at the National Institute for Agro-Environmental Sciences, Tsukuba, Japan, on 30 April 2008. The procedures were as reported previously (Shibayama et al., 2009). A certified white reference panel (SRT-99-120, Labsphere Inc., North Sutton, NH, USA) was used instead of drafting paper as the reference for the radiometric calibration, because the former reflects more (>0.96) than the latter (~0.8), and this larger reflectance is required to calibrate the NIR band across a wider light intensity range.
Considering the employed measurement configuration and illumination conditions, we use the term “reflectance factor” (RF) instead of “reflectance” for the radiometric value obtained in the present study. In a strict sense, observations from all directions are required to measure the reflectance of a target. Because only one view direction was allowed for each targeted spot in this experiment, we supposed that the term “reflectance factor” would be more appropriate.

Using a portable spectroradiometer (Shibayama and Akita, 2002), we measured the spectral RF of the targeted paddy field on 13 August 2008. In addition, an on-site validation for the estimated RF values was performed from 3 to 5 September by placing a gray scale board (90 × 45 cm, GSB) at the center of the PDC sight. The GSB consisted of black, gray and white painted boards with RF values measured in the laboratory of 0.045, 0.27 and 0.82 in RED, and 0.040, 0.27 and 0.80 in NIR, respectively.

3. Targeted paddy field and agronomic survey

The experimental paddy was located on the campus of the National Institute for Agro-Environmental Sciences in Tsukuba, Japan (36º01’ 27” N and 140º06’ 27” E, 25 m a.s.l.). Plots of a rice variety (*Oryza sativa* L. spp. japonica, cv. ‘Nipponbare’) were established in two adjacent concrete-framed paddy fields each measuring 10 m × 50 m (Fig. 1). The seedlings were transplanted into one of the fields using a riding transplanter on 16 May 2008 (early-planted), and into the other field on 2 June (late-planted). Seedlings were planted in approximate northeast-southwest rows with a row width of 30 cm and an interhill space of 15 cm. The basal fertilization level was 4 g N m⁻² applied with compound fertilizers (N-P₂O₅-K₂O = 8-8-8). The experimental design included two topdressing fertilization levels of 4 and 8 g N m⁻², in total, applied with compound fertilizers (N-P₂O₅-K₂O = 17-0-17). Half the amount of topdressing fertilizer was applied at the panicle formation stage, and the other half was applied at the full heading stage. In the field of view of the PDC, there were four plots of paddy rice each approximately 5 m × 30 m in size. Panicles headed on 9 August in the plots planted earlier, and on 21 August in the ones planted later.

The growth parameters of the rice plants — plant length (PL, cm), leaf greenness (SPAD, dimensionless) and leaf area index (LAI) — were collected 23 times for the early-planted plots, and 24 times for the late-planted plots. This was done from 18 June through 16 October at 4 or 5-day intervals, after the PDC was setup in the field. We measured the leaf area index (LAI) using a plant canopy analyzer (LAI-2000, LI-COR, Inc., Lincoln, NE, USA) and the leaf greenness using a hand-held chlorophyll meter (SPAD-502, Konica Minolta, Inc., Tokyo, Japan). The surveys were conducted at three points in each of the four plots. The three sampling points were denoted as “near”, “middle” and “far”, and were approximately 8, 18 and 28 m, respectively, from the PDC. We selected the surveyed areas from locations that were closest to the sample points in the PDC images, which will be described later. For each parameter, we made three measurements at each particular point and used arithmetic means for further study.

In addition, three plant hills were sampled from the four plots each survey day during the season. The samples were oven-dried at 70°C, and the aboveground dry weight (DW g m⁻²) was estimated. The sample hills were taken from areas where the removal of plants would not influence the PDC images. Ideally, in each established plot, plant growth should be spatially uniform to evaluate the reliability of estimated radiometric variables. If not, it would be difficult to assess the interaction between the effects of a variation in the plants’ agronomic variables and the bidirectional reflectance distribution function (BRDF) of plant canopy, both of which should affect RF values (Kimes, 1983).

Because there was no replication for the experimental field, we could not examine the data separately for each date. Therefore, we arbitrarily grouped three consecutive measurements made within 10 days. Seven subsets each consisting of data from three consecutive surveys were prepared for further investigations that assessed the uniformity of growth among the locations in the plots by applying analysis of variance (ANOVA) tests. The ANOVA model was applied separately for each plot and subset consisted of the factors “date” (number of levels = 5) and “distance from the PDC” (number of levels = 5). The means of three agronomic variables were statistically compared using Tukey’s HSD test with significance at the 5% level.

4. Image collection and reflectance factor (RF) calculation procedures

The PDC system was set up on 13 June, 11 days after the second (late) transplanting. The PDC took images at 10-min intervals from 0700 to 1700 JST daily until 20 October. A computer program employed five arbitrarily chosen exposure speeds, 0, 10, 20, 30, and 40 from a possible range of 0 to 80, for both bands. These values are dimensionless and larger values indicate higher sensitivity. The PDC view’s azimuth direction was from southwest to northeast, and the view zenith angle was approximately 56°.

The PDC digital output ranged between 0 and 255 (8 bits), and the images measured 640 × 480 pixels. To adjust the parallax between the RED and NIR images, we obtained simple linear regression equations using six pairs of corresponding coordinates manually chosen as control points from the images of 17 October, in which there remained clear unit sampling imprints in the fields. The
coefficients of determination ($R^2$) were 0.99 in both equations for lengthwise and crosswise coordinates.

The mean output value of the central $100 \times 100$ pixels of a given image was compared to the upper and lower limits accompanied with the calibration equation for the corresponding band and the exposure speed. When the output value was within the limits, each value in the image was spatially corrected using the equations provided for each band and exposure speed, and then converted to spectral irradiance ($\mu$W cm$^{-2}$ nm$^{-1}$). Essentially, the spectral irradiance should be converted to spectral radiance ($\mu$W cm$^{-2}$ sr$^{-1}$ nm$^{-1}$). However, assuming the reference panel and targets as uniform diffusers, the spectral irradiance value of the target was divided by the corresponding solar spectral irradiance to derive the RF. We selected three sample points in the central two plots, and two points in each of the two outside plots in the PDC images. The coordinates of the ten sample points in the images were determined manually by marking points close to the agronomic survey areas. The size of sample points in the images was consistently $20 \times 20$ pixels for all the plots regardless of the distance between the PDC and the targets (Fig. 1). The $20 \times 20$ pixel sample area was determined by the results described in the following section [Results 2 (3)].

Results

1. Agronomic parameters of the experimental plants

The observed LAI varied approximately from 0.2 to 5.9 depending on the growth stage, planting dates and fertilization levels. Although repeated measurements for verification were not conducted in the present study, Yamamoto et al. (1995) reported that the plant canopy analyzer (LAI-2000) could successfully detect paddy rice LAI of 5 or less during the vegetative growth period. The reliability of LAI values might decline after heading due to the shading effect from emerged panicles. The ANOVA tests indicated that the factor “date” was significant ($P<0.05$) in about 80% of the seven data subsets each consisting of agronomic variables of PL, SPAD and LAI from three consecutive surveys made for the four plots ($7 \times 3 \times 4 = 84$ cases in total). On the other hand, the factor “distance” (near, 8 m; middle, 18 m; and far, 28 m from the PDC) was not statistically significant ($P>0.05$) in 76% of the variables, plots or subsets. For LAI, however, the factor “distance” had statistically significant differences in about one third of the plots and subsets but there was no clear correlation with stage. That is, the “distances”; near, middle and far from the PDC showed irregular and inconsistent influence on agronomic variables. We carefully prepared experimental fields for plants to be uniformly grown inside each plot. However, it is necessary to understand the extent of non-uniformity in plant growth by comparing the mean values of PL, SPAD and LAI. The means of these three agronomic variables observed at the three distances in the two central plots in the seven 10-day subsets are presented in Table 1. We summarized the mean values only for the two central plots because the PDC images did not capture the nearest corners in the outside plots (Fig. 1). The results indicate that only a few of the plots in the early or late growth stages had significantly different PL, SPAD and LAI. The differences in PL and SPAD were less than 10%, with the worst figure being 20% in LAI that was observed in the earliest subset (18–27 June), in which the LAI values were less than 0.5. Hence, there may have been some occasional irregularity in plant growth in each plot but its influence on RF at the sample points in each plot was negligible.

2. Evaluating spectral images of the paddy field

(1) Reflectance factor (RF) estimations using the gray scale board (GSB)

Calculated RF values in RED and NIR of the GSB were relatively stable in terms of the employed exposure speed, from 0800 to 1600 JST when solar irradiance exceeded a certain level. In less illuminated conditions, however, RF values showed a sharp increase, and/or considerable fluctuation. Therefore, a minimum spectral irradiance threshold was tentatively given at 20 $\mu$W cm$^{-2}$ nm$^{-1}$ in both bands for the RF calculations. In RED, means of calculated RF for the 3-day measurement were 0.048 and 0.321 using the black board and gray board, respectively, with a standard deviation of 0.01 and 0.042, respectively. These values agreed well with laboratory-measured RF values of 0.045 and 0.27. However, in the white board observations,
the mean value was 0.835 and standard deviation 0.084. In NIR, the means of calculated RF for the 3-day measurement were 0.150, 0.301 and 0.677 and standard deviations 0.028, 0.035 and 0.060, respectively, using the black, gray and white boards. The calculated RF using the black board fluctuated between 0.11 and 0.17, which was larger than the laboratory-measured value of 0.04, that using the gray board, fluctuated between 0.25 and 0.32, which was within the laboratory-measured value of 0.27, and that using the white board was appreciably less than the laboratory-measured value of 0.80. These results indicate that the optoelectronic response of the PDC might have problems in terms of linearity, providing that the GSB is a uniform diffuser, and the camera for NIR does not suffer a “blooming effect”. This effect produces fringes (or feathers) of light around very bright objects in an image. However, expected band RF values from paddy rice generally do not exceed 0.2 in RED, and surpasses 0.1 in NIR from the maximum tiller number stage to harvest (Shibayama and Akiyama, 1989). Consequently, we concluded that the validation result was not completely satisfactory, but the obtained RF values were worth testing further with actual rice plant canopies. Based on these results, we fixed thresholds in solar spectral irradiance for each exposure speed in each band. By comparing the recorded solar irradiance to the thresholds, we could determine whether or not a particular image should be used for the daily-averaging calculation. The minimum spectral irradiance threshold was 20 μW cm⁻² nm⁻¹ in both bands. The largest spectral irradiance on a clear-sky day exceeded 100 μW cm⁻² nm⁻¹ during the study.

Table 1. Means of the three agronomic variables of paddy rice plants, plant length (cm), SPAD value and LAI observed at the three distances from the observation instrument (PDC) in the central two plots in the seven growing periods. Data from three observation dates were merged for each period and ANOVA tests were applied to each plot.

| Plant length (cm) | Transplanting date (TP) and fertilization (TN) | TP: 16 May, TN: 8 g m⁻² | TP: 2 June, TN: 12 g m⁻² |
|------------------|-----------------------------------------------|-------------------------|--------------------------|
| Merged dates     | Near      | Middle    | Far       | Near      | Middle    | Far       |
| 18, 23, 27 June  | 42.7 a    | 43.1 a    | 42.1 a    | 31.2 a    | 30.9 a    | 31.0 a    |
| 2, 7, 11 July    | 62.5 a    | 63.8 a    | 60.8 b    | 46.5 a    | 47.0 a    | 43.2 b    |
| 16, 22, 25 July  | 76.3 a    | 76.1 a    | 74.0 a    | 66.4 a    | 66.3 a    | 64.3 a    |
| 30 July, 4, 8 August | 89.9 a  | 91.3 a    | 89.3 a    | 81.9 a    | 81.5 a    | 81.7 a    |
| 13, 18, 22 August | 106.3 a  | 106.6 a   | 107.0 a   | 100.4 a   | 99.3 a    | 100.1 a   |
| 27 August, 1, 5 Sept. | 109.4 a | 107.1 a   | 109.5 a   | 110.0 a   | 107.7 b   | 109.1 ab  |
| 10, 17, 22 Sept.  | 108.2 a   | 108.2 a   | 110.1 a   | 109.1 a   | 108.1 a   | 110.8 a   |

| SPAD             | 18, 23, 27 June | 38.8 a    | 38.6 a    | 40.2 a    | 38.4 a    | 36.9 a    | 38.4 a    |
| 2, 7, 11 July    | 33.1 a    | 33.0 a    | 34.1 a    | 39.0 a    | 35.8 b    | 36.9 ab   |
| 16, 22, 25 July  | 30.5 a    | 30.5 a    | 29.8 a    | 30.5 a    | 30.5 a    | 28.9 a    |
| 30 July, 4, 8 August | 29.2 a  | 29.9 a    | 30.5 a    | 32.7 a    | 32.9 a    | 33.2 a    |
| 13, 18, 22 August | 30.4 a   | 31.0 a    | 31.2 a    | 32.3 a    | 32.8 a    | 31.5 a    |
| 27 August, 1, 5 Sept. | 33.0 a  | 33.2 a    | 32.7 a    | 36.5 a    | 36.1 a    | 36.9 a    |
| 10, 17, 22 Sept.  | 26.5 a    | 25.5 a    | 25.5 a    | 32.6 a    | 32.2 a    | 32.6 a    |

| LAI              | 18, 23, 27 June | 1.79 a    | 1.91 a    | 1.58 a    | 0.45 ab   | 0.46 a    | 0.38 b    |
| 2, 7, 11 July    | 3.22 a    | 3.42 a    | 3.32 a    | 2.19 a    | 2.06 ab   | 1.87 b    |
| 16, 22, 25 July  | 4.24 a    | 4.50 a    | 4.21 a    | 3.52 a    | 3.33 a    | 3.15 a    |
| 30 July, 4, 8 August | 4.59 a  | 4.68 a    | 4.50 a    | 4.04 a    | 3.91 a    | 3.92 a    |
| 13, 18, 22 August | 5.18 a   | 5.48 a    | 5.25 a    | 4.58 a    | 4.40 a    | 4.45 a    |
| 27 August, 1, 5 Sept. | 5.33 b   | 5.75 a    | 5.48 ab   | 5.12 a    | 4.93 a    | 5.00 a    |
| 10, 17, 22 Sept.  | 5.00 a    | 4.91 a    | 4.95 a    | 4.79 a    | 4.75 a    | 4.41 b    |

* Different letters beside the means within one row denote the difference between the pair of means that was significant in Tukey's HSD test at the 5% level. Underlines indicate that the pair of means is significantly different.
Diurnal RF variations in the rice paddy and daily-averaging calculation

The calculated RF values, averaged on 11 July, and 9 and 27 August in a 20 × 20 pixel area from the central part of the early-planted paddy field, were around 0.05 and 0.6 in RED and NIR, respectively (Fig. 2). These RF values varied little with the time of day except for the hours before 0900 and after 1500 JST, although the solar irradiance must have been changing due to clouds and solar elevation. Spectral RF observations using a hand-held radiometer at a height of 1.5 m looking toward nearly the identical view azimuth direction as the PDC and various view zenith angles varied around 0.05 in the 660-nm band, and ranged between 0.4 and 0.8 in the 830-nm band, respectively (Fig. 3).

The hand-held observations showed that instantaneous RF was obviously increased along with the view zenith angle. Comparing the RF values taken at around a view zenith angle of 56º, the angle of the PDC’s optical axis, the observed RF values using the hand-held radiometer were in approximate agreement with the PDC values in RED and NIR.

To produce seasonal RF signatures, we calculated daily-averaged reflectance factor (DARF) values from the data taken from 0900 to 1500 JST each day. We selected images taken at three exposure speeds, 0, 10 and 20 (dimensionless) for RED, and 10, 20 and 30 for NIR. Corresponding to these exposure speeds, the minimum threshold solar spectral irradiance levels, 70, 40, 20 μW cm⁻² nm⁻¹ for RED, and 30, 25, and 20 μW cm⁻² nm⁻¹ for NIR, were decided from the results of the GSB observations [Results 2-(1)]. Images taken under less illuminated conditions were omitted from the daily-averaging calculation.

Spatial variations of estimated RF values in the images

On a fine scale, less than a few centimeters resolution, RF of a plant canopy would not be spatially uniform because there would be sunlit and shaded plant organs and soil/water surfaces, especially in the early growth stages when the canopy closure is incomplete. However, our objective was to estimate the mean RF values from a larger area of the crop field (e.g., square meters) rather than from a pinpoint (e.g., square centimeters). First, we tested the RF variation in terms of the size of the viewing spot in the DARF images of RED and NIR captured on 18 June when the rice canopy did not completely cover the
The sampled spots were located at three positions: near, middle and far from the PDC (Fig. 4a). DARF values against the number of pixels on the side of the four square-shaped sampling spots indicated that the minimum required area should be a 20 × 20 pixel square (Fig. 4b).

Secondly, we investigated the estimated DARF values averaged in 20 × 20 pixel squares located at various positions in the images collected on 18 July for fully covered canopies. DARF values on the three horizontal cross-sectional lines indicated that the effects of location within the two planting-date plots were unclear (Fig. 5). The DARF values were satisfactorily uniform regardless of the coordinates in the PDC view. This suggests that images were appropriately corrected in terms of spatial distortion due to the optics of the cameras. Finally, the view angle effect on the estimated RF was examined by taking DARF values in 20 × 20 pixel square spots at various positions in the two central plots on 18 August (Fig. 6). The coordinates of the spots were converted into the approximate view zenith angles from the PDC. As shown in Fig. 7, the NIR

[Fig. 4](#) Three sampling locations—near, middle and far—with various sizes of sampling area in the two-band images observed on 18 June 2008 (a), and daily-averaged reflectance factor (DARF) values (b).

[Fig. 5](#) Daily-averaged reflectance factor (DARF) values in the two bands sampled at the locations indicated in the image (left side) observed on 18 July.
Shibayama et al. — LAI Estimation with Spectral Images of Rice Paddy

DARF values showed a slight upward trend with the increase in view zenith angle in the observations from 8 July to 18 August. However, the view angle effect was not as clear as that observed in the hand-held RF measurement (Fig. 3). We conducted further analyses on the assumption that estimated values averaged for a 20 × 20 pixel square in the DARF images are nearly uniform in terms of the view zenith angle in the image.

(4) Seasonal variations of DARF in the images

During the 130-day period from 13 June to 20 October the device operated all days except 13 July; the cause of the inoperability being unknown. The replacement of the computer hard disk storage system prior to this experiment might have improved the stability and confidence; results from the previous experiment lacked data for at least 20 days in the maturing period and other periods (Shibayama et al., 2009).

Estimating RF and the daily-averaging calculation for each pixel in each band provided RF band images for each day. The seasonal signatures of DARF values in the two bands were smooth and reasonable. On several dark, cloudy and rainy days, no images with sufficient solar irradiance were taken. Thus, there were 12 days without images in RED, and 6 days in NIR. For these days, data were complemented using images taken on the dates before and after the concerned date. The seasonal reflectance patterns in the RED and NIR bands of four points in the fields along with the amount of solar radiation and the duration of sunshine are shown in Fig. 8 (courtesy of the Weather Data Acquisition System of the National Institute for Agro-Environmental Sciences, Tsukuba, Japan). The RF values of less than 0.1 in RED, and from 0.2 to 0.6 in NIR seemed to be in general agreement with our field validations (Fig. 3). The NIR RF values of the early-planted plots were larger in the before-heading periods (vegetative growth phase plus panicle development period) than late-planted plots. The difference of the maximum NIR RF values in the early- and late-planted plots was larger than what could be simply explained by the difference in the final LAI values (Table 1). For instance, despite the almost identical LAI value of 4.0 measured in the early-planted spot# 2 on 16 July and late-planted spot# 5 on 4 August, the corresponding NIR DARF values of the spots# 2 and 5 observed on each date were 0.56 and 0.45, respectively. Not only plant growth, but other factors, such as plot locations and/or observation geometry, should also be taken into consideration. In the RED band, however, there was no clear difference between the early- and late-planted plots except for the initial 10–15 days.

3. Estimating LAI using PDC RF images

(1) Correlation analyses

Correlation coefficients between the daily-averaged radiometric variables from each sample point and the agronomic variables that included PL, SPAD, DW and LAI were calculated for the dataset from the middle sections of the four plots. The DARF values of RED and NIR, along with a widely used vegetation index, the Normalized Difference Vegetation Index (NDVI) [NDVI = (DARF in NIR–DARF in RED)/(DARF in NIR+DARF in RED),] were also calculated for the days of the corresponding plant growth survey. Radiometric variables were collected from the 20 × 20 pixel square areas centrally located in the four plots. Calculations were made separately for the whole dataset and for the dataset from the before-heading period. Results indicate that DARF in NIR has the largest r-value with LAI, whereas reflectance in RED and the NDVI show statistically significant (P < 0.01) but slightly lower r-values (Table 2). Among the four agronomic variables tested, LAI most closely correlates with the radiometric variables, especially in the before-heading period (Table 2). The largest correlation coefficient for LAI and NIR DARF is 0.91 for the 52 observations (P < 0.001) from the before-heading period.

(2) Multiple regression models for LAI estimation with stepwise variable selection

We tested a multiple linear regression model (1), shown in Table 3, that included the RED and NIR DARF values, the NDVI, and two dummy variables of “transplanting date” and “fertilization level” as the predictor variables for estimating the LAI. The data sampled from the four centrally located points in the plots in the before-heading period (observation number = 52) was analyzed by
regression analysis. Partial regression coefficients for RED DARF, NIR DARF and “transplanting date” among the tested variables in the regression model (II) were significant (P<0.01) in statistical t-tests, and the R² value was 0.939 (Table 3). Overall, as shown in Fig. 9a, model (II) performed appropriately for all 10 sample points, including the four centrally located points used to build the model. However, there was a remarkable positive bias from the 1:1 line in the middle range observed, especially in the data from the late-planted plots. In the case of model (III) without the dummy variable of “planting date”, the RED and NIR DARF values were highly significant but the R² value declined to 0.853. Moreover, the scatter diagram indicates that the fitting of the model is slightly inadequate (Fig. 9b). The Akaike’s Information Criterion (AIC) value of –61.7 was larger than the value –105.3 of
Table 2. Correlation coefficients of the agronomic and radiometric variables observed in the middle sample points of two central plots of the experimental paddy rice fields. The upper-right section of the table sums up the results for the before-heading periods (observation number = 52, P[|r|> 0.28] = 0.05, P[|r|> 0.36] = 0.01, P[|r|> 0.45] = 0.001). The lower-left section is for the results obtained for the whole dataset including the maturing stages (observation number = 94, P[|r|> 0.21] = 0.05, P[|r|> 0.27] = 0.01, P[|r|> 0.34] = 0.001).

| Variable          | SPAD | Plant length | DW | LAI | DARF in RED | DARF in NIR | NDVI** |
|-------------------|------|--------------|----|-----|-------------|-------------|--------|
| SPAD              | SPAD | Plant length | DW | LAI | DARF in RED | DARF in NIR | NDVI** |
| Plant length      | 0.51 | 0.94         | 0.90 | 0.34 | -0.60       | -0.49       | 0.72   |
| DW*               | -0.61 | 0.97         | 0.92 | -0.46 | 0.80       | 0.80       | 0.65   |
| LAI               | -0.50 | 0.92         | 0.84 | -0.56 | 0.91       | 0.84       |        |
| DARF in RED       | -0.60 | 0.33         | 0.55 | 0.18 | -0.44       | -0.78       |        |
| DARF in NIR       | -0.27 | 0.62         | 0.50 | 0.79 | -0.17       | 0.84       |        |
| NDVI**            | 0.16  | 0.18         | -0.05 | 0.38 | -0.72       | 0.70       |        |

*DW stands for above-ground dry weight.
**NDVI = (DARF in NIR – DARF in RED) / (DARF in NIR + DARF in RED).

Fig. 8 Seasonal patterns of daily-averaged reflectance factor (DARF) values in the RED (above) and NIR (middle) bands observed at the four middle sample points in the paddy rice fields. The daily amount of insolation and duration of sunshine are plotted against the day of year (below).
model (II), indicating that model (III) was less appropriate than model (II) (Akaike, 1974). Although the earlier transplanted plants might grow faster than the late-planted ones especially in the early growth period (Table 1), the transplanting date itself would have basically little effect on the radiometric LAI-RF relationship. Therefore, we inferred that the view azimuth directions for the early- and late-planted plots might be a contributing factor. It was difficult to arrange both early- and late-planted plots in each field, located on both the left- and right-hand side of

Table 3. Variable selection summaries of multiple linear regressions estimating paddy rice LAI using the daily-averaged reflectance factor (DARF) values in the RED and NIR bands with and without the dummy variables of transplanting date and fertilization level. The number of observations was 52 for the four middle sample points (spot #2, 5, 7 and 9 in Fig. 1).

| Model identifier | Predictor variable | Partial regression coefficient | Standard error | t | P | R² | AIC* | F |
|------------------|-------------------|--------------------------------|----------------|---|---|----|------|---|
| I I               | Intercept         | 0.7708                         | 1.1275         | 0.68 | 0.4977 | 0.942 | −104.2 | 155.0 |
|                  | DARF in RED       | −30.4811                       | 10.3199        | −2.95 | 0.0049 |
|                  | DARF in NIR       | 12.7181                        | 0.9885         | 12.87 | <.0001 |
|                  | NDVI              | −1.9667                        | 1.2242         | −1.61 | 0.115  |
|                  | Transplanting date| −0.5333                        | 0.0635         | −8.39 | <.0001 |
|                  | Fertilization level| 0.0043                         | 0.0499         | 0.09 | 0.9318 |
| II               | Intercept         | −0.8406                        | 0.4664         | −1.82 | 0.0757 | 0.939 | −105.3 | 245.9 |
|                  | DARF in RED       | −17.1374                       | 5.6950         | −3.01 | 0.0042 |
|                  | DARF in NIR       | 11.3711                        | 0.5884         | 12.12 | <.0001 |
|                  | Transplanting date| −0.5209                        | 0.0634         | −8.21 | <.0001 |
| III              | Intercept         | 0.9289                         | 0.6344         | 1.46 | 0.1495 | 0.853 | −61.7  | 142.2 |
|                  | DARF in RED       | −27.4518                       | 8.5244         | −3.22 | 0.0023 |
|                  | DARF in NIR       | 8.5661                         | 0.6389         | 13.41 | <.0001 |

* Akaike’s Information Criterion (Akaike, 1974).

Fig. 9. Before-heading period LAI of paddy rice estimated with a multiple linear regression model consisting of daily-averaged reflectance factors (DARF) in RED and NIR, with (a) and without (b) a dummy variable of “transplanting date” versus LAI measured using LAI-2000. The model equations identified as “II” and “III” are shown in Table 3. They were derived from a dataset collected from the four middle sample points (spot #2, 5, 7 and 9 in Fig. 1) and then applied to all ten sample points.
PDC to the target spot as well as from the position of the sun. The rice plants were planted in rows that ran from the foot of the PDC pole to the far side of the PDC view, in long rectangular-shaped plots. Moreover, the row direction was not parallel to the meridian. Although the DARF calculation used data collected from 0900 to 1500 JST, the meridian passage of the sun may need to be one of the model parameters. This would be much easier than taking the instantaneous solar position for each PDC shot. Assuming the view direction affects the LAI-RF relationship, we introduced the following two angles (Fig. 10). The first was the angle between a line from the PDC to the center of the target area and the row running through that target (A, degrees). The second was the angle between a line from the PDC to the target area and the meridian (B, degrees). For both angles, we considered only the horizontally projected geometry, and neglected the angular configuration in the vertical profile because this was only a preliminary attempt, and there was no remarkable difference in DARF values in terms of the view zenith angle of the PDC (Fig. 7). The regression analyses with stepwise variable selection used the cosine values of angles A and B as well as the DARF values to estimate the LAI (model (IV) in Table 4). The angles A and B of the 10 sample points ranged from 3.7° to 28.6°, and from 20.4° to 73.6°, respectively. The cosine A values were between 0.88 and 0.99, and the values of cosine B varied from 0.28 to 0.94. For the dataset from the middle sample points in each plot during the before-heading period, the variables cosine A and cosine B were both highly significant as was NIR DARF (P<0.0001) in the final model (V). The R² value of 0.926 was rather close to that given by the previous model (II) with the dummy variable of “transplanting date”. The AIC value –95.0 for model (V) indicated that it performed better than model (III) but not as well as model (II). For some reason, RED DARF was not a significant variable in this model. We then applied model (V) for the entire dataset from the 10 sample points, and the scatter diagram showed a favorable match between measured and estimated LAI values (Fig. 11). There is no obvious bias or skew in the scattering of data around the 1:1 line for either the early- or late-planted plots. The root mean square errors (RMSE) and r-values for the late-planted plots were slightly better with model (V) than with models (II) and

Table 4. Variable selection summaries of multiple linear regressions estimating paddy rice LAI using RED and NIR DARF values, NDVI, the cosine of the angle between the view and planting row direction (Cos A), and the cosine of the angle between the view and meridian directions (Cos B). The number of observations was 52 from the four middle sample points (spot # 2, 5, 7 and 9 in Fig. 1).

| Model | Predictor variable | Partial regression coefficient | Standard error | t | P | R² | AIC* | F |
|-------|-------------------|-------------------------------|----------------|---|---|----|------|---|
| IV    | Intercept         | –4.7711                       | 2.6978         | –1.77 | 0.0836 | 0.926 | –91.7 | 115.8 |
|       | Cos A             | 4.7400                        | 1.6619         | 2.86 | 0.0064 |
|       | Cos B             | –2.1838                       | 0.3277         | –6.66 | <.0001 |
|       | DARF in RED       | –3.6257                       | 14.7070        | –0.25 | 0.8064 |
|       | DARF in NIR       | 11.2670                       | 1.1067         | 10.18 | <.0001 |
|       | NDVI              | 0.2395                        | 1.5372         | 0.16 | 0.8769 |
| V     | Intercept         | –5.3496                       | 1.2988         | –4.73 | <.0001 | 0.926 | –95.0 | 198.8 |
|       | DARF in NIR       | 11.6863                       | 0.4994         | 23.40 | <.0001 |
|       | Cos A             | 5.2235                        | 1.2311         | 4.24 | 0.0001 |
|       | Cos B             | –2.2849                       | 0.2822         | –8.10 | <.0001 |

* Akaike’s Information Criterion (Akaike, 1974).
the instantaneous RF estimates into DARF values, which is most purposes for crop diagnosis. Our point is to sum up for more definitive objectives, but DARF values can serve from crop fields. Instantaneous RF values may be necessary at least daily-averaged reflectance factor (DARF) values even low-cost digital cameras could be used for collecting two wavelength bands. The results of our study suggest that provide reasonable RF values for rice plant canopies in the experiment demonstrated that the method could expand the available irradiance range to obtain a larger number of images. The field validation during the measurement period provided the solar spectral irradiance thresholds employed in the DARF calculations. We conducted the calibration more carefully under stable weather conditions and higher reference light intensity to obtain reliable parameters to estimate RF values in the present study. Both the validation with the GSB and the comparison with data from another spectroradiometer during the experiment showed that the method could provide reasonable RF values for rice plant canopies in the two wavelength bands. The results of our study suggest that even low-cost digital cameras could be used for collecting at least daily-averaged reflectance factor (DARF) values from crop fields. Instantaneous RF values may be necessary for more definitive objectives, but DARF values can serve most purposes for crop diagnosis. Our point is to sum up the instantaneous RF estimates into DARF values, which might reduce variation and noise due to changes in illumination (light intensity and direction).

Spatial variation should also be taken into consideration for image measurement. The spatial correction technique employed and calibration parameters for the cameras should work as well. A certain uniformity in the established crop plots was required to confirm the effectiveness of these calibrations, especially between the near, middle and far positions. As previously described, there was little variation in LAI or other agronomic variables among the near, middle and far points (Table 1). As we had concern over variation in soil fertility and/or planting density in each plot, and considering that the study dealt with open field crop plants, the resultant differences in the means of agronomic variables due to distance seemed to be small and inconsistent during the season.

Due to the bird’s-eye-view observations, angular effects might influence PDC outputs for reflected light from different positions in the viewing sight. The view zenith angles for the sample points in the images varied from approximately 34º for the nearest central points to 56º for the middle, and 68º for the far central points. Reflected light from inter-hill spaces, which are actually soil and water surfaces in a paddy, should be relatively more detectable in the sample points closer to the PDC than the more distant points. In addition, RF generally tends to increase along with an increase in the view zenith angle, which was obvious in our hand-held radiometry measurements (Fig. 3). This is due to the bidirectional reflectance distribution function (BRDF) characteristics of the vegetation canopy itself (Kim, 1989). In the present study, RF values of approximately 0.05–0.1 in the RED band and 0.2–0.6 in the NIR band may be about 1.5-times larger than previous results for rice paddies reported by other authors (Martin and Heilman, 1986; Shibayama and Akiyama, 1989; Zhu et al., 2007). The difference might be due to the fact that our observations were made at off-nadir view directions, but the previous authors measured targeted canopies from the nadir view direction (Shibayama and Wiegand, 1985). However, apart from the difference in the absolute values of RF, the effect of the view zenith angles was not clearly evident in the DARF images even though NIR DARF values measured from early July to mid August demonstrated a slight upward trend along with the view zenith angle (Fig. 7). This might be partly due to the fact that the daily-averaging procedure, which includes data taken under sunny, cloudy and overcast conditions as well as at various solar positions, may have reduced the effects of BRDF in the plant canopies. The daily-averaging procedure may obscure the effects of geometry between illumination and viewing directions. The fixed sample area of 20×20 pixels might also reduce the spatial variation among the sample locations. Hence, the simplistic approach of the present study neglected the
Automated observations for radiometric data that estimate agronomic variables would enable the comparison of year-to-year trends in crops' eco-physiological responses to environmental changes. Since it requires little labor cost to store the data, observations over several years are feasible for precise analysis and evaluation to plan for optimum environmental changes. Since it requires little labor cost to store the data, observations over several years are feasible for precise analysis and evaluation to plan for optimum environmental changes. Since it requires little labor cost to store the data, observations over several years are feasible for precise analysis and evaluation to plan for optimum environmental changes.

We introduced the two angular variables based on the view zenith angle effect on DARF. More detailed investigations, however, will be required in future applications. The deviation in RF values due to the viewing angle needs to be investigated further in perfectly arranged experimental fields in different years and under various conditions. Although further replication is required, but the results of the present study indicate that DARF estimates from a certain area in the view field of the PDC could be reliable as a field radiometric measure.

The scatter diagram of estimated and measured LAI values obtained using the simple regression model without the dummy variable of “planting date”, which was actually the right and left fields as seen from the position of the camera, showed a curved line around the 1:1 straight line (Fig. 9 b). Moreover, the asymptotic values of NIR DARF of the late-planted plots were 60–70% of the corresponding values of the early-planted plots during the period from 28 Jul to 27 Aug (DOY210-DOY240) (see Fig. 8), although final LAI values of late-planted plots were no less than 85–95% of the early-planted plots (Table 1). These facts might indicate that the initial models (II and III) describe only a part of the experimental results, and “observation direction” instead of “planting date” played an essential role. Because the frontal direction of the PDC was not aligned with the meridian (Fig. 10), view azimuth angles for the observed targets in the DARF image might have greater effect on the illumination-view relationship during the daily measurement period that started and ended at fixed times of the day (0900 to 1500 JST).

We introduced the two angular variables based on the camera’s view direction, planting row and the meridian. It was expected that a parameter including angle A might correct the effects on reflected light from combined targets that consist of soil and/or water surface, and shaded and lit foliage. The diversification of targeted objects in a spot viewed from the PDC would be particularly important when the plants are planted in rows and the vegetation cover is still incomplete. Angle B was simply introduced to partly correct the BRDF effect on RF measured at given illumination and reflection angles. Angles A and B are both determined with reference to the view azimuth direction. In other words, they indicate the view direction relative to the planting row and the mean solar position. Hence the effects of the interaction between the sun and planting row direction were not directly considered in the model. The experiment simply shows that the meridian direction might represent the transient sun position in the statistical model covering over two-month period based on the daily-averaged RF as an effective parameter. The BRDF effect is too complicated to be completely solved by a single parameter, but these variables are easy to measure with no additional information, particularly in terms of changing plant canopy parameters (plant growth). One of the advantages of introducing the angles A and B is that the skew in the distribution pattern in the scattered data points shown in the results of the model using them (Fig. 11) was less conspicuous than in the results of models with the dummy variables (Figs. 9a and 9b). This fact indirectly supports the usefulness of angles A and B in the model, although the causes have not yet been clearly determined. Preliminary results indicate that the newly introduced variables succeed in replacing the dummy variables although further tests in various cropping periods, site locations, planting rows and view directions, which are all affecting view and illumination geometry, are required to prove the validity and functions of the angular parameters A and B in the model.

The flat diurnal patterns of RF indicate that the sun position as well as clouds had little effect on the observed instantaneous RF values (Fig. 2). Moreover, there was little difference in DARF observed for the points spread over in the single-day DARF images (Figs. 4, 5 and 7). Those tests primarily show that little unnatural distortion or unevenness existed in the DARF images due to instrumentation problems. As a result, however, the present study neglected view- and sun-angle effects on RF values in the initial stage of analyses. The degree of BRDF effect could be reduced and inconspicuous on a short-term basis due to the employed observation method including the daily-averaging of RF values taken at various weather conditions, measurement deviation and/or noise. However, it may not be completely diminished and thus might affect the long-term and/or wide-range DARF outcomes. In future studies, other angular parameters, as well as A and B, such as the view zenith angle and the instantaneous solar
position that were ignored in the present study, should be examined to improve the accuracy of radiometric prediction of LAI and other variables.

Our empirical solution, however, may only be useful under restricted conditions: bird’s-eye-view observations, DARF calculations, row-planted crops, and mean DARF values for a sample area. It is necessary to investigate the effects of the proposed angular variables in further field observations, as well as in the physical modeling for the canopy in terms of light-plant-soil interactions (Jacquemoud et al., 2009). Although most existing models simplify actual vegetation canopy into homogeneous leaf layers, the parameters of planting row, for instance, have been introduced into some advanced studies (Cheng et al., 2006; Yao et al., 2008). Hence, our simple and low cost methodology may effectively be evaluated and/or improved by applying these computer models.

Another fact is that model (V) requires only one spectral band in NIR as the radiometric variable among the three independent variables (Table 4). This means that the system needs only a single set of camera boards and optical filters; simplifying the entire instrument and drastically reducing the associated costs. In the regression analyses, NDVI was inferior to the NIRDARF as an independent variable (Tables 3 and 4). In the present study, NDVI was derived using DARF values in RED and NIR instead of instantaneous RF values. This “pseudo NDVI” might not be effective because correction for solar insolation, one of the major functions of NDVI, did not necessarily work properly. However, even daily-averaged NDVI using instantaneous RF values was shown to be relatively ineffective in the previous work (Shibayama et al., 2009). Reflectance calculation using solar irradiance sensors may replace vegetation indices, such as NDVI, that have been used to compensate for illumination conditions. It also permits us to use each single band RF separately as an independent variable in the regression models.

Our trial on estimating rice LAI using DARF images has provided regression models only for the before-heading period. In a comparative study to estimate wheat LAI using various indices derived from spectral band RF values observed on the ground, Wiegand et al. (1992) presented separate regression equations for the pre-LAI maximum portion and the post-LAI maximum portion. Vaesen et al. (2001) measured spectral signatures of paddy rice canopies using a hand-held spectroradiometer to investigate their predictive power with respect to LAI, and concluded that a growth-stage-dependent variable improved the capability of the models. For maturing stages, different model equations should be built and used to predict LAI, because of the presence of headed panicles, and senescence and/or etiolation of leaves during progressive maturation.

In comparison to plant length and number of stems, LAI has been measured less frequently in agricultural experiments and surveys due to the requirement for expensive equipment such as leaf area meters, plant canopy analyzers, and/or time-consuming operations. If measuring LAI were more efficient and cost-effective, it would be more widely used because it directly indicates one of the major elements for photosynthetic production.

Conclusions

The present study indicated that low cost digital cameras, solar sensors and calibration procedures were adequate to derive daily-averaged reflectance factors (DARF) in the RED and NIR bands throughout the cropping season of paddy rice. The NIR DARF image observations as well as the view azimuth, planting row and the meridian directions were functional in a regression equation for estimating LAI during the period of vegetative growth. In principle, labor or time will not be required for surveying once the regression model and its coefficients are initially fixed, but further investigation is needed to refine the model equation in terms of the view and illumination directions and the canopy’s structural geometry. By applying this technique for automatically collecting accurate ground data and/or compensating for a lack of satellite images due to cloud cover, wider scale cropping management using airborne or satellite sensors looks promising.

Acknowledgments

Thanks are due to Tadao Suzuki, Hiroyuki Iino and Terushi Kamada at the National Institute for Agro-Environmental Sciences for their technical support in the field experiment.

References

Adamsen, F.J., Pinter, Jr., P.J., Barnes, E.M., LaMorte, R.L., Wall, G.W., Leavitt, S.W. and Kimball, B.A. 1999. Measuring wheat senescence with a digital camera. Crop Sci. 39: 719-724.

Akaike, H. 1974. Factor analysis and AR. Polychrometria 52: 317-332.

Akiyama, T. 1996. Spectroradiometric crop growth diagnosis (Review). Jpn. J. Crop Sci. 65: 379-389.

Akiyama, T. and Kasamura, K. 2003. Study of cloud cover ratio of Landsat 5 for the application on agriculture and forestry. J. Japan Soc. Photogramm. Remote Sens. 42: 29-34.

Akiyama, T. 2007. Remote sensing for agricultural census and crop growth management. J. Japan. Agric. Sys. Soc. 23: 103-110.

Asaka, D., Hayashi, T. and Shiha, H. 2006. The map for grain protein content of winter wheat using satellite observed NDVI at maturing stage. J. Japan. Agric. Sys. Soc. 22: 85-98.

Arar, G., Kanematsu, E.T. and Yoshida, M. 1985. Estimation of leaf area index from spectral reflectance of wheat under different cultural practices and solar angles. Remote Sens. Environ. 17: 1-11.

Baret, F. and Guyot, G. 1991. Potentials and limits of vegetation indices for LAI and APAR assessment. Remote Sens. Environ. 35: 161-173.
Casadesus, J., Kaya, Y., Bort, J., Nachit, M.M., Arasa, J.L., Amor, S., Ferrazzano, G., Maalouf, F., Maccaferri, M., Martos, V., Osabouh, H. and Villegas, D. 2007. Using vegetation indices derived from conventional digital cameras as selection criteria for wheat breeding in water-limited environments. Ann. Appl. Biol. 150: 227-236.

Cheng, Y.B., Zarco-Tejada, P.J., Riaño, D., Ruéda, C.A. and Ustin, S.L. 2006. Estimating vegetation water content with hyperspectral data for different canopy scenarios: Relationships between AVIRIS and MODIS indices. Remote Sens. Environ. 105: 354-366.

Crimmins, M.A. and Crimmins, T.M. 2008. Monitoring plant phenology using digital repeat photography. Ecosyst. Manag. 41: 63-75.

Daughtry, C.S.T., Walthall, C.L., Kim, M.S., Brown de Colstoun, E., Crimmins, M.A. and Crimmins, T.M. 2008. Monitoring plant phenology using digital repeat photography. Ecosyst. Manag. 41: 63-75.

Delécolle, R., Maas, S.J., Guérif, M. and Baret, F. 1992. Remote Jackson, R.D., Clarke, T.R. and Moran, M.S. 1992. Bidirectional

Jacquemoud, S., Verhoef, W., Baret, F., Bacour, C., Zarco-Tejada, P., Horio, M., Konya, H., Nishimura, Y., Hayashi, K. and Sugiyama, T. 2005. Estimating corn leaf chlorophyll concentration from leaf and canopy reflectance. Remote Sens. Environ. 74: 229-239.

Delécolle, R., Maas, S.J., Guérif, M. and Baret, F. 1992. Remote

Jacquemoud, S., Verhoef, W., Baret, F., Bacour, C., Zarco-Tejada, P.,

Horio, M., Konya, H., Nishimura, Y., Hayashi, K. and Sugiyama, T.

2004. Growth diagnosis of rice by hand-type remotely sensing device. Jpn. J. Crop Sci. 73 (Extra issue 2): 308-309**.

Jacquemoud, S., Verhoef, W., Baret, F., Bacour, C., Zarco-Tejada, P.,

Kharuk, V.I., Alshansky, A.M. and Yegorov, V.V. 1992. Spectral

Kawashima, S. and Nakatani, M. 2008. An algorithm for estimating

Kenny, J.A. 2006. Dynamics of directional reflectance factor distributions for vegetation canopies. Appl. Opt. 45: 1532-1537.

Kim, T.W. 2004. Nondestructive and rapid estimation of chlorophyll content in rye leaf using digital camera. Korom J. Crop Sci. 49: 41-45.

Kunii, Y. and Murai, S. 2008. Ideal situation for camera calibration using amateur digital cameras. J. Japan Soc. Photogramm. Remote Sens. 47: 44-51*.

Lee, K.H. and Akita, S. 2009. Factors causing the variation in the temperature coefficient of dark respiration in rice (Oryza sativa L.). Plant Prod. Sci. 3: 38-42.

Martin, R.D. Jr. and Heldman, J.L. 1986. Spectral reflectance patterns of flooded rice. Photogramm. Eng. Remote Sens. 52: 1885-1890.

Matsuda, M., Ozawa, S., Hosaka, Y., Kameda, K. and Yamashita, H. 2003. Estimation of plant growth in a paddie field based on proximal remote sensing – Measurement of leaf nitrogen contents by using digital camera. J. Remote Sens. Soc. Japan. 23: 506-515*.

Milton, E.J., Schaeppman, M.E., Anderson, K., Kneubühl, M. and Fox, N. 2009. Progress in field spectroscopy. Remote Sens. Environ. 113(Supplement 1): S92-S109.

Morton, M.S., Inoue, Y. and Barnes, E.M. 1997. Opportunities and limitations for image-based remote sensing in precision crop management. Remote Sens. Environ. 61: 319-328.

Morita, S. 2000. Effects of high air temperature on ripening in rice plants – Analysis of ripening performance under climate conditions by changing in cropping season and/or transferring pots from lowland to upland. Jpn. J. Crop Sci. 69: 18-20**.

Murakoa, H. and Koizumi, H. 2008. Satellite ecology (SATECO) – linking ecology, remote sensing and micrometeorology, from plot to regional scale, for the study of ecosystem structure and function. J. Plant Res. 122: 320.

Nishida, K. 2007. Phenological eyes network (PEN) – A validation network for remote sensing of the terrestrial ecosystems. Agric. Forest. 21: 9-13.

Okada, S. and Ikeba, M. 2008. Study of the easy method for crop diagnosis by multispectral camera in a paddie field. Proc. 44th Conf. Remote Sens. Soc. Jpn. 2008: 171-172**.

Onimine, M. 2007. Spectral digital camera for growth sensing of soybeans. J. Japan. Soc. Agric. Machinery. 69: 18-20**.

Purcell, L.C. 2000. Soybean canopy coverage and light interception measurements using digital imagery. Crop Sci. 40: 834-837.

Richardson, A.J., Wiegang, C.L., Arkin, G.F., Nixon, P.R. and Gerbermann, A.H. 1982. Remotely-sensed spectral indicators of sorghum development and their use in growth modeling. Agric. Meteorol. 26: 11-23.

Richardson, A.D., Jenkins, J.P., Braswell, B.H., Hollinger, D.Y., Ollinger, S.V. and Smith, M.L. 2007. Use of digital webcam images to track spring green-up in a deciduous broadleaf forest. Oecologia 152: 323-334.

Sakaiya, E., Inoue, Y. and Fujiita, M. 2008. Estimating protein content of brown rice in Central Tsugaru using airborne remote sensing [2]. Jpn. J. Crop Sci. 77(Extra issue 1): 178-179**.

Sakamoto, T., Yokozawa, M., Toritani, H., Shihayama, M., Ishitsuka, N. and Ohno, H. 2005. A crop phenology detection method using time-series MODIS data. Remote Sens. Environ. 96: 366-374.

Sakamoto, T., Shihayama, M., Takada, E., Inoue, A., Morita, K., Takahashi, W., Miura, S. and Kimura, A. 2010. Detecting seasonal changes in crop community structure using day and night digital images. Photogramm. Eng. Remote Sens. 76: 715-729.

Shihayama, M. and Wiegang, C.L. 1985. View azimuth and zenith, and solar angle effects on wheat canopy reflectance. Remote Sens. Environ. 18: 91-103.

Shihayama, M. and Akiyama, T. 1989. Seasonal visible, near-infrared and mid-infrared spectra of rice canopies in relation to LAI and above-ground dry phytomass. Remote Sens. Environ. 27: 119-127.

Shihayama, M., Sali, A., Hâme, T., Itohara, L., Heino, S., Alanne, M., Morinaga, S., Inoue, Y. and Akiyama, T. 1999. Detecting

Plant Prod. Sci. 113(Supplement 1): S56-S66.
phenophases of subarctic shrub canopies by using automated reflectance measurements. *Remote Sens. Environ.* 67: 160-180.

Shibayama, M. and Akita, S. 2002. A portable spectrophotometer for field crop canopies – Distinguishing species and cultivars of fully developed canopies by polarized light. *Plant Prod. Sci.* 5: 311-319.

Shibayama, M., Sakamoto, T., Takada, E., Inoue, A., Morita, K., Takahashi, W. and Kimura, A. 2009. Continuous monitoring of visible and near-infrared band reflectance from a rice paddy for detecting nitrogen uptake using digital cameras. *Plant Prod. Sci.* 12: 293-306.

Takada, E., Inoue, A., Shibayama, M., Sakamoto, T., Morita, K., Kimura, A. and Takahashi, W. 2009. Growth condition estimation of rice by fixed point camera images. *J. Japan. Agric. Systems Sci.* 25: 27-34*

Takahashi, W., Vu, N.C., Kawaguchi, S., Minamiyama, M. and Ninomiya, S. 2000. Statistical models for prediction of dry weight and nitrogen accumulation based on visible and near-infrared hyperspectral reflectance of rice canopies. *Plant Prod. Sci.* 3: 377-386.

Takahashi, W., Takada, E., Kimura, A., Yamaguchi, M., Akimoto, K. and Sakai, M. 2003. Operational application of spectral measurement to crop management. V. Development of the usable miniaturized sensor with GUI. *Jpn. J. Crop Sci.* 72 (Extra issue 2): 98-99**

Takemine, S., Rikimaru, A., Takahashi, K. and Higuchi, Y. 2007. Basic study for estimation of nitrogen content of rice plants from vegetation cover rate of rice obtained by a simple image measurement. *J. Japan Soc. Photogramm. Remote Sens.* 46: 61-65**

Tanaka, M., Goto, S., Maki, M., Akrama, T., Muramoto, Y. and Yoshida, K. 2008. Estimation and validation of leaf chlorophyll concentration in winter wheat at heading to anthesis stage using ground-based and aerial hyperspectral data. *J. Japan Soc. Photogramm. Remote Sens.* 47: 39-49*

Vaesen, K., Gilliams, S., Nackaerts, K. and Coppin, P. 2001. Ground-measured spectral signatures as indicators of ground cover and leaf area index: the case of paddy rice. *Field Crops Res.* 69: 13-25.

Vincini, M., Frazzi, E. and D’Alessio, P. 2008. A broad-band leaf chlorophyll vegetation index at the canopy scale. *Pra. Agric.* 9: 303-319.

Wiegand, C.L., Maas, S.J., Aase, J.K., Hatfield, J.L., Pinter, Jr., P.J., Jackson, R.D., Kanemasu, E.T. and Lapitan, R.L. 1992. Multi-site analyses of spectral biophysical data for wheat. *Remote Sens. Environ.* 42: 1-21.

Yamamoto, H., Suzuki, Y. and Hayakasa, S. 1995. Estimation of leaf area index in crop canopies using plant canopy analyzer. *Jpn. J. Crop Sci.* 64: 333-335**

Yagi, K. and Minami, K. 2005. Challenges of reducing excess nitrogen in Japanese agroecosystems. *Science in China. Ser. C: Life Sci.* 48: 928-936.

Yao, Y., Liu, Q., Liu, Q. and Li, X. 2008. LAI retrieval and uncertainty evaluations for typical row-planted crops at different growth stages. *Remote Sens. Environ.* 112: 94-106.

Zhu, Y., Tian, Y., Yao, X., Liu, X. and Cao, W. 2007. Analysis of common canopy reflectance spectra for indicating leaf nitrogen concentrations in wheat and rice. *Plant Prod. Sci.* 10: 400-411.

* In Japanese with English abstract.

** In Japanese.