野外分光反射測定によるイネの生育と収量の推定

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Spectral Observations for Estimating the Growth and Yield of Rice

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Abstract: Remote spectral observations of plant canopies provide information that may be useful for describing their growth and yield. In this paper we (1) present equations that describe how spectral reflectance observations, expressed as vegetation indices (VI), relate to leaf area index (L); fractional photosynthetically active radiation, PAR, absorbed (Fp); daily solar PAR absorbed (Sp); above-ground dry matter (DM); and, grain yield (YIELD), and (2) apply the equations to a rice (*Oryza sativa* L.) experiment conducted at Tsukuba in 1987. The 13 treatments consisted of incomplete combinations of 2 transplanting dates (21 May, 11 June), 6 nitrogen application rates (0, 2, 4, 6, 8 and 12 g/m^2), and 3 cultivars (Nipponbare, Koshihikari, and Shinanomochi).

Over the seasonal interval transplanting to physiological maturity of the grain, grain YIELD (g/m^2) and cumulative daily absorbed photosynthetically active radiation (ΣSp, MJ/m^2) were linear functions of the cummulative perpendicular vegetation index (ΣPVI). The efficiency of conversion to dry matter, e_C, was 2.9g DM/MJ for transplanting to 20 days after heading and ~2.5g DM/MJ for transplanting to physiological maturity. YIELD was linearly related to dry matter at heading, DM_h ($r^2=0.92$) which could be better estimated by the reflectance difference vegetation index at heading, $(R_{1100}—R_{1650})_h$ ($r^2=0.82$) than by PVI at heading, PVI_h, ($r^2=0.69$).

The functional relations suggested by the equations demonstrate how observable canopy attributes (L, DM) and plant processes (light interception, photosynthesis, growth) interrelate to VI and YIELD, and provide a basis for interpreting the variation in vegetation indices of rice canopies in terms of canopy development and grain yield.

Key words: Light conversion efficiency, Net assimilation, *Oryza sativa* L., PAR absorption, Remote sensing, Spectral components analysis, Yield estimation.

野外分光反射測定によるイネの生育と収量の推定：クレイグウィーガンド*・芝山道郎**・山形与志樹**・秋山侃**（*アメリカ合衆国農務省農業研究局・**農業環境技術研究所）

要　旨：作物の生育と収量に関する新しい推定手法として野外での分光反射測定がある．この測定により得られた作物の波長別反射係数間の相互演算結果（VI）が，葉面積指数，光合成有効放射（PAR）および同吸収率（Fp），PAR日吸収量（Sp），地上部乾物量（DM）および収量とどのように関係づけられるかを数式で提示し，これらを茨城県つくば市での実測データに適用してその有効性を検証した．

植物材料としては，15aの水田を13区に分割し，2移植期（5月21日，6月11日），6窒素施肥水準（0，2，4，6，8，12 g/m^2）を設けて3品種のイネ（日本晴，コシヒカリ，シナノモチ）を栽培したものを供し，10日ないし2週間隔で分光反射測定を行った．

移植期から登熟期において，収量ならびに積算Sp（ΣSp）はともに積算PVI（ΣPVI）の1次式で推定されることがわかった．PVIは赤および近赤外反射係数から算出されるVIである．またΣSpからDMへの転換効率（e_c）は移植期から出穂期20日までの期間で2.9g DM/MJ，移植期から収獲期までは2.5g DM/MJだった．一方収量と出穂期のDM（DM_h）とは$r^2=0.92$の高い相関関係を示した．DM_hと1100，1650nm反射係数間の差との相関関係は，PVIとのそれよりも密接であった．（$r^2=0.82$および0.69）．

キーワード：イネ，光合成有効放射吸収量，収量推定，純同化，スペクトルコンポーネント分析，光エネルギー転換効率，リモートセンシング．

It is now widely accepted that spectral reflectance of crop canopies correlates with leaf area index (L) and, therefore, with agronomic characteristics, such as above-ground dry phytomass (DM), during vegetative development. Also, fractional PAR absorption (Fp) can be estimated almost as well from spectral reflectance observations, reduced to vegetation indices (VI) as from L[1,2,17]. Remote spectral observations of crops

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are less difficult and labor intensive than direct measurement of L and Fp, and therefore, merit testing for crop growth and yield analyses.

Shibayama and Akiyama[13] and Shibayama et al.[12] have also shown that the difference between reflectance at 1100 and 1200 nm ($R_{1100}-R_{1200}$) and the difference between reflectance at 1100 and 1650 nm ($R_{1100}-R_{1650}$) estimated DM well until heading. Grain yield of rice can be estimated from DM at heading[8,9]. Therefore yields should be estimable from spectral observations of DM at heading, DM_h.

Wiegand and Richardson[16,17] reduced the relations among vegetation indices and L, Fp, DM and YIELD to equation form. Their approach which they named "spectral components analysis" (SCA) emphasizes the information contained in vegetation indices. The approach assumes implicitly, in agreement with agronomic experience, that (a) plant stands integrate the growing conditions experinced and express the net assimilation through the canopies achieved, (b) stresses severe enough to affect economic yield will be detectable through their effects on the development and persistence of photosynthetically active tissue in the canopies, and (c) high economic yields cannot be achieved unless plant canopies are achieved that fully utilize available solar radiation just prior to and during the reproductive period[16,17].

The purposes of this paper are to present the SCA relations for rice and apply them to data from an experiment conducted at Tsukuba during the 1987 growing season.

Spectral components analysis

The first of the three principal equations is

$$Fp=g(L_Z)=g(h(VI))=f(VI) \qquad [1]$$

wherein $L_Z=L/\cos Z$ and Z is the solar zenith angle at the time the canopy reflectance observations were made. Eq. [1] shows that Fp can be estimated from remotely observed VI.

The second one is

$$YIELD=q(r(s(\Sigma VI)))=p(\Sigma VI) \qquad [2]$$

in which $YIELD=q(DM_2-DM_1)$, $DM_2-DM_1=r(\Sigma Sp)=r(\Sigma(FpSp'))$, $\Sigma Sp=s(\Sigma VI)$, and Sp is absorbed daily incident PAR (MJ/m^2/day), Fp is fractional PAR absorbed (dimensionless), and Sp' is incident PAR (MJ/m^2/day). All variables in Eq. [2] are evaluated over the time interval specified by the beginning (DM_1) and ending (DM_2) dates of the DM change. Eq. [2] expresses why grain yield (YIELD, g/m^2) should be estimable from cumulative daily vegetation indices, that is, from the area under seasonal VI versus time curves.

When yield is proportional to DM at heading (DM_h) as it is for rice, and DM_h can be estimated from a vegetation index, then the relationships are expressed by

$$YIELD=n(DM_h)=n(o(VI_h))=m(VI_h). \qquad [3]$$

The equation for estimating rice canopy L_z using perpendicular vegetation index (PVI)[11], that corresponds to $L_z=h$ (VI) in equation [1], is[12],

$$L_z=0.022PVI^{1.7} \qquad [4]$$

in which

$$PVI=.778(R_{840})-.628(R_{660})-1.35 \qquad [5]$$

where, R_{840} and R_{660} are the bidirectional reflectance factors (%) at the 840 nm and 660 nm wavelengths, respectively. To calculate PVI for rice paddies it was necessary to devise a turbid water line[18], 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 was[12,18]

$$R_{660}=1.24(R_{840})-2.15. \qquad [6]$$

The Sp function of L modified from Horie's equation[3,4] is

$$\begin{aligned} Sp=Sp'Fp=0.48S[0.96 \\ -0.06\exp(-0.5L) \\ -0.9\exp(-0.45L)] \end{aligned} \qquad [7]$$

where Sp is daily absorbed PAR (MJ/m^2/day), 0.48 is the fraction of daily shortwave radiation, S, at Tsukuba that is PAR so that $Sp'=0.48S$ is the daily incident photosynthetically active radiation (MJ/m^2/day), and Fp is the fractional PAR absorbed by the canopy. Fp was not measured in our experiment so that equation [7] was used to estimate Sp from measured L.

Equation [7] expressed in terms of PVI and L_z is

$$\begin{aligned} Sp=0.48SFp=0.48S0.95\{0.96 \\ -0.06\exp[-.5(0.022PVI^{1.7})] \\ -0.9\exp[-0.45(0.022PVI^{1.7})]\}. \end{aligned} \qquad [8]$$

The part of equation [8] in brackets corresponds to Fp=f (VI) in equation [1]. Sp calculated from equation [7] or [8] using daily values of L or PVI and Sp' can be cumulated and plotted against DM and cumulative VI to determine the $DM_2-DM_1=r(\Sigma Sp)$ and $\Sigma Sp=s\ (\Sigma VI)$ relations of equation [2].

Equation [3] permits the instantaneous radiometric prediction of YIELD at about maximum L or heading stage. High percentage of cloud cover during the vegetative development stage of rice in Japan is ample reason for developing a method for predicting yield from observations on one or a few dates. A preliminary analysis reported by Shibayama et al[12]. demonstrated that three-date means of the radiometric variables, $(R_{1100}-R_{1200})_h$ and $(R_{1100}-R_{1650})_h$ where h designates observations surrounding the date of heading, predicted DM_h and YIELD well.

Materials and Methods

1. *Plant materials*

The field measurements were made at an experimental paddy facility at Tsukuba, Ibaraki, Japan (36°01' N latitude, 140°08' E longitude, 25 m above sea level), in 1987. Three cultivars (Koshihikari, Nipponbare, and Shinanomochi) of lowland rice (*Oryza sativa* L.), Japonica type, were grown in three concrete-lined paddies that were 10 m×50 m in surface dimensions. Cultivar names, fertilizer level and transplanting dates of thirteen subplots or treatments, are summarized in Table 1.

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 tillers 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 tillers 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 leaf sheaths and stems, green leaf blades, ears, and dead materials from each hill were separated. Area of green 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°C for 48 hours. The dry mass (DM) of all plant parts retained 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 green leaf dry mass of those hills and the specific leaf area for the one hill. The leaf areas so determined were averaged and the green leaf area index (L) was determined as leaf area per hill divided by ground area occupied per hill.

Dry matter (DM) was measured weekly during the growing season on 19 dates : 4, 11, 18, and 25 June ; 2, 9, 16, 23, and 30 July ; 6,

Table 1. Definition of treatments and observed heading dates.

Treatment	Symbol	Paddy Number	Cultivar	Nitrogen Applied (g/m^2)	Planting Data	Heading Date
1	80 N	8	Nipponbare	0	May 21 (141)[a]	18 Aug. (230)[a]
2	81 N	8	〃	4	〃	13 Aug. (225)
3	82 N	8	〃	8	〃	15 Aug. (227)
4	83 N	8	〃	12	〃	18 Aug. (230)
5	90 K	9	Koshihikari	0	〃	10 Aug. (222)
6	91 K	9	〃	2	〃	10 Aug. (222)
7	92 K	9	〃	4	〃	10 Aug. (222)
8	93 K	9	〃	6	〃	10 Aug. (222)
9	70 K	7	〃	0	June 11 (162)	25 Aug. (230)
10	70 N	7	Nipponbare	0	〃	25 Aug. (230)
11	72 K	7	Koshihikari	2	〃	18 Aug. (230)
12	72 N	7	Nipponbare	2	〃	25 Aug. (237)
13	72 S	7	Shinanomochi	2	〃	18 Aug. (230)

[a] Numbers in parentheses are day of year (DOY).

12, 20, and 27 August; 3, 10, 17, and 24 September; and, on 1 and 8 October. L measurements began on the fifth date of the DM observations and continued on every other date thereafter. However, estimates of L for 4, 11, and 18 June were made from leaf dry mass, that was measured on those dates, using the specific leaf area determined on 2 July. YIELD was determined by harvesting 36 hills, at each of 4 sites in each subplot, and composited so that the yield sample represented 1.62m^2. The grain was threshed to kernels with hulls and mass/m^2 at 14% moisture was determined. The "brown" grain with hulls at 14% water content was adjusted to brown rice without hulls at 0% water content by multiplying by 0.82 and dividing by 1.14.

Daily shortwave solar radiation, S, (MJ/day) was measured at the facility of the Division of Agrometeorology at NIAES, Tsukuba.

2. *Radiometric measurements*

The spectroradiometer[12)] designed at the Remote Sensing Laboratory and built by Unisoku Corp. (Osaka, Japan) had a 15° field of view. The optical fiber light guides that were 10 m long were held vertically about 2.5 m above the canopy surface by a wooden pole 5 m long resulting in a sample area 60 cm 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 readings were repeated 5 times for each paddy. The mean of 5 repetitions was divided by the readings from a reference panel sprayed with Kodak White Reflectance Coating ($BaSO_4$), to compute bidirectional reflectance factors (%) by the equation,

$$Rc=Rp(Lc/Lp)100,$$

wherein Lc and Lp are the dark level corrcted voltages for the canopy and reference panel observations, respectively; Rp is the reflectance (decimal fraction) of $BaSO_4$ provided by Kodak for each wavelength used; and Rc is the reflectance of the canopy. The reference panel observations were made under the same ambient conditions as the canopy observations but the reference panel was not calibrated in the field[6)].

The total measurement time per 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 since solar noon occurs at about

Table 2. Leaf area index (L) and oven-dry above-ground dry matter (DM_h) at sampling dates nearest the heading dates, as well as YIELD as air-dry brown rice with hulls and oven-dry brown rice without hulls, DM, and harvest index (HI) at harvest.

		Sampling date nearest heading				YIELD (Br. Rice with hulls at 14% H_2O)	DM (0% H_2O)	YIELD[a] (Br. Rice withnot hulls at 0% H_2O)	HI[b]
		DOY	L	DOY	DM_h	(g/m^2)	(g/m^2)	(g/m^2)	
1	80 N	224	2.89	224	641	520	1,069	374	.350
2	81 N	224	3.78	224	753	611	1,349	439	.326
3	82 N	224	6.24	224	995	725	1,429	521	.365
4	83 N	224	6.88	232	1,114	706	1,400	508	.363
5	90 K	224	2.44	224	623	518	925	373	.403
6	91 K	224	2.86	224	789	595	1,138	428	.376
7	92 K	224	3.71	224	949	649	1,222	467	.382
8	93 K	224	3.56	224	995	701	1,323	504	.381
9	70 K	224	2.50	232	555	527	938	379	.404
10	70 N	239	2.52	239	598	484	969	348	.359
11	72 K	224	3.30	232	713	585	1,232	421	.342
12	72 N	239	2.29	239	684	530	1,114	381	.342
13	72 S	224	2.52	232	507	469	942	337	.358

[a] Brown rice without hulls at 0% calculated by multiplying br. rice with hulls by 0.82 and dividing by 1.14.

[b] Harvest index.

11 : 30 at Tsukuba. The date and time informationn, along with the coordinates of the site, were used in a debugged version of the Walraven program[14)] to calculate the solar zenith angles at the time of radiometric measurements. The radiometric measuring dates were 17 and 30 June ; 8, 17, and 30 July ; 9 and 26 August ; 14 and 21 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 (%) for the 5 nm intervals centered on 840 and 660 nm were used in Eq. [5] to calculate PVI, and reflectance factors for the 10 nm intervals centered on 1100, 1200 and 1650 nm were used to calculate the differences ($R_{1100}-R_{1200}$) and ($R_{1100}-R_{1650}$).

Smoothng of L, DM, and PVI Measurements In order to cumulate Sp and PVI of Eq. [2] by daily time steps it was necessary to estimate daily values of L, DM, and PVI from the biweekly L and the weekly DM and PVI measurements. Daily estimations for L were calculated by fourth degree polynomial equations expressed as :

$$L=\exp(A_0+A_1t+A_2t^2+A_3t^3+A_4t^4) \quad [9]$$

where t=DOY/200, and A_0, A_1, A_2, A_3, A_4 are the coefficients. Equations were prepared for each treatment (Table 1) ; the coefficients of determination (R^2) varied from 0.96 to 0.99.

In the same way, equation sets for DM (third degree expressions for the earlier planting date, and fourth degree expressions for the later planting date) and PVI (fifth degree expressions) were also prepared. The smoothed and experimental data agreed well, except in a few cases, through physiological maturity of the grain, about DOY 266 in this study.

Results

The heading dates of each plot are presented in Table 1. Koshihikari matured earlier than Nipponbare and Shinanomochi. The 8 subplots of the 3 week earlier planting date headed 8 to 17 days ahead of the second planting depending on cultivar. The two planting dates gave a wide range in L and DM during vegetative development.

In Table 2, agronomic data at heading and harvest time are summarized for the 13 treatments. YIELD was lower for the later planting in agreement with the shorter vegetative growth and ripening period that reduced both the DM and harvest index (HI) of those plots.

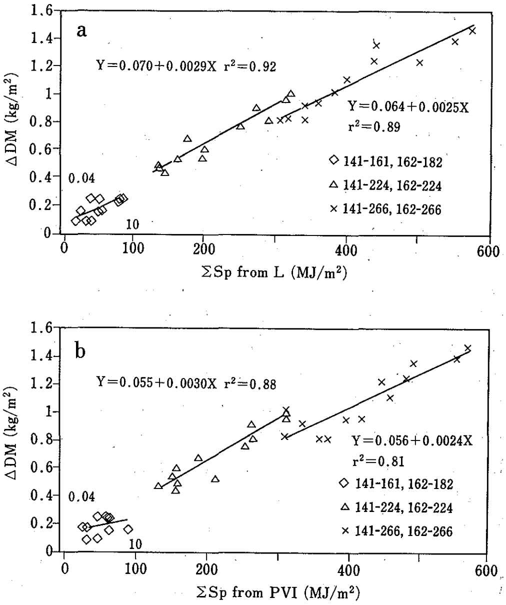

Fig. 1 Smoothed above-ground dry mass increase versus cumulative absorbed PAR, ΣSp, calculated from Eq. [7] or leaf area index, L (part a) and from Eq. [8] or perpendicular vegetation index, PVI (part b) for three seasonal intervals. The intervals were the first three weeks after transplanting (DOY 141—161 and 162—182, respectivery, for early and late plantings) ; from transplanting to approximately average heading date (DOY 141—224 and 162—224), and from transplanting to approximately physiological maturity of the grain (DOY 141—266 and 162—266.) The interior scale applies for the three week interval right after transplanting.

Equation [2]

1. *Sp derived from L and PVI and its relation to DM*

As shown by Eqs. [7] and [8] , respectively, the fractional PAR absorbed, Fp, can be estimated either from L or PVI, and then the daily PAR absorption, Sp (MJ/day) = (.48) (daily shortwave radiation, S) (Fp). Cumulative daily Sp, ΣSp, is used to determine the DM2−DM1=r(ΣSp) and ΣSp=s(ΣVI) relations in Eq. [2] .

Figure la displays the DM change for three time intervals during the growing season versus ΣSp for those three intervals based on L (Eq. 7) while Fig. 1b displays the same DM changes vesus ΣSp calculated from PVI (Eq. 8). The three time intervals were the first three weeks after transplanting (DOY 141—161 and 162—182, respectively, for early and late plantings), from transplanting to approximately average heading date (DOY 141—224 and 162—224), and from transplanting to approximately physiological maturity of the grain (DOY 141—266 and 162—266). The scale on the interior of Figs. 1a and 1b is 10 times as sensitive as the outer scale and applies to the data for the three week interval right after transplanting. The patterns of data in Figs. 1a and 1b are similar but there was more variation in estimating rice canopy Fp and hence Sp from PVI than from L.

The slope of $DM_2—DM_1$ versus cumulative Sp is defined as the efficiency of conversion of absorbed PAR to dry matter, e_c, g DM/MJ PAR. As determined statistically the efficiencies of conversion, for the time intervals transplanting to DOY 224 and transplanting to DOY 266,were 2.85 and 2.48 g DM/MJ for Fig 1a and 3.00 and 2.43 g DM/MJ for Fig. 1b. For comparison, Horie and Sakuratani[4] reported the efficiency of conversion for 10 experiments with Nipponbare to be 2.88 and 2.75 g DM/MJ PAR for the periods transplanting to 20 days after heading and transplanting to 40 days after heading, respectively.

2. *Cumulative PVI and cumulative Sp, DM, and YIELD*

The ΣSp from L plotted against ΣPVI in Fig. 2a is the graphical display of the $\Sigma Sp = s(\Sigma VI)$ relation in equation [2]. PVI cumulated daily is a measure of the area under the PVI versus time curve. The scatter increased when time interval included dates after DOY about 245 or about 20 days after heading (Table 1). The equation

$$\Sigma Sp = 13.1 + 0.27(\Sigma PVI) \qquad r^2 = 0.86 \qquad N = 13 \qquad [10]$$

in Fig. 2a estimated cumulative Sp from transplanting (DOY 141 or 162) to heading (DOY 224). The coefficient, 0.27 MJ/PVI unit, is the efficiency of PAR absorption in terms of the perpendicular vegetation index, e_a, for the season up to heading. For the time interval from transplanting to 40 days past heading, e_a was 0.21 MJ/PVI (Fig. 2a).

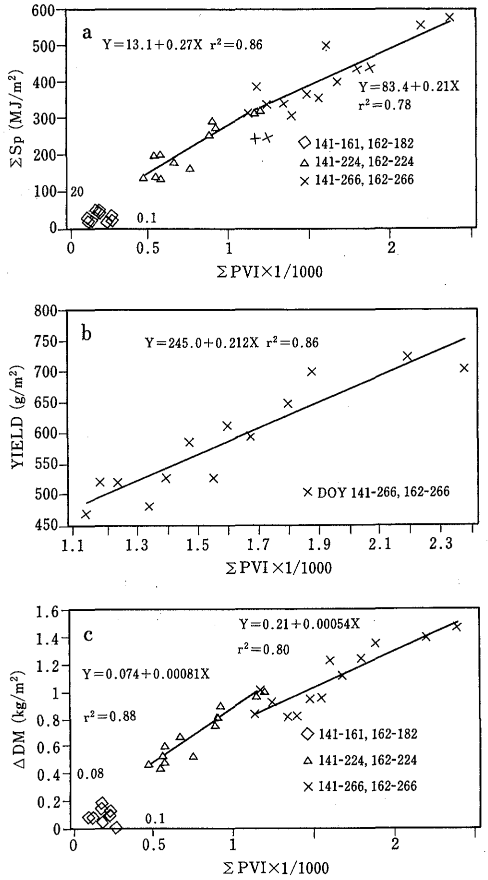

Fig. 2. Cumulative PVI versus cumulative Sp (part a), YIELD (part b), and dry mass (part c). Parts (a) and (c) for the same time intervals as in Fig. 1 while part (b) is for the whole season only (DOY 141 or 162 to 266). The interior scale of parts a and c apply for the three week interval right after transplanting. Parts (a), (b), and (c) in Fig. 2 are $\Sigma Sp = s(\Sigma VI)$, $YIELD = p(\Sigma VI)$, and $DM = r(s(\Sigma VI))$, respectively, of Eq. [2].

Cumulative daily PVI from DOY 141 to 266 (8 treatments) and DOY 161 to 266 (5 treatments) versus YIELD, corresponding to $YIELD = p(\Sigma VI)$ in Eq. [2], is shown in Figure 2b. The r^2 in Eq. [11] for these data indicates that YIELD can be estimated directly from ΣPVI as well as ΣSp can. The two data points furtherest to the right in Fig. 2b are for subplots of early planted Nipponbare (treatments 82N and 83N in Table 1) that had leaf area indices of 6.2 and 6.9 at heading. Only these two plots had high enough L to be approaching the limiting yield asymptotically. Therefore, YIELD (g/m^2) was fit by a linear equation

$$YIELD = 245 + 0.212(\Sigma PVI)$$

$r^2=0.86 \qquad N=13. \qquad [11]$

The relations displayed in Fig. 1b and 2a, respectively, and their product in Eq. [2] suggest the examination of ΔDM (g/m^2) versus ΣPVI as in Fig. 2c. The pattern in Fig. 2c for ΔDM versus ΣPVI closely resembles that for ΔDM versus ΣSp in Fig 1b, and suggests that ΣPVI could be used to estimate the DM change. Such a relation would be valuable for rice because of the close relation between DM at heading and YIELD. For the 13 treatments of Fig. 2c, the equation for the season through DOY 224 was

$$DM=73.64+0.811(\Sigma PVI)$$

$$r^2=0.88 \qquad N=13 \qquad [12]$$

where DM is expressed in g/m^2.

3. *Seasonal solution*

The solutions of Eq. [2] for each of the 13 treatments for the whole season, transplanting to DOY 266, are summarized in Table 3 as expressed in terms of PVI by

$$\frac{YIELD}{\Sigma PVI}=\frac{YIELD}{DM_2-DM_1}\times\frac{DM_2-DM_1}{\Sigma Sp}\times\frac{\Sigma Sp}{\Sigma PVI} \qquad [2a]$$

The functional relations for individual treatments reduce to simple ratios and the mean ratios among all treatments approximate the slopes of linear functional relations describing the pooled treatments for the same time interval (Figs. 1a, 1b, 2a and 2b).

The most general result in Table 3 is that the yield efficiency, e_y, YIELD/ΣPVI, is in the same order within cultivars and planting dates as the light absorption efficiency, $\Sigma Sp/\Sigma PVI$. Variation in $\Sigma Sp/PVI$ within a cultivar or planting date (relative to the mean) ranged up to 15% whereas it was typically about 5% for the other two terms. Consequently, in the product of terms, the efficiency of absorption dominated the yield efficiency. The variations produced the scatter in the graphs of the Eq. [2] terms shown in Figs. 1a, 2a, and 2b, and in the product of the last two right hand terms shown in Fig. 2c. In Figs. 1a and 1b the slopes for $(DM_2-DM_1)=r(\Sigma Sp)$ for the whole season data are 2.5 and 2.4 g DM/MJ and close to the mean value of 2.6 g DM/MJ in Table 3. The average value of 0.26 MJ/PVI unit for $\Sigma Sp/\Sigma PVI$ in Table 3 is also intermediate between the slopes in Fig. 2a of 0.27 MJ/PVI unit from transplanting to DOY 224 and 0.21

Table 3. Solution of equation [2] term by for the whole season, DOY 141 or 162 through 266.

Plot	Treatment	$\frac{YIELD^a}{\Sigma PVI}$	=	$\frac{YIELD^b}{DM_2\text{-}DM_1}$	$\frac{DM_2\text{-}DM_1{}^c}{\Sigma Sp}$	$\frac{\Sigma Sp^d}{\Sigma PVI}$
		g/PVI unit		g/g	g DM/MJ	MJ/PVI unit
1	80 N	0.441		0.509	2.629	0.330
2	81 N	0.381		0.495	2.4410	0.316
3	82 N	0.330		0.520	2.504	0.253
4	83 N	0.296		0.478	2.538	0.244
5	90 K	0.417		0.557	2.704	0.277
6	91 K	0.355		0.534	2.758	0.241
7	92 K	0.360		0.522	2.813	0.245
8	93 K	0.372		0.516	3.055	0.236
9	70 K	0.378		0.646	2.630	0.223
10	70 N	0.360		0.592	2.371	0.256
11	72 K	0.396		0.615	2.610	0.247
12	72 N	0.341		0.558	2.615	0.234
13	72 S	0.412		0.564	2.603	0.280
	Mean :	0.372		0.547	2.636	0.260

[a] Yield efficiency, e_y, in terms of cumulative perpendicular vegetation index.

[b] Harvest index, HI, when dry matter at transplanting, DM_1, is ignored and DM_2 is dry matter at harvest.

[c] Efficiency of conversion of absorbed PAR to dry matter, e_c.

[d] Efficiency of absorprion, e_a, in terms of perpendicular vegetation index.

Yield is observed grain yield in harvest samples but DM for DOY 266 was estimated from periodic samples by an equation of the form of Eq. [9].

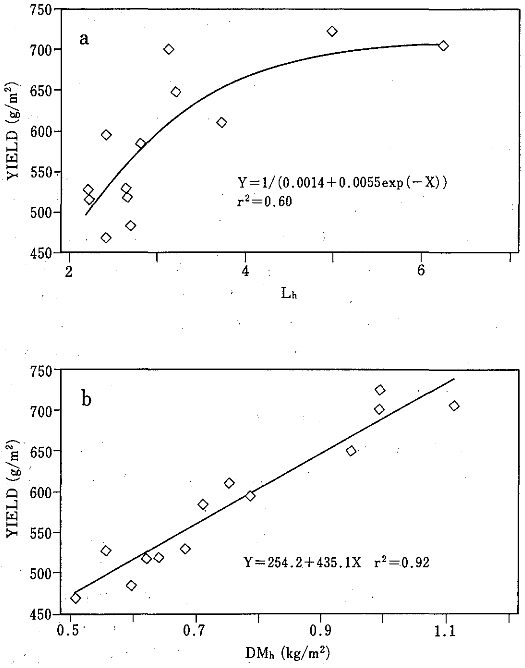

Fig. 3. Grain YIELD (g/m^2) versus leaf area index at heading L_h (part a), and above-ground dry mass, DM_h (part b).

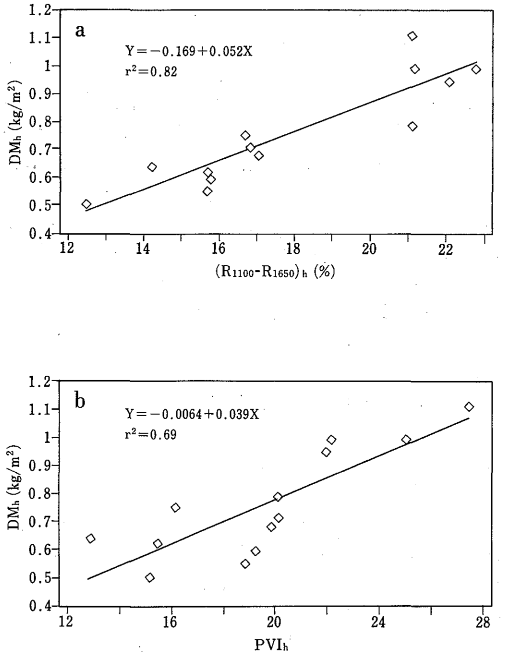

Fig. 4. Above-ground dry mass at about heading (DM_h) versus $(R_{1100}—R_{1650})_h$ (part a), and PVI_h (part b). The figures display the DM_h= o (VI_h) funtion of Eq. [3].

MJ/PVI unit from transplanting to DOY 266 for the $\Sigma Sp = s\ (\Sigma PVI)$ function.

The last 3 entries (72K, 72N, and 72S) in Table 4 permit a comparison of the relative values of the terms in Eq. [2a] for these three cultivars at the same fertility level, 2g N/m^2. The cultivar Shinanomochi had the highest yield efficiency (left hand term), in agreement with having the highest photosynthetic light absorption efficiency (third term on right). The experimental PAR conversion efficiencies ranged only from 2.603 to 2.615.

Equation [3]

4. Relations among DM, YIELD, and VI at heading, or maximum L stage

The means of measurement data on three dates close to the heading date of each plot were calculated and used as L_h, DM_h, and VI_h. The three measurement dates used for DM_h and L_h were DOY 211, 224, and 239 for all treatments (Table 1) except 70N and 72N (matured later) for which the dates were 224, 239, and 254. The dates of the spectral measurements were DOY 211, 221, and 238 except for 70N and 72N for which sampling dates were 221, 238, and 257. Plots with high YIELD had relatively large L_h and DM_h.

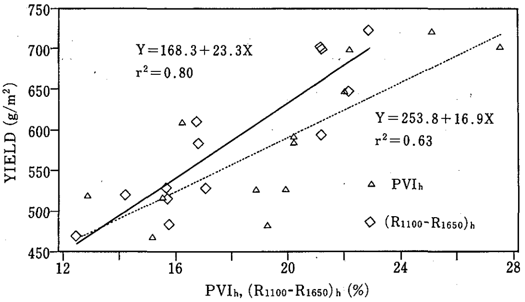

Fig. 5. YIELD versus $(R_{1100}—R_{1650})_h$ and PVI_h. The figures display the YIELD=o (VI_h) function of Eq. [3].

YIELD (g/m^2) is plotted against L_h and DM_h in Figs. 3a and 3b, respectively. DM_h (g/m^2) related almost linearly to YIELD (Fig. 3b) as expressed by

$$YIELD = 254.2 + 0.435(DM_h)$$
$$r^2 = 0.92 \qquad N = 13 \qquad [13]$$

In contrast YIELD approached a limiting value asymptotically versus L_h (Fig. 3a).

To predict YIELD, a VI_h sensitive to DM_h should be used. Figures 4a and 4b are $(R_{1100}$

$-R_{1650})_h$ and PVI_h versus DM_h, respectively. DM_h was estimated better by $(R_{1100}-R_{1650})_h$ ($r^2=0.82$) than by PVI_h ($r^2=0.69$) especially in the DM range 500 to 700 g/m^2. The number of observations in the data set is small but it is clear that $(R_{1100}-R_{1650})_h$ is more useful than PVI to estimate DM_h. The equation (Fig. 4a)

$$DM_h=-169.+52.0(R_{1100}-R_{1650})_h \quad r^2=0.82 \quad n=13 \qquad [14]$$

corresponds to the function $DM_h=o\ (VI_h)$ in equation [3] . Substituting [14] into [13] gave

$$YIELD=181.0+22.6(R_{1100}-R_{1650})_h \qquad [15]$$

The coefficient of determination between YIELD estimated by [15] and measured YIELD was 0.81.

Fig. 5 relates $(R_{1100}-R_{1650})_h$ and PVI_h, respectively, to YIELD. PVI versus YIELD is similar in pattern to PVI_h versus DM_h (Fig. 4b) and the pattern for $(R_{1100}-R_{1650})_h$ versus YIELD resembles that for $(R_{1100}-R_{1650})_h$ versus DM_h (Fig. 4a). $(R_{1100}-R_{1650})_h$ better estimated both DM_h and YIELD than did PVI_h.

Discussion

Data analyses demonstrated the use of the spectral components analysis equations. Fp can be estimated from PVI instead of L as expressed by equation [1] . This can be done using equations [7] or [8] but calibrations of equation [1] should be developed for rice from simultaneous field measurements of reflectance factors and canopy light absorption as has been done for various other field crops[1,2,17]. The main reason for desiring to calibrate Fp directly as a function of VI is that measurements of L consume more labor and time than spectral observations.

The functional relations of the individual terms of Eqs. [1] , [2] , and [3] demonstrate the linkage of spectral observations to the agronomic characteristics of the crop and the biophysical processes that permit growth and reproduction. Equation [1] links spectral observations, expressed as vegetation indices, to canopies' light absorption capability. Equation [2] links YIELD to cumulative daily estimates of vegetation indices through the efficiency of light absorption, efficiency of conversion of PAR energy to dry matter, and the harvest index. Equation [3] links YIELD to one or a few spectral observations at about heading (or anthesis) through the relation between YIELD and DM_h, a relation that is well-accepted for rice.

As a whole the functional relations that constitute spectral components analysis provide new interpretations of crop canopy observations that are consistent with the behavior of crops in the field. They also provide ways to use spectral observations in conjunction with plant process modeling. In addition to estimation of Fp, they can provide information on photosynthetically active tissue development and persistence, stresses, and an independent check on YIELD as predicted by the models[5,7,15].

The objective of smoothing data is to produce daily values of L, Sp, and PVI, so that equation [2] terms can be numerically integrated by time steps of one day. Various empirical polynomial expressions were tested for our data. Expressions of the form of equation [9] gave especially good fit for the younger stages such as 0 through 20 days after transplanting ; other functions often gave negative values during this time even if they fit well in later stages. The polynomial expressions used for smoothing do not always level eff (DM) or decline (L, VI) as fast as the experimental data near the end of the season so that manual smoothing may sometimes be necessary. No manual smoothing was done in this study, however.

There is a relatively good relation between cumulative PVI and DM through physiological maturity (Fig. 2c) even though the relation between DM and PVI is usually poor for instantaneous PVI observations after L_{max}. Useful relations between VI and YIELD or DM have been reported for paddy rice[10], but coefficients in empirical equations such as [11] , [12] , [13] , and [14] can be expected to differ for climatically different locations.

In relation to Figs 1a and 1b and Table 3 we must clarify that Eqs. [4] and [8] are based on the pre-L_{max} data set only (73 VI and L observations through DOY 224[12]. We recommend that the VI measured in the post-L_{max} period be used in the Fp versus VI relation developed for the period up to L_{max}[17]. This procedure helps keep from overestimating Fp and, consequently, Sp during the latter part of the growing season when nonphotosynthesizing tissue increasingly shades the sensor measuring light transmission, the main component of Fp. In this study, neither Fp=g(L_z) nor Fp=f(VI) was directly determined; consequently, a valid comparison of the effect of method of estimating Fp on efficiency of conversion of Sp to DM, e_c, cannot be made. Such a study is needed. Our values of e_c using Eq. [7] (slopes of 2.9 and 2.5 g DM/MJ in Fig. 1a, and the mean value 2.64 g DM/MJ in Table 3) compare favorably with values reported by Horie and Sakuratani[4] when crop development periods are considered.

Canopy light absorption approaches a limiting value asymptotically as L increases and so did YIELD (Fig. 3a). But DM_h was more closely associated with YIELD (Fig. 3b), so that in the absence of post-heading diseases, insects, and weather damage, DM_h is a good predictor of YIELD. The harvest index, HI, the ratio of YIELD to DM at harvest (Table 2) was highest for the nonfertilized treatments. However, commercially grown rice in Japan is fertilized so that the harvest indices of the fertilized plots is considered typical. (Note: The harvest indices of Table 3 differ from those in Table 2 because they are based on grain plus hulls at 14% water content as in Figs. 2b, 3a and b, and 5 and on smoothed DM on DOY 266).

The reflectance differences ($R_{1100}-R_{1650}$) and ($R_{1100}-R_{1200}$) at heading related more closely to DM_h than did PVI_h, which is based on visible red (630—690nm) and near infrared (760—900nm) reflectances. PVI_h responds mainly to the photosynthetically active plant parts dominated by leaves and does not necessarily relate closely to DM_h (Fig. 4b) while the 1200 and 1650 nm wavelengths respond to the water content of the canopy which completely obscures the paddy water at the heading stage of rice development. The differences $(R_{1100}-R_{1650})_h$ and $(R_{1100}-R_{1200})_h$ are the best vegetation indices identified to date for estimating dry matter at heading, DM_h (Fig. 4a). On the other hand, PVI and other vegetation indices based on visible and near infrared bands are superior for estimating green leaf area index, L, and consequently Fp.

It remains to combine these 1987 data for Tsukuba with results for other years and locations and to determine their generality. The Fp=f (VI) relation also needs to be developed from direct experimental observations. We anticipate that Fp=f (VI) will be applicable over a large geographical area but that ΔDM=q (ΣSp) could differ among climatically different sites. If so, YIELD=m ((VI_h) and YIELD=p (ΣVI) would differ in slope and range among locations. Once developed the relations should hold where they apply, however, unless genotypes or cultural practices change drastically.

In conclusion, Eqs. [1], [2], and [3] provide a framework within which to examine, analyze, and interpret the growth, photosynthetic capability, and YIELD of rice and other crops as affected by their environments and stresses. The approach interfaces well with classical crop growth and yield modeling, and provides alternative ways of estimating fractional PAR absorption and documenting stresses.

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