水稲の分光反射特性とLAI,DWとfPARに関する基礎的研究

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Study on Relationships among *LAI, DW, fPAR* and Spectral Reflectance in Paddy Rice

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Abstract

In recent years, many studies have been reported on remote sensing techniques in agricultural production to utilize the advantage of simultaneous and wider monitoring capability of satellite data. Several studies have been conducted to develop links between spectral reflectance and temperature for traditional paddy rice cultivation. In our study to characterize the spectral reflectance of paddy rice (*Oryza sativa* L., cv. Hinohikari) with the lengthening growing days, the spectral reflectance of rice leaves from 400 nm to 1,100 nm wavelength range was acquired with a handheld spectroradiometer. A wide range of nitrogen (N) was applied in experimentally field-grown paddy rice. To develop a growth model for paddy rice we analyzed physical parameters, spectral reflectance and fractional photosynthetically active radiation (*fPAR*). The following conclusions were drawn: (1) Different spectral characteristics were observed during the growth stages for different N-treatments; (2) Detection of significant differences between N-treatments was realized with the ratio vegetation index (*RVI*) at full heading stage; (3) Red edge points poorly correlated with leaf area index (*LAI*), dry weight (*DW*) and *fPAR*; (4) The *R*830/*R*550 ratio highly correlated with *LAI* and *DW* during the entire growing season. The prediction accuracy of *fPAR* was also very high using the *R*830/*R* 550 ratio. Though our study accounts for only limited factors, it was concluded that growth models for monitoring paddy rice could be based on *RVI* and the *R*830/*R*550 ratio.

Key words: Dry weight, *fPAR*, Leaf area index, Nitrogen, Paddy rice, Spectral characteristics.

1. Introduction

Sustainable crop production is the important idea of modern agriculture. Farmers must face many challenges with the added responsibility of safeguarding the environment. To optimize crop yield and maintain environmentally friendly agriculture, farmers must balance the competing goals of supplying adequate N for their crops while minimizing N losses to the environment.

Canopy reflectance measurements and remote sensing techniques offer the potential for monitoring crop growth conditions over large areas (Bauer, 1975; Walburg *et al.,* 1982) and may be an alternative tool for estimation of N status (Bausch *et al.,* 1994). In remote sensing studies *NDVI* has been closely related to aboveground biomass (Rouse, 1974). Good estimates of actual biomass, land cover and *LAI* have been derived from spectral measurements (Bouman *et al.,* 1992; Leblon *et al.,* 1991; Clevers, 1989).

Paddy rice differs from other crops in that the floodwater may affect the spectral reflectance. This prohibits the unconditional use of vegetation indices (VIs) for monitoring rice biomass production (Patel *et al.,* 1985; Gilabert and Melia, 1990). Spectral characteristics of growing stages have been analyzed separately in the previously reported studies on rice growth models. However, very few studies have been reported on the entire growing season. The present study made the attempt to (1) examine veg-

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etation indices for differentially managed rice leaves during the entire growing season; (2) analyze the relationship of vegetation indices with respect to *LAI, DW* and *fPAR*; (3) examine the spectral information (*e.g.* red edge position, *R*830/*R*550 nm) for predicting *LAI* and *DW*; and (4) examine best estimation of *fPAR* with spectral information. Our study examined the possibility of using ground-measured information for monitoring paddy rice growth as a basis for developing a method to use satellite data.

2. Materials and Methods

Ten field plots (10 m × 10 m each) were prepared on a well-drained sandy loam soil of the agricultural farm of Kagoshima University, Kagoshima in 1999. In each plot a small area was kept unplanted for soil reflectance measurements, which were used for calculating perpendicular vegetation index (*PVI*) and weighted difference vegetation index (*WDVI*) (data not shown). Sowing and transplanting were done on 25 May and 14 June respectively. Seedlings of rice (*Oryza sativa* L., cv. Hinohikari) were transplanted in a 30 cm × 18 cm planting density (18.5 starins/m^2) by a conventional planting technique using moldboard plow tillage. Three replications were applied for each plot for spectral measurements. The 6 levels of N fertilizer (ammonium sulfate) were applied at 0% (0 gN/m^2), 35% (2 gN/m^2), 50% (3 gN/m^2), 70% (4 gN/m^2), 100% (6 gN/m^2), 150% (8 gN/m^2) of the recommended N rate and the remaining 4 levels were slow released fertilizer mentioned as LP 40, LP70, LP100 and LP140. Numbers after LP refers to the days after showing at which nitrogen starts to release slowly at an average soil temperature of 25℃. 35% (2 gN/m^2) of the recommended N rate (optimal N rate) was applied as basal dressing for all slow-released N. Recommended N rate refers to 6 gN/m^2 for profitable rice yield in Kagoshima prefecture.

Measurements of leaf reflectance were made with a portable handheld spectroradiometer developed by Kagoshima University and ELM Company Ltd. (Kagoshima, Japan), which records the percent reflectance at 4 nm intervals from 400 nm to 1,100 nm. The field of view was 3°. The sensor was mounted on a tripod stand. Five reflectance measurements were taken at each sample point. An average reflectance of five measurements was taken into account as a possible solution to the limitation of the narrow view angle of the spectrometer and to minimize the deviation of inclination angle of a leaf due to wind. Thus, a mean value of 15 (5 per each plot × 3 replication) spectral measurements was used for each N-treatment. To cover the target area with leaves, observations were made from a height of 0.1 m to 0.5 m above the canopy at nadir viewing angle. Reflectance factor was calculated as a relative value to a Lambertian surface with a barium sulfate (Ba_2SO_4) panel.

Five fixed sample points towards the middle of each plot were selected to minimize variability. White board reflectance and object reflectance were taken consecutively. This procedure was repeated for each sample.

The leaf reflectance was taken from three weeks after transplanting. Measurements were planned to be taken once a week in fine weather conditions, between 9:00 a.m. and 11:00 a.m. during the entire growing season. Due to bad weather we could only obtain reflectance samples six times on days 189, 195, 237, 252, 260, 272 of the year (DOY) respectively. Where 189 DOY was vegetation stage, 195 DOY was panicle formation stage, 237 DOY was full heading stage (except for 0% and LP70), 252 DOY was after full heading stage, 260 DOY was maturity stage, and 272 DOY was ripening stage.

Leaf area index (*LAI*) included green leaves only, calculated by one-sided leaf area divided by subtending ground area. Green leaf area was measured with an area meter (AAC-400, Hayashi Denkoh Co. Ltd., Tokyo, Japan). Dry weight (*DW*) was measured by sampling five hills per plot, divided into stems, leaves, heads, roots and dead parts. The plants were desiccated in an oven at 80℃ for 24 hours. *LAI* and *DW* data were collected on 189, 195, 237 and 250 DOY respectively.

Thematic mapper (TM) bands (Markham and Barker, 1985) have been applied to the spectrum, in order to reproduce TM3 (630 nm–690 nm) and TM4 (760 nm–900 nm). These values have been used to calculate normalized difference vegetation index (*NDVI*) and ratio vegetation index (*RVI*) as follows;

$$NDVI = (\mathrm{TM4} - \mathrm{TM3})/(\mathrm{TM4} + \mathrm{TM3})$$

$$RVI = \mathrm{TM4}/\mathrm{TM3}$$

Red edge position was analyzed in a wavelength of 680 nm–750 nm, in terms of the wavelength corresponding to the maximum derivative. In our study we calculated photosynthatically active radiation (*fPAR*) as;

$$fPAR = 1 - \exp(-K \cdot LAI)$$

where K is the extinction coefficient. For rice, K is found to increase with development stage as more erectophile leaves ($K=0.35$) at the vegetative stage become more planophile ($K=0.47$) during the pre heading period and ($K=0.62$) the post heading period, as proposed by Casanova *et al.* (1998).

A mean value of 15 (5 per each plot × 3 replication) samples of each plot was used in spectral analysis. An analysis of variance (statistical analysis system; SAS, 1995) was done to analyze the treatment difference in vegetation indices. The predetermined acceptable level of probability was 5% ($p < 0.05$) for all comparisons. When a difference was found, the Duncan Multiple Range Test was utilized to identify significant differences between parameter means.

3. Results and Discussion

3.1 Vegetation indices and biophysical states

Detection of significant differences between N-treatments was realized with *RVI* at full heading stage (Table 1). The *RVI* was able to separate optimal N rates of 50%, 100%, 140%, LP40 and LP 140.0% optimal N rate could be statistically separated from the other optimal N rates, except from LP70. The *NDVI* could not clearly separate all the N-treatments. The *NDVI* could only significantly separate 0% N rate from 140% and LP 140. Figure 1 presented the time course of vegetation indices during the growing season. Six N-treatments were selected for clarity. Changes in *NDVI* during the growing season could not significantly distinguish N-treatments except at vegetation stage (189 DOY). Significant differences in the near infrared region with non-significant change in the visible region might have caused such a temporal pattern in *NDVI* (Fig. 1 A). *RVI* under the same weather condition varied with respect to N-treatments and had a steep increase before full heading stage (from 195 DOY to 237 DOY). *RVI* in all N-treatments had peaks on same day (237 DOY), except 0% of the optimal rate and LP70 (Fig. 1 B).

The time course of *LAI* over the growing season continuously increased in all N-treatments, with a saturation towards maturity. And the effect of vari-

Table 1. Difference in *NDVI* and *RVI* on 237 DOY (full heading stage) of rice leaves with different N-treatments.

Fertilizer rate (%)	*RVI*	*NDVI*
(0%)	35.40 a	0.94 a
(35%)	64.59 b	0.95 ab
(50%)	74.76 c	0.95 ab
(70%)	66.72 b	0.93 a
(100%)	41.67 d	0.87 b
(140%)	86.93 e	0.96 b
(LP40)	28.22 f	0.93 a
(LP70)	36.97 a	0.93 a
(LP100)	65.67 b	0.95 ab
(LP140)	60.41 g	0.96 b

Within column means followed by the same letter are not significantly by Duncan's multiple range test. The predetermined acceptable level of probability was 5% ($p < 0.05$) for all comparisons.

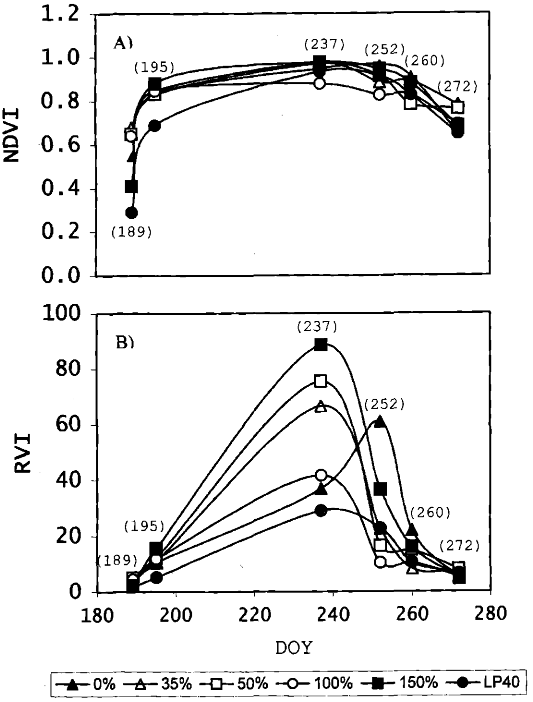

Fig. 1. Time course in vegetation indices for differentially managed rice canopies. Parenthesis value represents Day of Year (DOY).

189 DOY: vegetation stage
195 DOY: panicle formation stage
237 DOY: full heading stage
252 DOY: after full heading stage
260 DOY: maturity stage
272 DOY: ripening stage

ation of N-treatments was clearly distinguishable.

When the relation between *VI* and *LAI* was drawn, at higher canopy green *LAI* (>2), both *NDVI* and *RVI* saturated (Fig. 2 and Fig. 3). Several studies highlighted *NDVI* and *RVI* to be highly correlated with *LAI*. Gilabert and Melia (1990) reported on corn canopy that *NDVI* was found useful to describe *LAI*. Many studies have shown positive correlations between *NDVI* and *LAI*, although *NDVI* tends to saturate as *LAI* increases (Curran, 1983; Asrar *et al.*, 1984; Running *et al.*, 1986 ; Bahdwar *et al.*, 1986 ; Franklin, 1986 ; Peterson *et al.*, 1987; Spanner *et al.*, 1990). Vaesen *et al.* (2001) reported for paddy rice that the single visible near infrared band explained more model variability than *NDVI*, perpendicular vegetation index (*PVI*) and weighted difference vegetation index (*WDVI*). In our study *LAI* could be best explained with an exponential equation for *NDVI* and with a logarithmic equation for *RVI*. R^2 values for *NDVI* and *RVI* were 0.56 and 0.60 respectively, significant at 5% level. A good correlation (r^2= 0.68) was found with *LAI* and *NDVI* at panicle formation stage, which was found saturated at full heading stage as the *LAI* increased. *NDVI* reached a peak at 237 DOY and decreased, but not noticeably. That is why *LAI* could be best explained with an exponential function. *NDVI* is extremely sensitive to canopy cover when the cover is low. This illustrates the difficulties of using *NDVI* as an indicator of canopy structure or chemical content for well-developed canopies; beyond a certain density (Sellers, 1987). It was observed that except 0% N-treatment, *LAI* continued to increase for a while after *RVI* reached its peak value. For this reason, the logarithmic expression has resulted in a better way to adjust the data. In Fig. 1 and Fig. 2, it was observed that *DW* continued to increase after the *NDVI* and *RVI* reached the maximum value. We concluded that the *RVI* had a good correlation between *LAI* and *DW* after full heading stage, which was not the case prior to heading. Nevertheless, for establishing predictive models of sensing immediate changes in crop physiology and metabolism to lead

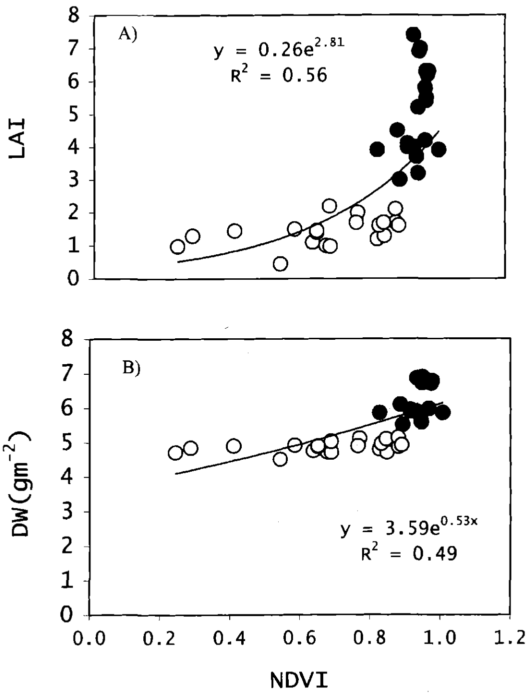

Fig. 2. Regression plots for *NDVI* with A) *LAI* and B) *DW*. Open and closed symbol represents data before heading and after heading respectively.

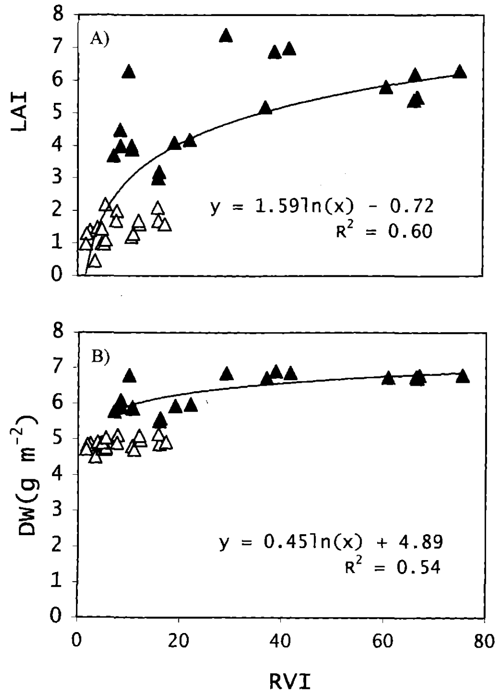

Fig. 3. Regression plots for *RVI* with A) *LAI* and B) *DW*. Open and closed symbols represent data before heading and after heading respectively.

to methods for timely correction of the problem before irreversible damage is done (McMurtrey *et al.*, 1994), detection at any stage is very essential.

3.2 Red edge structure

Red edge points moved to longer wavelengths as *LAI* and *DW* increased (Fig. 4). An increase in chlorophyll concentration caused a broadening of the chlorophyll absorption feature in the red and consequently moved the position of red edge to longer wavelengths (Munden *et al.*, 1994). There was a poor correlation between *LAI* and *DW*. In this regard, it can be concluded that red edge points does not have any significant advantage with respect to *NDVI* and *RVI*. The red edge is proposed for use in estimating absorbed photosynthetically active radiation (Hall *et al.*, 1990), estimating the severity of stress (Rock *et al.*, 1988) and crop condition (Kochubey *et al.*, 1986). On the other hand Demetriades-Shah *et al.* (1990) concluded that the red edge of canopy reflectance is a poor estimator of chlorophyll levels. In another study Railyan *et al.* (1993) reported for triticale that the red edge exhibited a complex structure and its slope and position vary continuously throughout the growing season.

3.3 *R*830/*R*550 nm ratio

Figure 5 showed the relationships among *R*830/*R*550, *LAI* and *DW*. *R*830/*R*550 was found useful to describe phonological events for paddy rice canopy, as it significantly correlated with *LAI* and *DW* during the entire growing season. With a simple linear model, no other spectral combination performed so well for the entire growing season, especially for *DW*. Our results implied that for the whole phenological evolution of paddy rice, the *R*830/*R*550 nm ratio seems to be a very good indicator of *LAI* and *DW*.

Inada (1985) concluded that the spectral ratio *R*800/*R*550 was the most effective in estimating leaf chlorophyll content. Takebe *et al.* (1990) showed a linear correlation between leaf nitrogen content and *R*830/*R*550 nm for the vegetative stage of rice. In another study Inoue *et al.* (1998) agreed to that of Inada (1985) and reported that correlation between *R*830/*R*550 nm and leaf nitrogen content was poor during the ripening period, although this was not the case before heading.

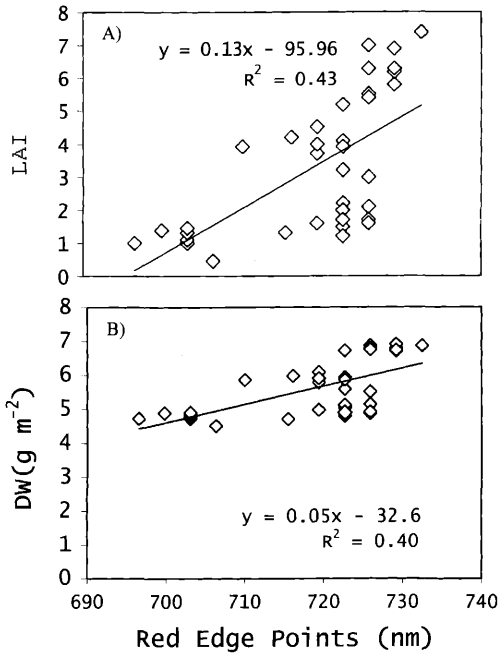

Fig. 4. Red edge points with relation to A) *LAI* and B) *DW*.

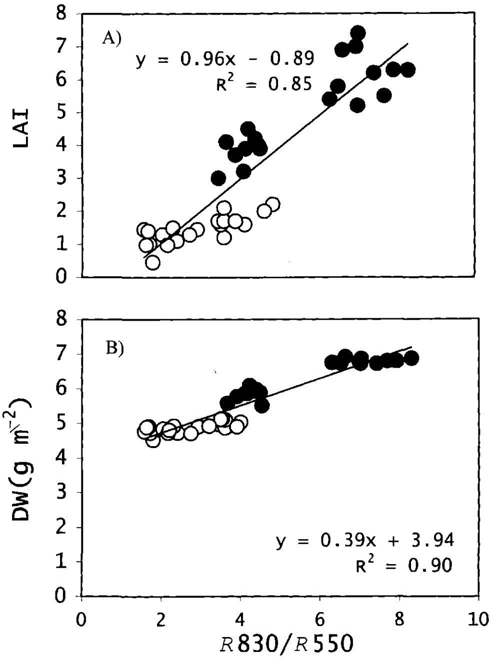

Fig. 5. Regression plots for *R*830/*R*550 ratio with A) *LAI* and B) *DW*. Open and closed symbols represent data before heading and after heading respectively.

3.4 *fPAR*

In our study the relationship between rice leaf reflectance and *fPAR* has been investigated. In Fig. 6, our results showed that *NDVI* and *RVI* could not correlate to *fPAR* with a linear fit. Although an exponential equation could fit the data for *NDVI* values, the degree of correlation was lower ($r^2=0.56$). Baret *et al.* (1991) reported that there is a limitation for two band vegetation indices because they are strongly affected by the background while the vegetation cover is low and *RVI* become saturated when vegetation cover is high.

Our results suggested that *fPAR* could be best estimated with red edge points by inverting a linear fit with a very poor degree of correlation ($r^2=0.47$). It was concluded that Red edge points as a whole performed very poorly to explain rice phenology.

Spectral reflectance of a canopy is more directly related to *fPAR* than to other plant variables such as *LAI*, biomass, chlorophyll, and geometry, because both canopy reflectance and *fPAR* are the components of the radiation budget of a canopy (Asrar *et al.*, 1989). Many studies have reported on *fPAR* for various crops (Daughtry *et al.*, 2000; Gallo *et al.*, 1985; Asrar *et al.*, 1989; Leblon *et al.*, 1991). Inoue *et al.* (1998) has also studied rice canopies and reported that *VI* had a close relationship with *fPAR*, but became less sensitive when *fPAR* was larger than 0.4.

A similar analysis was carried out for the *R*830/*R*550 ratio. Our results suggested that *fPAR* could be best estimated from *R*830/*R*550 by inverting the linear equation. The prediction accuracy of *fPAR* was also very high using the *R*830/*R*550 ratio (Fig. 7). The predictability was much improved by using this ratio. This close linear relationship between predicted and measured data suggests that the usefulness of this ratio is robust. But more systematic and practical use awaits further investigation.

4. Conclusion

Leaves of paddy rice produced significant reflectance changes during the growing season for different N-treatments. Our results demonstrated that *NDVI*, *RVI* and red edge points derived from leaf reflectance were poor indicators of *LAI*, *DW* and *fPAR*. Significant difference in *RVI* for different N levels in field grown paddy rice leaves were found

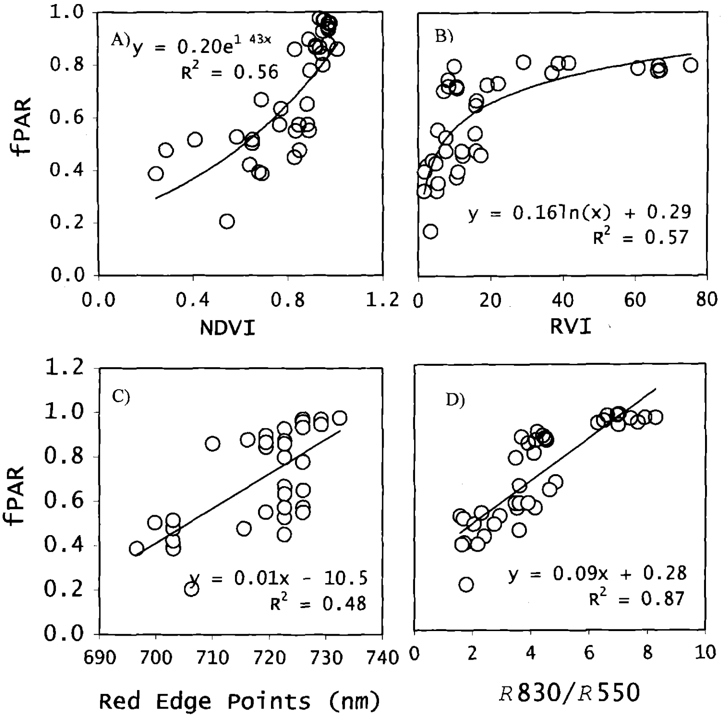

Fig. 6. Relationship among *fPAR*, *NDVI* (A), *RVI* (B), red edge points (C) and *R*830/*R*550 ratio (D).

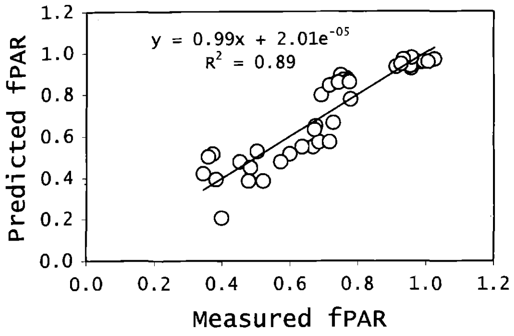

Fig. 7. Relationship between measured and predicted *fPAR* of rice leaves for entire growing season as a function of *R*830/*R*550 ratio.

only at full heading stage.

On the other hand, the *R*830/*R*550 could provide acceptable estimates of *LAI, DW* and *fPAR*, during the entire growing season. It is very promising for incorporation into a simple process model of rice because N management in fields is one of the major issues in Japan. Prediction of *fPAR* for a canopy with the *R*830/*R*550 nm ratio may be a useful and unique variable for linking remote sensing to simple crop models. It is a key variable in most simple models and the spectral measurements by remote sensing can be directly related to *fPAR* in principle. It is noted that the reflectance measurements were centered over the leaves, middle part and did not include the entire canopy. Therefore, experimental spectral indices values corresponding to the development of paddy rice are not quite as representative for the whole canopy. But as a possible solution to this limitation, several measures were taken in the spectral measurements. Information from the present study is thus believed to be very useful for further research to improve the accuracy and consistency of ground measured spectral information. The present research results with a narrow bandwidth are also promising for hyperspectral remote sensing. Hyperspectral data allows one to plot data as a quasi-continuous narrow bands which are usually superior for most purposes to broader band multispectral data, simply because so much more detail for the features to be identified is acquired. This study suggests that for monitoring rice growth during the entire growing season, our results can be used for further modeling using hyperspectral satellite data.

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水稲の分光反射特性と*LAI*, *DW*と*fPAR*に関する基礎的研究

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要　　約

広範囲を同時に測定できる衛星データの利便性を利用して，農作物の収量予測にリモートセンシングの手法を用いる試みは多く報告されている。温度等をパラメータとした従来の水稲の生育モデルに分光反射特性をファクターに加えた研究が近年多く報告されている。筆者等も分光反射特性を利用した水稲の生育モデルを構築する研究の一環として，異なる窒素量を施肥した水稲の試験区を設定し，水稲の分光反射特性と草丈・分げつ数・葉面積・乾燥重量等を測定し，植生指標と施肥量，植生指標と水稲の生物物理量，分光反射特性と*fPAR*等について検討し，以下の結論を得た。(1) 生育期間中における水稲の分光反射特性の変化は，窒素施肥量ならびにその効果時期により異なる特性を示した。(2) *NDVI*は施肥量による差異は明確には認められなかったが，*RVI*の変化はとりわけ登熟期間で大きく異なった。(3) Red Edge Pointsは葉面積指数（*LAI*）乾燥重量（*DW*）ならびに光合成有効放射量（*fPAR*）には高い相関は認められなかった。(4) 登熟期に有効とされる*R*830/*R*550は全生育期間において*LAI*と*DW*に対して高い相関を示した。とりわけ*fPAR*は非常に高い相関を示した。本研究で得られた分光反射特性より導出した*RVI*の対数と*R*830/*R*550は水稲の生育モデルを構築する際の有効なファクターとなることが示唆された。

キーワード: 水稲，分光反射特性，葉面積指標，乾燥重量，光合成有効放射量，窒素施肥量