Radiometric Predictions for Agronomic Variables of Rice Canopies Using a Visible to Mid-infrared Spectroradiometer

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Abstract

A nominal 15^{o} field of view field spectroradiometer that senses in the 400-1900 nm wavelength interval was devised to collect crop canopy reflectance data. The system components include two sets of diffraction grating monochromators and detectors that operate simultaneously to scan the 400-900 nm and 900-1900 nm wavelength regions, respectively, in 22 sec. A pair of quartz optical fibers 10m long, is used as the light guide to facilitate field measurements.

This system was used to measure spectral reflectance factors for paddy rice canopies grown at Tsukuba, Japan, in 1987. Radiometric and agronomic measurements were made biweekly from June to October for early and late plantings of three cultivars. Eight vegetation indices derived from 480, 560, 660, 840, 1100, 1200, and 1650 nm reflectances were tested for estimating above-ground dry mass, grain yield, and LAI. Total dry mass and yield were both linearly related to the simple difference between 1100 and 1200 nm or 1100 and 1650 nm (r^2=0.85 and 0.81, respectively) reflectance factors. LAI adjusted by the cosine of solar zenith angle was best described (r^2=0.94) in pre-LAI maximum growth stage by a power function of perpendicular vegetation index (PVI) using a turbid water line.

Introduction

Although some radiometric studies on paddy rice have been reported (Patel et al., 1983; Miller et al., 1983; Martin and Heilman, 1986), the wavelengths or bands mainly used were restricted to Landsat MSS bands and the crop information sought was mainly LAI. Dusek et al. (1985) and Gardner et al. (1985) measured visible (VIS) to mid-infrared (MIR) reflectances for winter wheat and corn fields, respectively. They found that the TM5 (1550-1750 nm) and TM7 (2080-2350 nm) bands were more useful than the TM4/TM3 (760-900 nm, 630-690 nm) ratio for estimating agronomic variables, except LAI. However, few studies of paddy rice canopies have been conducted in this mid-infrared wavelength region that seemed promising for nondestructively assessing the agronomic characteristics of crop canopies. Furthermore, no field radiometer for use over small plots that could scan from VIS to MIR wavelength ranges precisely at small wavelength intervals in a short time could be purchased within Japan in 1987.

Several handheld or truck mounted systems have been developed in Japan and other countries for measuring spectral responses of crop canopies. They include light weight systems that employ bandpass filters (Tucker et al.,1981; Milton,1980; Fukuhara et al., 1978; Robinson et al., 1980), and the heavier, more complex systems that use gratings or circular variable filters (Leamer et al., 1973; Miyazaki et al., 1985). Leamer et al. (1973) succeeded in developing a wide wavelength range (370-13880 nm) field radiometer using circular variable filters (CVF).

The first grating type, computer-controlled spectroradiometer built in our laboratory (Munakata and Shibayama, 1985) was a rather heavy and large system for portable usage and the time per scan was long (100 nm/min). Therefore, we designed and built a second spectroradiometer to improve on some characteristics of the first system.

The purpose of this paper is to report the application of vegetation indices calculated from reflectance factor measurements made with the new instrument to estimation of above-ground total dry mass (TDM), grain yield (YIELD), and LAI for a rice experiment conducted at Tsukuba, Japan.

Materials and methods

Spectroradiometer

The spectroradiometer designed and built had the following characteristics:

1. The monochromator and the detector for the 400-900 nm (VIS and NIR) range and those for the 900-1900 nm (NIR and MIR range) were driven at the same time in order to shorten the scanning time and reduce the measurement time difference between the two wavelength ranges. Using the optical fiber light guides the instrument resolved a wavelength interval narrower than 2.8 nm in the 400-900 nm range and narrower than 5.6 nm in the 900-1900 nm range. Thus we summarize observations by 5 nm intervals in the shorter and by 10 nm intervals in the longer of these ranges.

2. The 10 m long quartz fiber optical light guides obviate the need to elevate the radiometer to obtain a representative canopy sample when data are taken from the nadir view position. The field of view of the light guide is 15^{o}. The light attenuation for the light guide is less than 25%.

3. The whole system including the radiometer, a microcomputer data logger, and a standard reference surface are mounted on a small cart maneuverable by one person.

Photographs of the spectroradiometer are shown in Fig. 1. Main components of the system are summarized in Table 1.

Plant materials

The field measurements were made at an experimental paddy facility at Tsukuba, Ibaraki, Japan (36^{o} 01' N latitude, 140^{o} 08' E longitude, 25 m above sea level), in 1987. Three cultivars of lowland rice (*Oryza sativa* L.), Japonica type, were grown in three concrete-lined paddies that were 10 m x 50 m in surface dimensions. The cultivars Nipponbare and Koshihikari were transplanted into two of the paddies on 21 May and subplots 10 m x 12.5 m in size were established. Nitrogen fertilizer was applied at the rate of 0, 4, 8, and 12 g N/m^2 to the Nipponbare, and 0, 2, 4, and 6 g N/m^2 to the Koshihikari cultivars, respectively. The other paddy was divided into 5 subplots 10 m x 10 m in size and the cultivars Koshihikari and Nipponbare were transplanted on 11 June into two subplots and Shinanomochi into the remaining subplot. One subplot of each cultivar received 2 g N/m^2 while one subplot each of Koshihikari and Nipponbare received no fertilizer. Hills consisting of three plants were spaced 18 cm apart in rows 25 cm apart. The soil in the paddies was fine-textured Gray Lowland soil (grayish brown type, Tatara series) that is productive for rice plants.

For the agronomic measurements, number of stems in 3 consecutive hills at each of four different randomly selected places in each subplot was counted, and the hill with the median number of stems was pulled from the ground, the soil was washed from the roots, the roots were excised and discarded, and the above-ground fresh mass was determined. Then the stems, leaves, ears, and dead materials from each hill were separated. Area of leaves of one randomly selected hill was determined using an area meter (Hayashi Denkoh, Tokyo). The plant parts by hill were dried in an oven at 80^{o} C for 48 hours. The total dry mass (TDM) of all plant parts provided the above-ground dry mass for each hill which was averaged to obtain a mean value for each treatment of each cultivar on each sampling date. The specific leaf area of the one hill on which leaf area was determined was used to calculate leaf area of the other three hills from the leaf dry mass of those hills and the specific leaf area for the one hill. The leaf areas so determined were averaged and the leaf area index (LAI) was determined as leaf area per hill divided by ground area occupied per hill.

Dry matter was measured weekly during the growing season on 19 dates: 4, 11, 18, and 25 of June; 2, 9, 16, 23, and 30 of July; 6, 12, 20, and 27 of August; 3, 10, 17, and 24 September; and, on 1 and 8 October. LAI measurements began on the fifth date of the TDM observations and continued on every other date thereafter. However, estimates of LAI for 4, 11, and 18 of June were made from leaf dry mass, that was measured on these dates, using the specific leaf area determined on 2 July. Yield was determined by harvesting 36 hills, 9 at each of 4 sites in each subplot, and composited so that the yield sample represented 1.62 m^2. The grain was threshed to kernels with hulls (glumes) and mass/m^2 at 14% moisture was determined.

Radiometric measurements

The light guides of 15^{o} field of view were held vertically about 2.5 m above the canopy surface by a wooden pole 5 m long resulting in a sample area 60cm in diameter at the canopy surface. Radiometric readings were made at 5 nm intervals in the wavelength range 400 to 900 nm and at 10 nm intervals in the range 900 to 1900 nm. Twenty-two seconds was required to complete one scan and the readings were repeated 5 times for each paddy. The mean of 5 repetitions was divided by the readings from a standard panel, which was sprayed with Kodak White Reflectance Coating, to compute reflectance factors (%). The total time required for each plot was between two and three minutes including the time for the reference surface reading. Measurements were made from 8:30 to 15:00 on cloudless days because solar noon occurs at about 11:30 at Tsukuba. The date and time information, along with the coordinates of the site, was used in a debugged version of the Walraven (1978) program to calculate the solar zenith angles at the time of radiometric measurements. The radiometric measuring dates were 17, 30 of June; 8, 17, and 30 of July; 9 and 26 of August; 14 and 21 of September, for both planting dates and on two additional dates, 5 June for the early planting, and 3 October for the late planting.

Reflectance factors and vegetation indices

In this paper we will describe the reflectance factor (%) at x nm as Rx. R480, R560, R660, R840, R1100, R1200, R1650 were selected from the spectral signatures. Five of them except R1100 and R1200 are the centers of the Landsat TM bands. Measurements at the 1100 and 1200nm were included, also, because they were useful for estimating rice plant biomass in our previous experiments (Shibayama and Munakata, 1986; Shibayama and Akiyama, 198-). The following VIs calculated from the 7 bands selected were tested in this study:

NIR/GRN=R840/R560 (1)

NIR/RED=R840/R660 (2)

NDG=(R840-R560)/(R840+R560) (3)

NDR=(R840-R660)/(R840+R660) (4)

D(1100,1200)=R1100-R1200 (5)

D(1100,1650)=R1100-R1650 (6)

GR5=-.23R480-.19R560-.35R660+.74R840+.48R1650 (7)

PVI=.778R840-.628R660-1.35 (8)

where, NDR and NDR are the so-called normalized differences. D(X1,X2) is a simple difference between RX1 and RX2. GR5 is the greenness index calculated from 5 band reflectance factors by the N-space prcedure developed by Jackson (1983). To calculate it and PVI (perpendicular vegetation index; Richardson and Wiegand 1977) for rice paddies it was necessary to devise a turbid water line, so that the PVI of plants growing out of the water background could be calculated. The turbid water line determined using the spectral data for a paddy with no plants in 1986 (Shibayama, unpublished data), is:

R660=1.24R840-2.15. (9)

Results

The early-transplanted Koshihikari plots headed 10 August, the early-transplanted Nipponbare headed from 13 through 18 August, the late-transplanted Koshihikari and Shinanomochi headed 18 August, and the late-transplanted Nipponbare plots headed 25 August.

The analyses consist of two parts according to "spectral components analysis" proposed by Wiegand and Richardson (1984, 1987). First, instantaneous predictions for TDM and YIELD using the VIs taken at around heading and/or maximum LAI stages were investigated because of high probability of cloud coverage in rice growing season in Japan. (Where "instantaneous" means based on one or a few observation dates once the canopies are fully developed.) Instantaneous yield predictions for grain sorghum and then for wheat and corn using perpendicular vegetation index (PVI) were reported by Wiegand and Richardson (1984, 198-). In the second part, the relationship between LAI corrected by solar zenith angle (LAI/cosZ) and VI was investigated especially in the pre-LAI maximum stages, where Z is the solar zenith angle at the time of spectral measurement. This result (LAI prediction equation) can be substituted into the function for the fractional photosynthetically active radiation used in agrometeological crop models for rice plants (Horie and Sakuratani 1985).

TDM and YIELD predictions

Data of VIs, LAI, LAI/cosZ, TDM, taken on three dates that surrounded the heading date of each cultivar were selected and their means were used in analyzing the relation between VI and agronomic variables (Table 2). In Table 2, the bar (—) on the variable indicates the three-date mean surrounding heading. YIELD was the unhulled, air-dried grain yields (g/m^2) measured at harvest. Correlations are about the same with $\overline{TDM}$ at heading as with $\overline{YIELD}$ because those two are highly correlated (r=0.96). $\overline{D(1100,1200)}$ and $\overline{D(1100,1650)}$ best relate to $\overline{TDM}$ and YIELD (correlations are greater than 0.9). The simple ratios, $\overline{GR5}$ and $\overline{PVI}$ are more closely correlated with $\overline{LAI}$ than the other indices. $\overline{NIR/GRN}$, $\overline{NIR/RED}$, and $\overline{GR5}$ were about equally useful for $\overline{LAI}$ predictions, but not as good as $\overline{D(1100,1200)}$ and $\overline{D(1100,1650)}$ for $\overline{TDM}$ and YIELD predictions (Table 2).

$\overline{TDM}$, harvest index (HI=YIELD/TDM, Donald and Hamblin, 1976), and YIELD are plotted against $\overline{D(1100,1200)}$ in Fig. 2. The harvest index (HI) shown is based on TDM at harvest and brown rice at 0% water content. The good correlation between $\overline{D(1100,1200)}$ and YIELD derives from the good relation between $\overline{TDM}$ at heading and $\overline{D(1100,1200)}$. The relation between HI and $\overline{D(1100,1200)}$ is not very close (r=0.45), but the two outliers of high HI are from the non-fertilized Koshihikari plots. All commercially produced rice in Japan is fertilized, so that the nonfertilized plot results could be ignored in practical application..

LAI-VI correlations are improved by the cosZ adjustment of LAI for VI that contain NIR bands (Table 3). However, relations degraded slightly if the VI contain only 1100, 1200 and 1650 nm bands.

TDM for the whole season smoothed using cubic polynominals was plotted against D(1100,1200) in Fig. 3 (N=134). D(1100,1200) did not relate closely to TDM when TDM was less than 100 g/m^2, corresponding to the first 30 days after transplanting, but thereafter D(1100,1200) related linearly to TDM. The D(1100,1200) versus TDM relation degraded for the cultivar Koshihikari in the late mature or harvest stage, but it did not degrade for the other two cultivars.

LAI predictions

In Table 3, the pre-LAI maximum data set (N=73) is for data taken on and before 12 August and the post-LAI maximum data set (N=48) is for observations on and after 27 August. Data taken on 8 July are not included because the LAI measurements were not made within 5 days of the radiometric measurements. Simple correlations between LAI, lnLAI, LAI/cosZ, ln(LAI/cosZ), and NIR/GRN, NIR/RED, NDG, NDR, GR5, and PVI are calculated separately for pre- and post-LAI maximum data sets. Correlations are much better in pre-LAI maximum data set than in post-LAI maximum data set. In the pre-LAI maximum data set, all the VIs except GR5 give equal or better correlations with LAI/cosZ than with LAI. NDR and NDG relate more closely to lnLAI and ln(LAI/cosZ) than to LAI and LAI/cosZ, respectively. NIR/GRN, NIR/RED, and PVI have highest correlations with LAI/cosZ, while NDG and NDR correlate best with ln(LAI/cosZ). The LAI/cosZ observations are plotted versus GR5, NIR/RED, PVI, and NDR in Fig. 4. NIR/RED appears to relate linearly to LAI/cosZ whereas power form functions fit the others better. The best coefficient of determination is given by PVI (Fig. 4c) in the power form equation:

$$LAI=0.022PVI^{1.7} \qquad R^2=0.94. \qquad (10)$$

Although the equation for NDR also gives $R^2=0.94$, there are large errors in estimating high values of LAI (Fig. 4d).

Discussion

1. Analyses (Table 2, Fig. 2) showed that VIs using R1100, R1200, and R1650 such as D(1100,1200) and D(1100,1650) were more usefull than VIS and NIR VIs such as NIR/RED or NDR for predicting TDM at heading. TDM increases throughout the season until physiological maturity of the grain whereas LAI starts to decline even before reproduction begins. Therefore, it is necessary to find a VI that senses TDM or panicle mass instead of leaf mass or LAI. The N-space greenness, PVI, ratios, and normalized differences VIs using VIS and NIR bands are useful for estimating LAI during the vegetative or pre-LAI maximum growth stages, but are not useful for estimating TDM at heading and later growth stages. The candidate VIs for estimating TDM need to contain the 1100, 1200, or 1650 nm bands since these are sensitive to TDM. The 1200 and 1650 nm bands are located each side of the strong water absorption band at 1300-1450 nm. Thus reflectance factors for these two bands should be affected by water content of the materials in the instrument's field of view. Large values of D(1100,1200) observed soon after transplanting rice to paddies (Fig. 4) may be explained by the fact that the turbid water surface of paddies is not well obscured by the plant leaves. R1200 is closer to the strong water absorption band than R1100, so it gives lower reflectances. D(1100,1200) for Koshihikari declined more than for Nipponbare as harvest approached (Fig. 4). The response is associated with senesence as verified by the LAI measurements; on 24 September the average LAI of the 6 Nipponbare treatments was 2.6 whereas it was 1.4 for the 6 Koshihikari treatments. Rice doesn't die at maturity; assimilates produced after physiological maturity are stored in roots and crown to support the ratoon or second crop.

2. YIELD prediction from observations at heading is imprecise if unfavorable weather or pest damage occurs during grain filling and maturation. However, in the average season, the final yield of rice has been decided by date of heading in Japan (Matsushima, 1979) because number of head/m^2 and number of fertile florets per head (kernels/head) rather than mass per kernel dominate the yield components.

3. LAI divided by cosine solar zenith angle (LAI/cosZ) was more highly correlated than was LAI with VIs, such as PVI, that contained NIR and VIS bands. Solar zenith angle changes both seasonally and diurnally, and affects the number of leaves encountered by light transversing the canopy. Results in this paper indicate that LAI/cosZ is a simple and proper method for taking sun position into account. Shibayama et al. (1986) demonstrated, for example, that the ratio of off-nadir to nadir PVI increased as view and solar zenith angles increased.

4. PVI is shown to be a useful VI, also, for lowland rice plant canopies by introducing a turbid water line in lieu of a soil line. PVI and GR5 are both based on a turbid water line, but PVI is simpler and was as responsive or slightly more so to LAI than was GR5. However, the representativeness of data points used in the calculation of GR5 and PVI should be reexamined, and other bands might be used to calculate GRn. NIR/RED or NIR/GRN are handy VIs for LAI estimation because the relations are linear to a good approximation (Fig. 4b). PVI showed a non-linear relation to LAI/cosZ. (Fig. 4c). NDR became strongly asymptotic in the high LAI region; all indices must become asymptotic to the LAI or LAI/cosZ axis to realistically describe

canopy light interaction (Allen and Richardson, 1970). However, PVI is more general because it removes the brightness of the background water surface from the vegetation information which is most important at LAI below 2 (Shibayama et al., 1986). In agreement with this understanding, Huete (1987) has specifically shown that at partial canopy cover of the soil, ND and ratio VIs are sensitve to line of sight sunlit and shaded soil in the field of view, whereas PVI is not.

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*:In Japanese with English summary.

Table 1. Components of the visible to mid-infrared field spectroradiometer and their characteristics.

Component	Characteristics
Light collecting system:	Quartz optical fibers. Seven, 0.2mm in diameter and 10m long. One set for each of two wavelength intervals.
Field of view:	15^{o}
Diffraction grating:	Jobin Yvon 510-20-110 (900-1900 nm) " 520-28-110 (400-900 nm)
Method of mounting system:	Czerny-Turner type
Focal length:	200mm
Slit width:	0.4mm
Reciprocal dispersion:	300 lines/mm (900-1900 nm) 600 lines/mm (400-900 nm)
Light detecting system	
Detector:	Hamamatsu Photonics B2034-01 (900-1900 nm) " S1226-8 (400-900 nm)
Chopper:	100Hz
Amplifier:	Logarithmic. Range is from 1 to 10000, and 2.5V/decade.
A/D converter:	Datel HX-12GC, 12bit
Microcomputer:	Sharp MZ-2200
CPU:	Z80A
Memory:	RAM 64k byte

Table 2 Simple correlation coefficients of three-date (30 July, 9 and 26 August) means of vegetation indices versus three-date (30 July, 12 and 27 August) means of total dry mass, LAI, and LAI/cosZ and unhulled grain yield of paddy rice canopies. N=13.

	NIR/ GRN	NIR/ RED	NDG	NDR	D(1100, 1200)	D(1100, 1650)	GR5	PVI
Total dry mass	0.80	0.80	0.69	0.66	0.90	0.91	0.78	0.83
Yield	0.80	0.78	0.71	0.67	0.92	0.90	0.77	0.79
LAI	0.83	0.84	0.70	0.63	0.59	0.61	0.81	0.74
LAI/cosZ	0.84	0.86	0.71	0.65	0.56	0.58	0.83	0.75

For N=13, $r_{0.05}$=0.55 and $r_{0.01}$=0.68.

Table 3 Simple correlation coefficients between LAI, lnLAI, LAI/cosZ, ln(LAI/cosZ), and VIs for pre-LAI maximum (a) and post-LAI maximum data sets (b).

(a) Pre-LAI maximum data set (N=73)

	NIR/ GRN	NIR/ RED	NDG	NDR	GR5	PVI
LAI	0.91	0.91	0.86	0.83	0.90	0.92
lnLAI	0.88	0.82	0.94	0.96	0.88	0.89
LAI/cosZ	0.94	0.94	0.88	0.85	0.90	0.93
ln(LAI/cosZ)	0.88	0.83	0.94	0.97	0.87	0.83

For N=73, $r_{0.05}$=0.23 and $r_{0.01}$=0.30.

(b) Post-LAI maximum data set (N=48)

	NIR/ GRN	NIR/ RED	NDG	NDR	GR5	PVI
LAI	0.66	0.67	0.65	0.66	0.41	0.65
lnLAI	0.66	0.67	0.68	0.73	0.35	0.62
LAI/cosZ	0.51	0.51	0.51	0.53	0.49	0.68
ln(LAI/cosZ)	0.51	0.51	0.53	0.56	0.42	0.63

For N=48, $r_{0.05}$=0.28 and $r_{0.01}$=0.37.

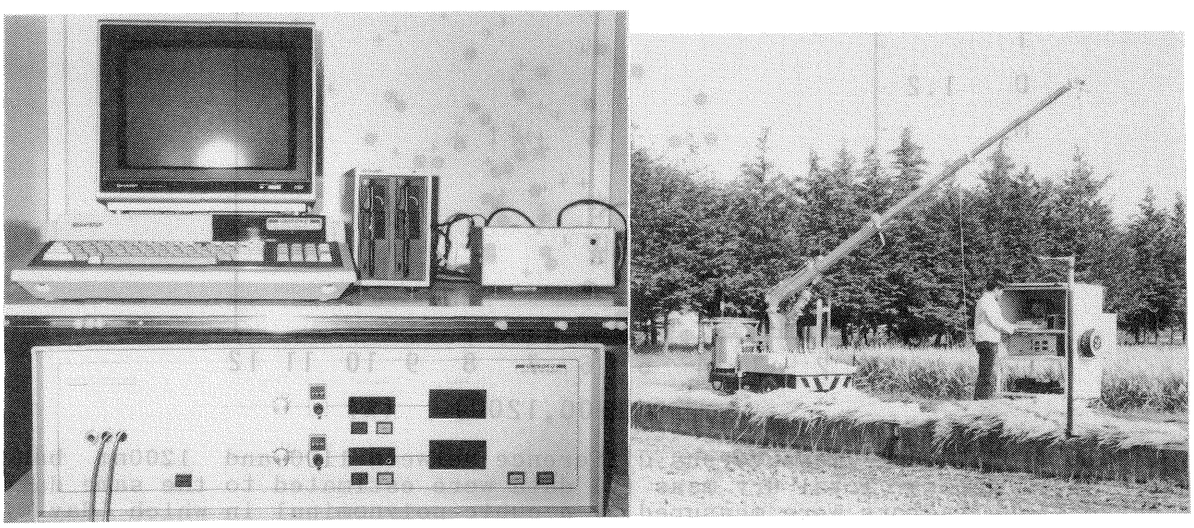

Fig. 1. Photographs of the visible to mid-infrared field spectoradiometer.

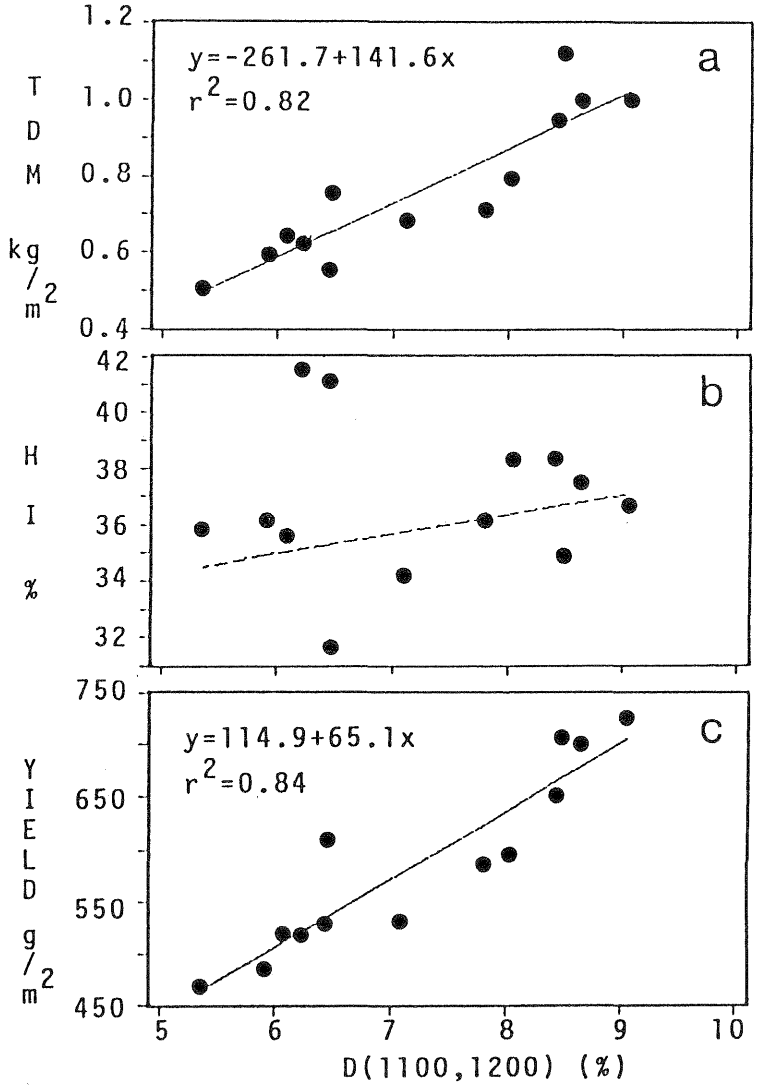

Fig. 2. Three-date mean near date of heading of total dry mass, and of harvest index, and unhulled grain yield of paddy rice plants versus simple difference between 1100 and 1200nm band reflectance factors.

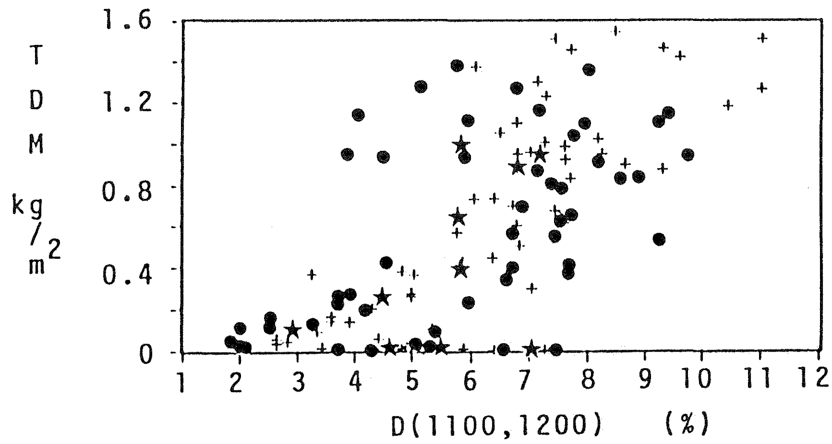

Fig. 3. Total dry mass versus difference between 1100 and 1200nm band reflectance factors. Total dry mass (y) data were estimated to the same date as reflectance factors were measured by a cubic polynominal in which (day of year/200) was the x variable.
Cultivar: +, Nipponbare; ●, Koshihikari; ★, Shinanomochi.

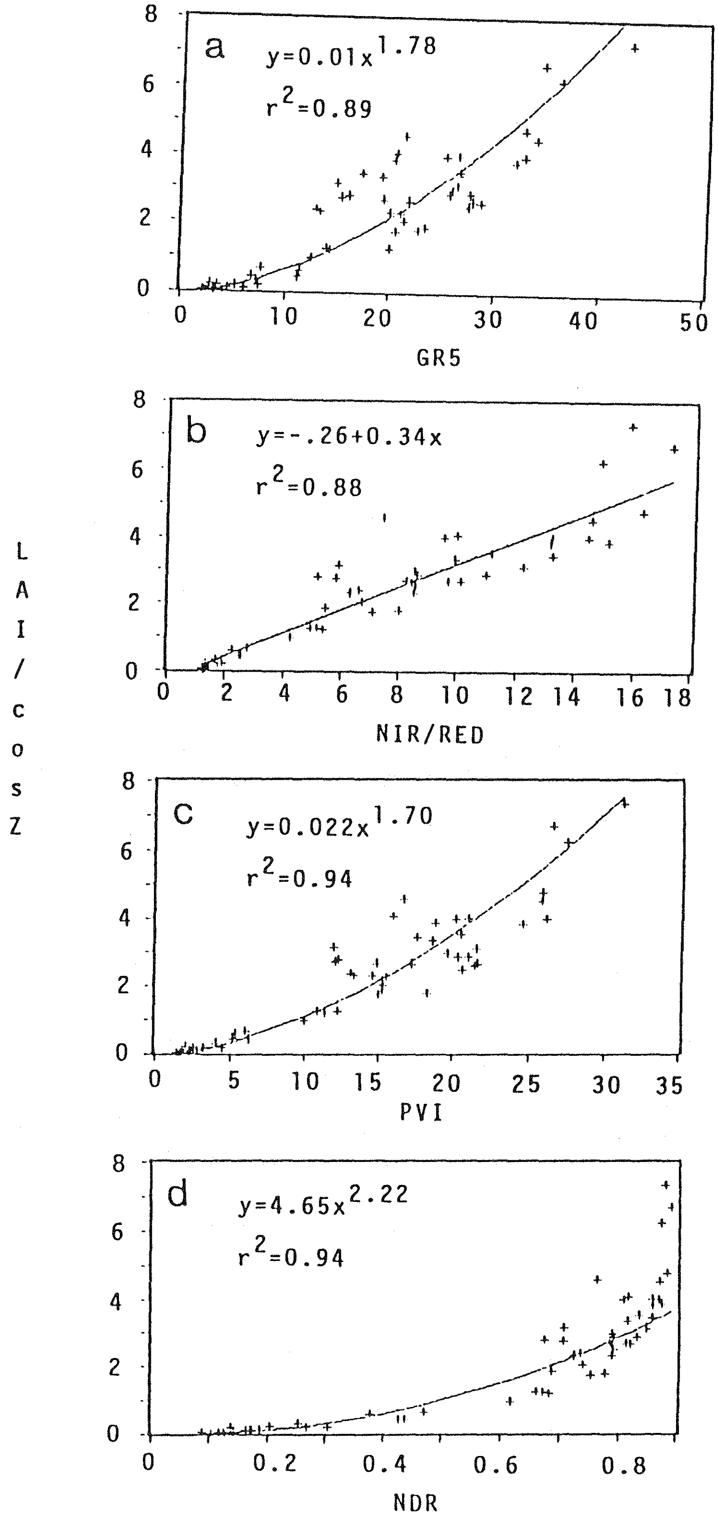

Fig. 4. LAI divided by cosine solar zenith angle versus vegetation indices. a, Greenness index (GR5); b, Simple ratio (NIR/RED); c, Perpendicular vegetation index (PVI); d, Normalized difference (NDR).