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Monitoring leaf photosynthesis with canopy spectral reflectance in rice

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Abstract

Non-destructive and rapid method for assessment of leaf photosynthetic characteristics is needed to support photosynthesis modelling and growth monitoring in crop plants. We determined the quantitative relationships between leaf photosynthetic characteristics and canopy spectral reflectance under different water supply and nitrogen application rates. The responses of reflectance at red radiation (wavelength 680 nm) to different water contents and nitrogen rates were parallel to those of leaf net photosynthetic rate (P_N). The relationships of reflectance at 680 nm and ratio index of R(810,680) (near infrared/red, NIR/R) to P_N of different leaf positions and leaf layers in rice indicated that the top two full leaves were the best leaf positions for quantitative monitoring of leaf P_N with remote sensing technique, and the ratio index R(810,680) was the best ratio index for evaluating leaf photosynthetic characteristics in rice. Testing of the models with independent data sets indicated that R(810,680) could well estimate P_N of top two leaves and canopy leaf photosynthetic potential in rice, with the root mean square error of 0.25, 0.16, and 4.38, respectively. Hence R(810,680) can be used to monitor leaf photosynthetic characteristics at different growth stages of rice under diverse growing conditions.

Additional key words: chlorophyll; leaf area index; net photosynthetic rate; nitrogen supply; *Oryza sativa*; remote sensing; water content.

Introduction

Photosynthetic productivity of plant is the primary power to drive and sustain the whole ecological system (Yu *et al.* 1999). Ninety percent of dry matter in plant is produced by plant photosynthesis, which is the basis of dry matter accumulation and yield formation in crops (Zhang *et al.* 2001). Among other factors, the impact of water and nitrogen stress on photosynthesis of crops is one of the main causes leading to yield loss and quality variation. To determine the photosynthetic parameters of plant by remote sensing technique is helpful for establishing simulation models for evaluating biomass production and estimating crop yield (Zhang and Fu 1999). Thus, a non-destructive, quantitative, and rapid method for assessment of plant leaf photosynthetic characteristics under varied growing conditions would evidently contribute to monitoring growth status and estimating yield and quality characters of crop plants.

Some researchers have already studied the relationships between plant photosynthetic characteristics and spectral traits in plant growth monitoring with remote sensing (Sellers 1985, 1987, Carter 1998, Choudhury 2001, Boegh *et al.* 2002). Nevertheless, majority of these investigations dealt with the relationships of spectral reflectance to plant photosynthetic functional units or green photosynthetic areas such as chloroplast amount or chlorophyll (Chl) content, leaf area index, *etc*. (Dusek *et al.* 1985, Hatfield *et al.* 1985, Shibayama and Akiyama 1989, Jin *et al.* 1992, Liu *et al.* 2000, Thiemann and Kaufmann 2000, Sims and Gamon 2002). Chl content of green leaves is frequently used as an indicator of plant photosynthetic productivity, because of close correlation between them. Since the spectral reflectance in visible wavelength regions of plant is mainly affected by Chl content (Al-Abbas *et al.* 1974), many authors investigated the relationships between reflectance spectra and Chl content of plants. They found that the reflectance at 550

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Abbreviations: CSI – canopy structure index; FWC – field water capacity; L – green leaf area index; LWC – leaf water content; N_c – canopy nitrogen concentrations; PAR – photosynthetically active radiation; P_N – net photosynthetic rate; R(λ1, λ2) – ratio index; SR – simple ratio vegetation index.

or 675 nm band was sensitive to Chl content (Al-Abbas *et al.* 1974, Aldakheel and Danson 1997). Also the ratio index of 840 nm or 850 and 560 nm could well estimate Chl content of rice (Inada 1985, Shibayama and Akiyama 1986). Aoki and Totsuka (1985) found the spectral reflectance ratio of 880/550 nm is a more promising vegetation index for evaluating Chl content of mono-crop. Serrano *et al.* (2000) found a close linear relationship between ratio vegetation index of R(900,680) and Chl content (product of Chl *a* and leaf area index, LAI). The red edge traits of spectra are important in assessing Chl content and LAI (Horler *et al.* 1983, Filella and Penuelas 1994, Gupta *et al.* 2001). Sims and Gamon (2002) developed and tested a new Canopy Structure Index (CSI) that combined the low absorptance water bands with the simple ratio vegetation index (SR) to produce an index with a wider range of sensitivity to photosynthetic tissue area at all canopy thicknesses.

Recent studies have focused on the relationships between remote sensing information and photosynthetic rates in crops. In general, the relationships between the vegetation indices and net photosynthetic rate (P_N) are curvilinear, but the relationship must be distinguished for C_3 and C_4 crops (Choudhury 2001). Other studies indicated that the simple ratio vegetation index (SR) should be near-linearly related to the derivatives of the unstressed canopy photosynthesis with respect to photosynthetically active radiation (PAR) (Sellers 1987, Verma *et al.* 1993). By studying NOAA-AVHRR images at different growth stages of winter wheat, Zhang and Fu (1999) and Zhang and Wang (2003) found that normalized difference vegetation index derived from NOAA-AVHRR images closely tracked the changes of photosynthetic characteristics at different stages, with a linear correlation. Carter (1998) showed that the ratio of reflectance at 701±2 nm to reflectance at 802±2 nm or a normalized difference vegetation index (NDVI) computed from these values regressed more strongly to photosynthetic capacity than the first derivatives of spectral reflectance or wavelength at the red edge inflection point. Moreover, Boegh *et al.* (2002) found that green leaf area index (L) and canopy nitrogen contents (N_c) were significantly correlated with the spectral reflectance or vegetation indices acquired by the Compact Airborne Imager (CASI). Thus CASI-based maps of N_c and L were produced for use in a mechanistic photosynthesis/stomatal conductance model of vegetation with C_3 pathway, and both temporal and spatial estimates of P_N and transpiration rates were derived successfully. However, too many complicated parameters were involved in these previous mechanistic models evaluating crop photosynthetic rate with remote sensing information, which limited their practical application (Zhang *et al.* 2000). Further information is needed about a quantitative and simple method for monitoring of leaf photosynthetic characteristics in crop plants including rice under different environments with remote sensing technique.

Therefore, we tried first to elucidate the relationships between canopy reflectance spectra and leaf photosynthetic rates of rice under different water supply and nitrogen application rates, and then to develop a simple and reliable algorithm based on spectral parameters for monitoring leaf photosynthesis in rice by remote sensing technique. The expected results would be used for modelling photosynthetic production and monitoring growth status of rice plant.

Materials and methods

Experiment setup: The study was conducted on the campus experiment station at Nanjing Agricultural University of China (32°N, 119°E), involving three separate experiments in 2001 and 2002. The experiment 1 was conducted with pot culture in 2001, and the experiments 2 and 3 with pool culture in 2001 and 2002.

In the experiment 1, the japonica rice (*Oryza sativa* L. cv. Wuxiangjing 9) was planted on 11 May, and transplanted to rectangular pots (0.635×0.400 m) with 0.25 m^2 area on 12 June. The soil was gleyed paddy soil with field water capacity (FWC) of 22.8 %, containing (at 0–25 cm) 15.9 g kg^{-1} organic matter, 0.94 g kg^{-1} total N, 43.8 mg kg^{-1} available phosphate (P_2O_5), and 80.16 mg kg^{-1} available K (K_2O). There were five different soil water levels, created by controlling soil water contents at 70, 80, 90, and 100 % of FWC and water-logging from the critical tillering stage to maturity. The experiment was a randomized complete block design with five replications. All treatments had the same nitrogen rate of 20 g m^{-2} (200 kg ha^{-1}), which was divided into 50 % as basal nitrogen, 10 % at tillering, 20 % at elongation, and 20 % at booting. The ratio of nitrogen and P_2O_5 and K_2O was 2 : 1 : 2, but all P_2O_5 and K_2O were applied as basal fertilisers.

In the experiments 2 and 3, the cement pool was square with 1 m^2 area and 80 cm deep. The soil property, cultivar, transplanting date, and fertilisation were detailed as in the Exp. 1. In 2001, four water management practices as the systems of rice intensification (SRI), plastic ground-cover system (PGS), intermittent irrigation system (IIS), and conventional flooded rice system (CK), and two N application rates (15 and 30 g m^{-2} denoted as N_{15} and N_{30}, respectively) were set up throughout rice growing period. In 2002, four different soil water contents at 70, 80, and 90 % of FWC and water-logging from the critical effective tillering stage to maturity, and N_{15} and N_{30} were carried out. The experiment was a 2-way factorial arrangement of water×N treatments in the randomised complete block design with 3 replications.

In the above pot and pool experiments, each pot or pool was loaded with equal quantity of soil. The soil was saturated with water, and the FWC was measured by annular reamer method when soil layer structure was formed. Then soil water content was controlled at the target water content by weighing method (removing mass of plant periodically) in pot trial, whereas in pool experiments, soil at 0–20 cm was taken every 2–3 d to determine soil water content and then irrigated as required.

Canopy spectral reflectance was measured at the stages of elongation, booting, heading, 20 d after heading, and maturity in pot culture experiment, and at the stages of critical effective tillering, elongation, and heading in pool experiments. The spectral reflectance of the plant canopy over the wavelength range of 447–1 752 nm was determined at 16 specific wavebands (approximate centre wavelengths of 460, 510, 560, 610, 660, 680, 710, 760, 810, 870, 950, 1 100, 1 220, 1 480, 1 500, and 1 650 nm). A portable ground *MSR16* radiometer (*Cropscan*, Rochester, MN, USA) was used. To record reflectance a data acquisition device (*DLC* model *2000*, *Cropscan*) equipped with sun angle cosine correction capacity was used. During measurements with pot culture, four pots in each plot were moved close enough to form a quadrate rice canopy with 1.5 m^2, then measurements were made over each plot, looking straight down from 1.0 m above the canopy. With a 31.1º field of view, the sensor viewed an area of 0.5 m in diameter. Five scans were averaged as each measurement. Radiometer calibration was conducted daily with an opal glass diffuser using the two-point (*2-Pt. Up/Dn*) method (*Cropscan 2000*). All spectral measurements were made on cloudless or near cloudless days at 10:00-14:00 h. In pool experiments, canopy spectral measurements were obtained by on-site scans, with the similar procedures as with pot experiment.

Leaf P_N and Chl content. Immediately after each completion of canopy spectroradiometry, P_N and Chl content of four leaves from the top of stem (L1, L2, L3, L4) were measured using a *CI-310PS* portable photosynthesis system (*CID*, Camas, WA, USA) with controlled 1 200 µmol m^{-2} s^{-1} photon flux (PAR) and the *SPAD-502* Chl meter (*Minolta*, Osaka, Japan). Three replicates were made, each of three leaves on main stems, at 10:00-11:00 h.

LAI and water content. The leaves of three rice plants per plot were sampled and weighed immediately after spectral measurement (fresh mass, FM), then area of these green leaves were determined by Laser Area Meter *CI-203* (*CID*) and dried in an oven at 80 ºC until constant mass (dry mass, DM) was reached. Finally leaf water content (LWC) was calculated according to the following formula: LWC = (FM – DM)/FM×100 [%]. LAI for each plot was calculated using the ratio of green leaf area to dry mass.

Canopy leaf photosynthetic potential was calculated from P_N averaged over L1 to L4 multiplied by LAI, and the net P_N of L1, L2, L3, and L4 was denoted as PSL1, PSL2, PSL3, and PSL4, respectively.

Data analysis: Reflectance spectra and ratio indices were obtained through growth cycle of rice, along with leaf photosynthetic characteristics. Data collected from the pool experiment in 2002 were used for deriving the regression equations and data from pot and pool experiments in 2001 for testing the performance of the equations under different water and nitrogen conditions. All possible ratio indices and normalized difference indices of NIR bands to visible bands were calculated from the raw reflectance data. Then regressions of reflectance and ratio indices and normalized difference indices to leaf photosynthetic characteristics, canopy leaf photosynthetic potential were made using SAS software (SAS 1990). An overwhelming proportion of the best spectra–photosynthesis relationships was either linear or non-linear power. On rare occasions, exponential or quadratic models provided only marginal increase in r^2 values, but these increases were generally insignificant. Hence only linear was reported throughout the paper. Then, the leaf photosynthetic traits were predicted from the reflectance measurements based on the best regression model. For validation of the monitoring model, root mean square error (RMSE) and relative error (RE) were calculated to test the goodness of fit between the predicted and observed values along with 1 : 1 plotting. The formulae used were as follows:

ratio index: $\rho_{\lambda1}/\rho_{\lambda2}$;

normalized difference index: $\rho_{\lambda1} - \rho_{\lambda2}\ (\rho_{\lambda1} + \rho_{\lambda2})^{-1}$

where $\rho_{\lambda1}$ and $\rho_{\lambda2}$ denote reflectances of bands λ1 and λ2, respectively.

Results and discussion

Changes of leaf photosynthesis and canopy spectral reflectance under different water and N conditions: Rice growth was significantly affected by soil water contents and N application rates, and thus leaf photosynthesis and canopy spectral reflectance changed correspondingly to varied water and N contents. Leaf P_N on unit area basis increased with increasing soil water content in rice at each growth stage, and it was somehow similar under N_{15} and N_{30} with adequate soil water but opposite in soil water stress (Fig. 1). These might reflect the effects from the interactions of nitrogen and water in relation to the different growth stages. In addition, under different soil water contents, the change trend of P_N at different leaf positions on rice stem was PSL1 > PSL2 > PSL3 > PSL4 (data not shown).

As expected, the water and N treatments caused large variation in leaf Chl content (leaf SPAD), leaf water content, and LAI (Table 1). These changes in leaf growth characters would have a significant impact on leaf P_N as shown in Fig. 1, further leading to the changed photon

Table 1. Leaf characters at different growth stages under different experiments in rice. Leaves for measuring water contents were sampled between 10:00 and 11:00 h.

	2001						2002		
	Pot experiment			Pool experiment			Pool experiment		
	LAI	SPAD	LWC [%]	LAI	SPAD	LWC [%]	LAI	SPAD	LWC [%]
Elongation	3.2~4.6	41.3~47.9	64.1~71.6	1.1~3.1	36.2~46.1	65.2~70.9	3.3~4.6	41.0~48.1	66.2~74.9
Heading	3.8~6.8	37.4~52.7	66.6~72.1	2.6~7.8	36.1~54.3	64.6~73.0	3.3~6.9	36.1~52.3	63.0~71.0
Filling	3.5~6.7	34.8~51.8	66.3~72.3	2.7~7.3	32.6~52.2	65.5~72.9	2.7~6.1	33.8~51.4	65.0~71.8
Maturity	2.5~3.9	33.2~45.2	63.4~68.6	2.1~4.7	32.2~46.8	62.2~68.5	2.2~4.8	31.2~46.1	61.4~68.7

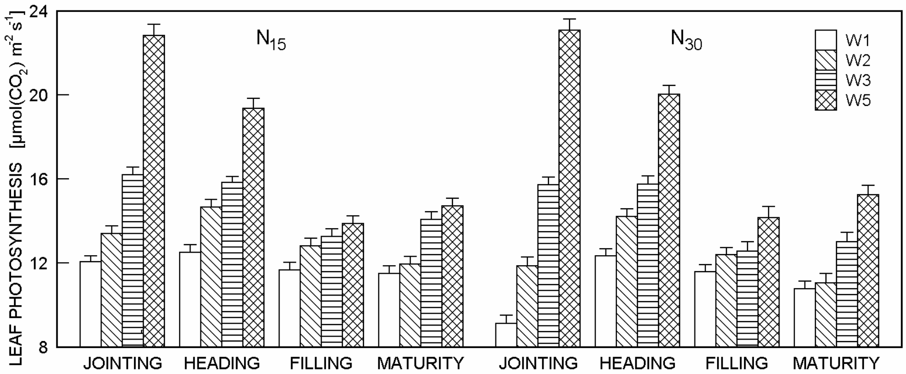

Fig. 1. Net photosynthetic rate of the first leaf from top at different growth stages of rice under different water (W1 – 70, W2 – 80, W3 – 90 % of full water content, W5 – water-logging) and nitrogen (N_{15} – 15 g m^{-2}, N_{30} – 30 g m^{-2}) treatments.

absorption and reflection by leaf canopy under the different treatments.

Spectral reflectance decreased in the visible wavelength regions and short-wave infrared (SWIR) (1 400–1 700 nm) regions with increasing water supply. Absorption of the 450–700 nm radiation by pigments of leaf was aggravated while in the near infrared (NIR) (750–950 nm) wavelength regions the spectral reflectance increased with increasing water supply and formed a high reflectance spectra flat roof (Fig. 2). The differences between different water contents in canopy spectral reflectance at 460, 680, 810, and 1 500 nm, respectively, were significant at 1 % level, the same pattern over the growth circle (680, 810, and 1 500 nm as examples in Fig. 2). This indicates that varied water status in rice could be discriminated by specific spectral variables. Under different water regimes and N rates, canopy spectral reflectance exhibited the similar change patterns under different water contents (Fig. 3). Canopy spectral reflectance in visible wavelength regions and SWIR regions under high N supply was lower than under low N supply, but went the reverse in NIR wavelength regions under the same soil water content. Spectral reflectances at 810 and 1 500 nm were evidently affected by leaf inner structure and leaf water status, respectively (Curcio and Petty 1951, Gausman *et al.* 1970), hence they were not good indicators of leaf P_N in rice. Yet 680 nm was the strong absorption band of plant Chl, which could well indicate the photosynthetic productivity of green leaf, and response of reflectance in 680 nm band to different water and N contents was parallel to the leaf P_N in the present study. Thus, the spectral reflectance at red radiation band (680 nm) is proposed as an indictor of photosynthetic productivity capacity of rice plant.

Relationships between single band spectra and leaf photosynthesis: P_N of L1 was correlated to canopy spectral reflectance of single band in visible regions (500–700 nm) and SWIR regions (1 450–1 650 nm), with strong regressions at 680 nm and 1 500 nm (Fig. 4), but weak regressions at NIR regions (750–1 400 nm). Both canopy spectral reflectance at 1 500 nm and leaf P_N were correlated to leaf water status, which may explain why the strong correlation existed between canopy spectral reflectance at 1 500 nm and leaf P_N in rice. Besides, the results also confirmed that the red band at 680 nm was the sensitive band as proposed in the previous section.

The correlation analyses were further made between canopy spectral reflectance at 680 nm and P_N at different leaf positions (Table 2, $n = 20$). The correlation degree with the top four leaves in rice was L1>L2>L3>L4. Hence the first full leaf from top in rice was the most sensitive leaf of canopy spectral reflectance, the fourth leaf the least sensitive. This is because the upper leaves from the top are better exposed to sunlight, and thus contribute more to the canopy spectral reflectance than lower leaves in rice. Also, the correlation degree between canopy spectral reflectance at 680 nm and P_N averaged over different

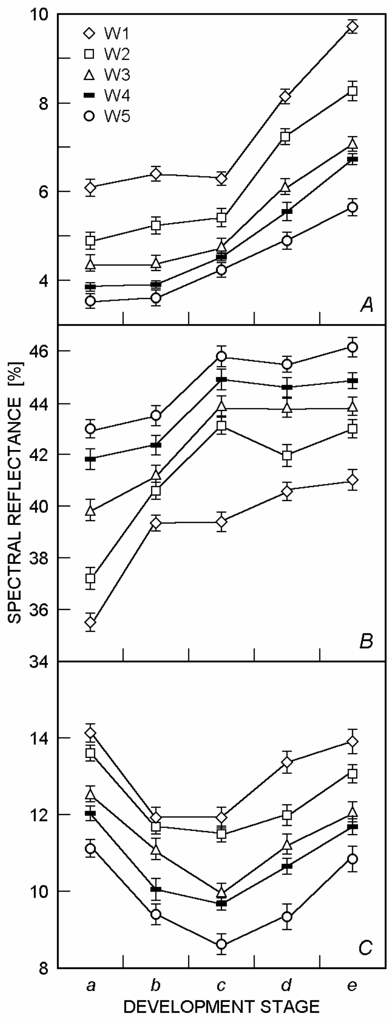

Fig. 2. Changes in reflectance at 680 (*A*), 810 (*B*), and 1 500 (*C*) nm over the growth period (*a* – elongation, *b* – booting, *c* – heading, *d* – milking, *e* – maturity) of rice under five different soil water contents (W1 – 70, W2 – 80, W3 – 90, W4 – 100 % of full water content, W5 – water-logging).

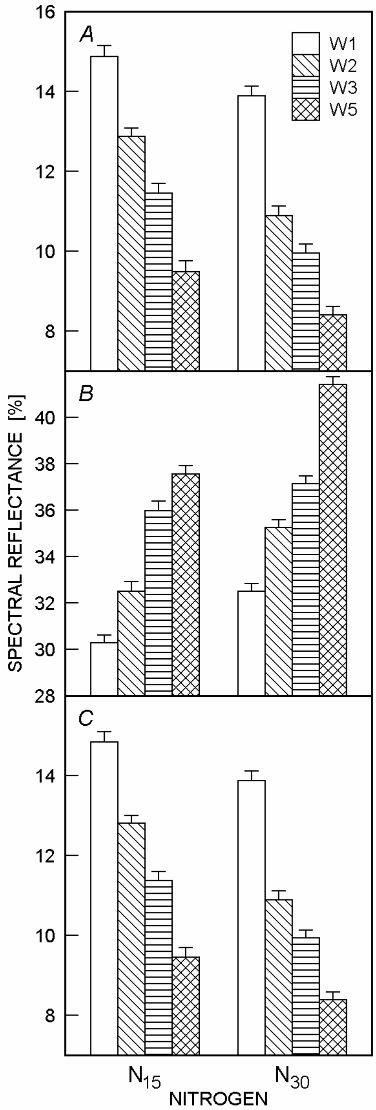

Fig. 3. Canopy reflectance at 680 (*A*), 810 (*B*), and 1 500 (*C*) nm at elongation stage of rice under different water (W1 – 70, W2 – 80, W3 – 90 % of full water content, W5 – water-logging) and nitrogen (N_{15} – 15 g m^{-2}, N_{30} – 30 g m^{-2}) treatments.

layer leaves was L12>L123>L1234>L1 (Table 2), suggesting that the top two leaves in rice were the best leaf positions for monitoring leaf P_N with remote sensing technique. The top two leaves are the main photosynthetic functional leaves of rice, and their photosynthetic productivity directly indicates the status of plant growth and affects the formation of grain yield and quality. Thus quantitative evaluation on photosynthesis of top functional leaves in rice by remote sensing technique is of both theoretical and practical meaning.

Relationships between spectral index and leaf photosynthesis: Canopy spectral reflectance at single band is often subject to the disturbance of biomass, background, *etc*. Daughtry *et al.* (2000) found that attempts to assess plant N status based on canopy spectral reflectance at a single band were often confounded by the variability in background reflectance and/or LAI. Yet ratio of two

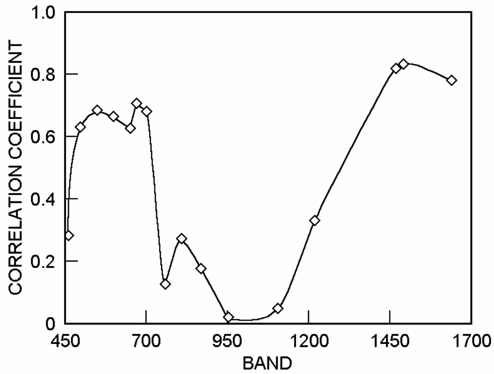

Fig. 4. Coefficients of correlation between leaf photosynthesis and single band reflectance in rice.

Table 2. The coefficients of correlation between canopy spectral reflectance and leaf net photosynthetic rate of different leaf layers at three growth stages of rice. L12, L123, L1234 denoted the two leaves, three leaves, and four leaves from the top of stem in rice, respectively.

Spectral band	Stage	Leaf layer L2	L3	L4	L1	L12	L123	L1234
680 nm	Elongation	0.75	0.71	0.64	0.79	0.94	0.90	0.84
	Heading	0.76	0.68	0.67	0.92	0.92	0.88	0.86
	Filling	0.73	0.70	0.65	0.83	0.93	0.89	0.86
R(810,680)	Elongation	0.81	0.77	0.70	0.85	0.92	0.93	0.85
	Heading	0.82	0.74	0.73	0.84	0.98	0.94	0.90
	Filling	0.79	0.76	0.71	0.85	0.96	0.91	0.86

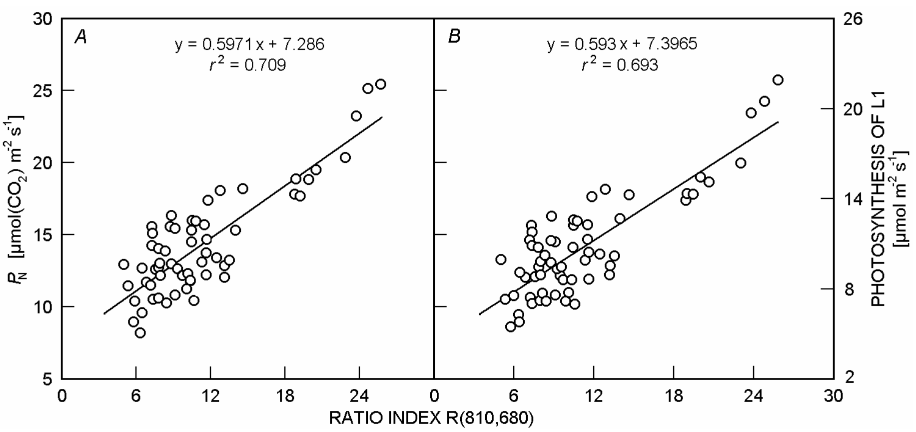

Fig. 5. Relationships between net photosynthetic rate (P_N) of means of leaves L1 and L2 (*A*) or L1 only (*B*) and the ratio index R(810,680) in rice.

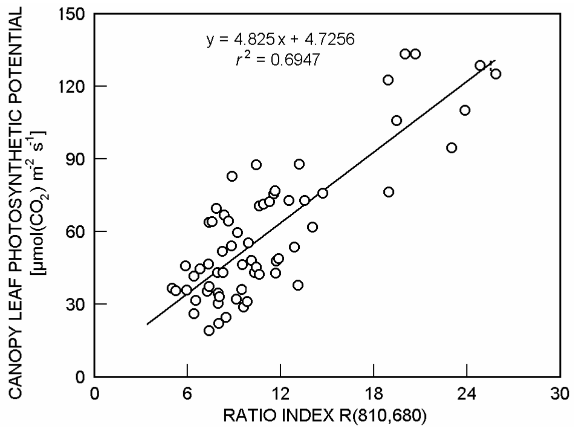

Fig. 6. Relationship between canopy leaf photosynthetic potential and ratio index R(810,680) in rice.

bands can alleviate the disturbance of topography, enlarge the difference of spectral reflectance between objects, especially vegetations, also sufficiently exploit all spectra information of reflectance bands and reduce the correlation between spectral data, so improve the estimation precision by spectral reflectance finally (Tracy *et al.* 1994). Consequently, in order to eliminate part of the disturbance of leaf and canopy structure and establish prediction model for assessing leaf P_N and canopy leaf photosynthetic potential, all regressions between ratio indices, normalized difference indices, and photosynthesis of L1 and L12, canopy photosynthetic potentials were calculated. We found that the ratio index of 810/680 nm was well related to both leaf P_N and canopy leaf photosynthetic potential (Figs. 5 and 6), with the correlation degree of L12 photosynthesis>canopy photosynthetic potential>L1 photosynthesis. Yet no significant correlation between photosynthetic characteristics of rice and normalized difference indices was found. These may be because red wavelength (680 nm) is a sensitive band of plant Chl content (Horler *et al.* 1983, Liu *et al.* 2000) which is located in red edge position and closely related to plant photosynthesis. Spectral reflectance of NIR wavelength (810 nm) is mainly determined by leaf inner structure, less correlated with photosynthesis of plant, and thus it is an insensitive band of photosynthesis. However, the ratio between the reflectance values of stress-sensitive band and the stress-insensitive band could correct the variation of canopy spectral reflectance resulted from the variation in irradiance, leaf orientation, irradiance angles, and shading (Tarpley *et al.* 2000). Therefore, the ratio index of 810/680 nm can be a suitable vegetation index for monitoring leaf photosynthetic status in rice, as seen in the present study.

The further analyses on the correlation between vegetation ratio index R(810,680) and photosynthesis in different leaf positions and leaf layers in rice (Table 2, n = 20) showed that the correlation degree of ratio index R(810,680) to leaf P_N was L12>L123>L1234>L1>L2>L3>L4 at different growth stages, the same results as with the single band regression. This may be because the radiometric sensor viewed the upper canopy layer much more than the lower leaves as the lower leaves were partially masked by the upper leaves, and thus the upper leaves were better related to canopy reflectance index than the lower leaves. These results confirmed that the top two leaves in rice were the best leaf positions for quantitatively assessing leaf P_N with remote sensing technique.

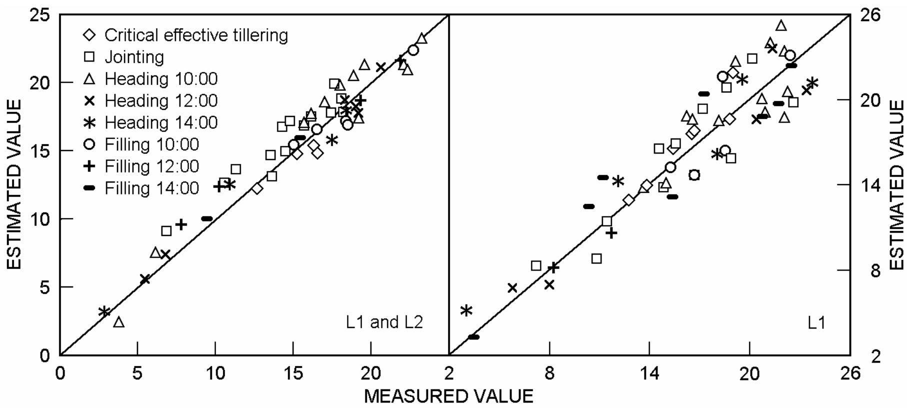

Fig. 7. Comparison of measured with estimated leaf photosynthesis (L1+L2 or L1) of rice under different water and N conditions. Individual points mean different stages and daily times of measurement on the same day.

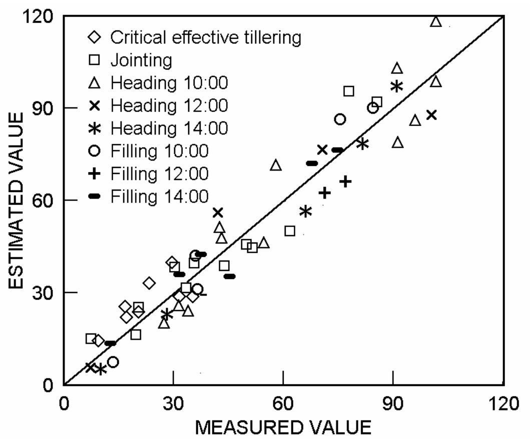

Fig. 8. Comparison of measured with estimated canopy leaf photosynthetic potentials of rice under different soil water and N conditions. Individual points mean different stages and daily times of measurement on the same day.

Testing of the ratio index R(810,680) for monitoring leaf photosynthesis: In order to make the remote sensing technique useful, an algorithm for predicting leaf photosynthetic status should be applicable over a wide range of vegetation types. To test the above linear models based on the ratio index R(810,680), two data sets from the independent experiments were used to predict photosynthesis of L1 and L12 and canopy photosynthetic potential in rice. As expected, the validation results indicated a good agreement between the predicted and observed values (Figs. 7 and 8), although the data sets involved varied growth stages and different soil water contents and N application rates. The monitoring models gave estimated precisions of 0.86, 0.94, and 0.92 (r^2), RMSE of 0.25, 0.16, and 4.38, and relative error of -0.007, -0.013, and 0.042, respectively, for L1 photosynthesis, L12 photosynthesis, and canopy photosynthetic potential. These results proved that the ratio of NIR band and red band, R(810,680) could be used as a reliable index for estimating leaf photosynthetic status in rice plant.

The above photosynthesis monitoring models were based on different water and N conditions and growth stages, and tested by different experiments involving the data sets from daily changes and different water and N contents. Thus the model partly excluded the disturbances of water and N status, daily times, and seasonal stages. In theory, this makes the present model reliable and applicable under diverse growing conditions of rice. However, the models were based on single rice cultivar Wuxiangjing 9 in Nanjing, China, and the actual robustness of this methodology and its use needs to be verified in other sites and for other rice cultivars, although it performed well in this study. Thus, further work should focus on testing the monitoring models on different leaf colour and plant type cultivars of rice, and validating the models at different ecological sites.

Conclusion: The responses of reflectance at red wavelength 680 nm to different water contents and N rates were parallel to those of leaf P_N, so the red band 680 nm was proposed as the sensitive band of leaf photosynthesis in rice. The relationships between the reflectance spectra and the photosynthesis of different leaf positions and leaf layers in rice indicated the correlation degree as L12>L123>L1234>L1>L2>L3>L4. This suggests that the top two full leaves in rice were the best leaf positions for quantitative monitoring of leaf net photosynthetic rate with remote sensing technique.

The ratio index of NIR/R, R(810,680), was the best ratio index for evaluating leaf photosynthetic characteristics in rice. The correlation degree of R(810,680) with leaf P_N and canopy leaf photosynthetic potential was L12 photosynthesis>canopy leaf photosynthetic potential>L1 photosynthesis. The performance of the present model for photosynthesis monitoring was independent of growth stages, daily changes, and soil water and N application rates, and testing with different data sets showed a good fitness between the estimated and actual values. Thus, the ratio index R(810,680) is a promising vegetation index for leaf P_N monitoring in rice crops.

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