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Potential for Using FORMOSAT-II Data Simulated by Hyperspectral Reflectance to Estimate Growth and Predict Yield of Rice [1]

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ABSTRACT

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This study assessed the potential for using FORMOSAT-II data, simulated by ground-based remotely sensed high resolution reflectance spectra, to estimate growth and predict yield of rice (*Oryza sativa* L. cv. TNG 67) crops. Field experiments were conducted in the Taiwan Agricultural Research Institute Experimental Farm at Wufeng to measure canopy reflectance spectra, leaf area indices ($\mathrm{LAI_{measured}}$), and yields of rice grown in the cropping seasons from 2000 to 2002. Reflectance values of broadband sensors equipped in the satellite FORMOSAT-II were simulated by using the mean values of reflectance in the respective band regions obtained from hyperspectral data. The values of normalized difference vegetation index (NDVI) were calculated using the mean reflectance in red (630-690 nm) and near-infrared (760-900 nm) regions defined in FORMOSAT-II. Both $\mathrm{NDVI_{NB}}$, which was computed from narrow bands of hyperspectral data, and $\mathrm{NDVI_{FORMOSAT\text{-}II}}$, which was computed from simulated FORMOSAT-II data, showed a quadratic time trend during rice growth. Changes in $\mathrm{NDVI_{FORMOSAT\text{-}II}}$ nearly paralleled the changes in $\mathrm{NDVI_{NB}}$, but to a lesser extent. The relationship between $\mathrm{LAI_{measured}}$ and $\mathrm{NDVI_{NB}}$ was fitted well by an exponential function, through which the estimates of satellite LAI ($\mathrm{LAI_{FORMOSAT\text{-}II}}$) were obtained. Results further showed that values of $\mathrm{LAI_{FORMOSAT\text{-}II}}$ were lower than values of $\mathrm{LAI_{NB}}$ along plant development, while both of these estimated LAIs were lower than $\mathrm{LAI_{measured}}$ after approximately 55 days after transplanting. Results indicated that yield may be predicted by the accumulated values of $\mathrm{LAI_{measured}}$ during the growing periods. By substituting $\mathrm{LAI_{measured}}$ with the values of $\mathrm{LAI_{NB}}$ and $\mathrm{LAI_{FORMOSAT\text{-}II}}$, it was found that the predicted yields were lower than the measured yields. Results suggest that the lower predicted yield by the FORMOSAT-II satellite data is attributable to lower level of $\mathrm{LAI_{FORMOSAT\text{-}II}}$ as aforementioned.

Key words: FORMOSAT II, Hyperspectral reflectance, Rice growth estimation, Yield prediction, Simulation.

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INTRODUCTION

With the rapid development of remote sensing technology, a variety of issues are being raised on the utilization of the satellite observational data on aspects of the biotic controls in agricultural production processes. The common use of remote sensing techniques is identification and establishment of relationships between spectral characteristics and related biophysical properties of vegetation cover, which are governed by biological and physical reactions, vegetation type, amount, distribution, and associated functional attributes (Goetz 2002). The feasibility and availability of the techniques are mainly dependant employed statistical methodologies and inference. In this respect, spectral vegetation indices were developed as an external physical quantity that is correlated with certain biophysical properties of the vegetation canopy such as fractional vegetation cover, vegetation condition, leaf area index (LAI) and biomass to estimate crop growth status.

Among spectral vegetation indices, the normalized difference vegetation index (NDVI) is probably the most renowned one (Rouse & Haas 1973). This is generally defined by the surface reflectances averaged over wavebands in the red and near-infrared regions of canopy spectrum. In many cases, comparisons are made to estimate the differences in vegetation attributes, discriminate the levels of stresses (or treatments), evaluate the constraints of independent practices and assess the validation of models. However, there are a number of limitations in using NDVI. When detected from space, the components of NDVI are sensitive to attenuation in the atmosphere and by aerosols (Liu & Huete 1995). At lower altitude, it may be affected by soil background and shadows cast by plant parts (Maas 2000; Richardson *et al*. 1992; Wiegand *et al*. 1990, 1992). The relationship between NDVI and LAI becomes less sensitive when values of LAI are beyond a certain threshold level. At lower level of LAI the brightness of soil may produce large variation in NDVI (Liu & Huete 1995), while the overlapping of leaves along vertical layers of plants may affect reflectance behavior and decrease sensitivity of the relation above the upper boundary of LAI (Carlson *et al*. 1990). The value of this upper limit, determined from measurements, depends on vegetation type, age, and leaf water content (Paltridge & Barber 1988). Within this asymptotic regime, the change in NDVI with LAI becomes insignificant (Carlson & Riply 1997) and the perceptive surface is almost completely covered by leaves (Curran 1983). The value of NDVI at 100% of vegetation cover can then be identified, but the biomass may not be assessed accurately (Calson & Riply 1997).

Recently remotely sensed hyperspectral data from various platforms such as near-ground, aircrafts, and satellites are available on commercial acquisition to the general public. With the high radiometric resolution spectrum, details of spectral characteristics from the target surface are detectable and discernible. The spectral visibility of such details open up many new applications in areas such as of agriculture, forestry, ecology, and land cover classifications, which require the use of radiometric information contained in the target's spectra. The sun synchronous satellite FORMOSAT-II, which is the second satellite of Taiwan ROC launched on 21 May 2004, is equipped with the sensors that can generate 2-m panchromatic and 8-m multispectral images with 1-day revisit rate. The panchromatic imagery has a spectral waveband interval of 520-820 nm. The multispectral imagery contains four wavebands in the blue (450-520 nm), green (520-600 nm), red (630-690 nm) and near-infrared (760-900 nm) regions. These high spatial and spectral resolutions of FORMOSAT-II satellite images and radiometric data allow for various environmental and agricultural applications, including growth, development and production monitoring of crop vegetation.

When environmental applications are carried out at field scale, very high resolution satellite data can be a useful input for data analysis and decision making. In that case, geometrical and radiometric resolution should be able to resolve intra-field variability in crop condition. By detecting within-field spatial variability of biophysical attributes, a precision farm management becomes possible and the resulting increase in canopy uniformity is expected to improve crop yield and quality (Barnes *et al*. 1997; Garcia & Vrindts 2001; Johnson *et al*. 2001). However, the mathematical relationships between spectral characteristics and biophysical parameters should be established before an application. Therefore main objectives of this study were to evaluate the feasibility and variability of plant growth using the simulated FORMOSAT-II data mimicked from ground-based remotely sensed high-resolution reflectance spectra. By using the accumulated values of $\mathrm{LAI}_{\mathrm{NB}}$ (the estimates of LAI from narrow bands of hyperspectral data) and $\mathrm{LAI}_{\mathrm{FORMOSAT\text{-}II}}$ (the estimates of LAI from broad bands of the simulated FORMOSAT-II data) to replace with $\mathrm{LAI}_{\mathrm{measured}}$ (the measured LAI), grain yields and their variability predicted from hyperspectral and simulated FORMOSAT-II data were also micmicked and compared.

MATERIALS AND METHODS

In this study, procedures for estimating rice growth (Yang & Chen 2004) and predicting yield production (Chen & Yang 2005) from ground-based high-resolution reflectance data and LAI were employed. The relationship between LAI and $\mathrm{NDVI}_{\mathrm{NB}}$ (NDVI computed from narrow bands of hyperspectral data) was compared with the relationship established between LAI and $\mathrm{NDVI}_{\mathrm{FORMOSAT\text{-}II}}$ (NDVI computed from the corresponding broad bands of simulated FORMOSAT-II data), in order to evaluate the feasibility and variability of plant growth using the simulated FORMOSAT-II data was evaluated. The method of Chen and Yang (2005) to obtain the predicted yield from the accumulated values of $\mathrm{LAI}_{\mathrm{measured}}$ (the measured LAI) was replaced with the accumulated values of $\mathrm{LAI}_{\mathrm{NB}}$ (the estimates of LAI from narrow bands of hyperspectral data) and $\mathrm{LAI}_{\mathrm{FORMOSAT\text{-}II}}$ (the estimates of LAI from broad bands of the simulated FORMOSAT-II data) to determine variability of yield prediction.

FIELD EXPERIMENTS

Two experiments were conducted for this study. The objective of experiment one was to collect the required data for assessing the potential for using simulated FORMOSAT-II data to estimate rice growth. Ground-based remotely sensed high-resolution canopy reflectance spectra were taken and leaf area indices of rice canopy were measured regularly from 20 field plots (0.5 ha per field plot) located in the experimental farm of Taiwan Agricultural Research Institute (24°45′ N, 120°54′ E, elevation of 85 m), during the cropping seasons from 2000 through 2002. Three- to four-leaf-aged seedlings were machine transplanted in north-south rows with an intra-row spacing of 0.18 m and inter-row spacing of 0.3 m, a density of approximately 185,000 hills ha^{-1}. Transplanting occurred on 18 February 2000 and 27 February 2002 and harvest occurred on 16 June 2000 and 25 June 2002 for the first crops. The second crops were transplanted on 5 August 2000 and 3 August 2001 and harvested on 6 December 2000 and 26 November 2001.

The soil was a Fluvaquentic Dystrochrept, with pH of 4.5 to 5.7 and organic matter content of 0.011 to 0.021 kg kg^{-1}. The basal dose of fertilizer ($\mathrm{N}:\mathrm{P_2O_5}:\mathrm{K_2O}$= 36:54:36 kg ha^{-1}) was applied 5 to 7 days before transplanting, the second dose ($N:P_2O_5:K_2O$ = 20:5:10 kg ha^{-1}) was applied 1 wk (second crops) or 2 wk (first crops) after transplanting, and the third dose ($N:P_2O_5:K_2O$= 40:10:20 kg ha^{-1}) was applied 3 wk (second crops) or 4 wk (first crops) after transplanting. About 20 d before heading (6–8 wk after transplanting), ammonium sulfate (21% N) was applied at 160 kg ha^{-1} as the last dose. For weed control, herbicide butachlor (5% granule, 1.5 kg a.i. ha^{-1}) was applied within a week after transplanting and bentazon (44.1% solution, 200X, 1.3 L a.i. ha^{-1}) was applied 3 wk after transplanting. Pesticide carbofuran (40% WP, 800X, 0.48 L a.i. ha^{-1}) was used to control planthopper [*Nilaparvata lugens* (Stal)] and leaffolder [*Cnaphalocrocis medinalis* (Guenee)], and cartap (6% granule, 1.8 kg a.i. ha^{-1}) was used to control stem borer (*Rupella* spp.). Validamycin A (50% S, 1000X, 0.5 L a.i. ha^{-1}) was used to protect against infection by sheath blight (caused by *Rhizoctonia solani* Kühn).

In experiment two, main objective was to collect data to test the accuracy of yield prediction by using the simulated FORMOSAT-II data. Another experimental field in TARI Experimental Farm was selected to grow rice in the first and the second cropping seasons of 2001 and 2002. Again, LAI and reflectance measurements of rice canopy were made during rice growth and grain yields were measured at harvest. The experimental field was of loamy soil with a pH of 5.60 and was divided into six 50 m × 15 m plots. Different levels of nitrogen fertilizer, in form of ammonium sulfate, were applied to different plots in order to produce various LAIs, reflectance spectra and grain yields. The six levels of nitrogen fertilizer, i.e., 0, 30, 60, 90, 120 and 150 kg N ha^{-1}, were applied to the first crop of 2002 and the second crops of 2001 and 2002. Each quantity was divided into 3 equal dressings, applied on the week of transplanting, 4 weeks (Second Crop) or 6 weeks (First Crop) after transplanting, and 3 weeks before heading. In the first crop of 2001, an extra plot treated with 180 kg N ha^{-1} was added. Rice seedlings were transplanted on 27 February 2001 and 27 February 2002 for the first crops and on 6 August 2001 and 8 August 2002 for the second crops.

LEAF AREA AND SPECTRAL MEASUREMENTS

Measurements of canopy reflectance spectrum and leaf area were made on the same sampling dates every two to three weeks beginning one month after transplanting until harvest. Most parts of the reflectance spectrum were found not affected by background noise after the rice crop canopy reached more than 70% of land cover. Only reflectance data not affected by background effects were used for NDVI calculations. For hyperspectral data, reflectance values at narrow band of chlorophyll absorption maximum (R_{RED}) and narrow band of the near-infrared peak (R_{NIR}) were identified dynamically, and were used to calculate $NDVI_{NB}$ by the equation: $(R_{NIR}-R_{RED})/(R_{NIR}+R_{RED})$. The mean values over 630-690 nm and 760-900 nm regions were computed for simulating the reflectance values of red and near-infrared wavebands as that of FORMOSAT-II broad-band sensors.

Leaf area was determined by destructive sampling of six plants from the target regions of each of the 20 plots in the first experiment, and the 6 plots in the second experiment, on each sampling, using an area meter (LI-3000A, Li-Cor Inc., Lincoln, NE, USA). LAI (m^2 m^{-2}) was calculated as the total green leaf area (m^2) per unit land area (1 m^2).

Radiance measurements in a range from 330 to 2600 nm were made by a field portable spectroradiometer (model GER-2600, Geophysical and Environmental Research Corp., Millbrook, NY) with 10° field-of-view (FOV) lens during the cropping seasons. The radiometer contains two spectrometers, one for measuring the radiance within a waveband range of 330 to 1050 nm with 1.5-nm resolution and another for measuring a waveband range of 1050 to 2600 nm with ca. 11.5-nm resolution. The band centers were rounded off to the nearest whole number in applications, and only radiance data in the 350 nm to 2400 nm range were used because of the severe noise in both ends of the spectrum. A notebook computer, driven by software supplied by GER, was connected to the radiometer unit to automatically record the readings from all the 537 channels. The software is able to control spectral measurements and display radiance, percentage reflectance, and other modes for data interpretation.

The radiometer unit was mounted 5.8 m above the rice canopy in a nadir viewing on an adjustable mobile lift to result in a sampled area of 1 m in diameter. On each targeted area, a setup of four consecutive full spectral range scans was made to compute an averaged radiance spectrum, which was then divided by the radiance spectrum from a spectral reference panel (‘Spectralon’, Labsphere, Inc., North Sutton, NH) of known spectral characteristics to obtain reflectance spectrum. Target measurements were collected immediately after the reference measurements for reflectance spectrum calculation. About 15 spectra were obtained from random target regions on each field plot of the first experiment or each plot of the second experiment on measuring days. A single mean reflectance spectrum was produced from all the 15 spectra collected from each plot and used in the statistical analyses. Such practices were intended to compensate for the effects of narrow sensor FOV (10°) and low sensor height (5.8 m) so that the radiance measurements were more analogous to those obtained from the sensor at satellite altitude. All reflectance data were collected under near cloud-free conditions between 10:00 to 13:00 local standard time.

GROWTH ESTIMATION AND YIELD PREDICTION

The relationship between LAI and NDVI was analyzed with paired values of $\mathrm{LAI}_{\mathrm{measured}}$ and $\mathrm{NDVI}_{\mathrm{NB}}$. All the computed NDVIs were regressed against the measured LAIs to obtain the regression equation. The estimates of $\mathrm{LAI}_{\mathrm{NB}}$ were extracted from the fitted regression function. The analysis was then conducted for calculating values of $\mathrm{NDVI}_{\mathrm{FORMOSAT\text{-}II}}$ which were computed from the mean reflectance values of near-infrared and red regions as those of broad-band sensors of FORMOSAT-II. The values of $\mathrm{NDVI}_{\mathrm{FORMOSAT\text{-}II}}$ were used as inputs for the previous $\mathrm{LAI}_{\mathrm{measured}}$-$\mathrm{NDVI}_{\mathrm{NB}}$ relationship to obtain the estimates of $\mathrm{LAI}_{\mathrm{FORMOSAT\text{-}II}}$.

Correlation between grain yield and $\mathrm{LAI}_{\mathrm{measured}}$ was determined from 50 days after transplanting (DAT) to harvest (Chen & Yang 2005). The determination coefficients (R^2) from regression analyses were plotted to determine the optimal timing for predicting yield with $\mathrm{LAI}_{\mathrm{measured}}$. Further more, the quantitative relationships between accumulated values of $\mathrm{LAI}_{\mathrm{measured}}$, computed from different periods during rice growth, and yields, produced under different levels of nitrogen applications, were analyzed to obtain the optimal period that may improve yield prediction with the cumulative $\mathrm{LAI}_{\mathrm{measured}}$. Based on the $\mathrm{LAI}_{\mathrm{measured}}$-$\mathrm{NDVI}_{\mathrm{NB}}$, the estimates of $\mathrm{LAI}_{\mathrm{NB}}$ and $\mathrm{LAI}_{\mathrm{FORMOSAT\text{-}II}}$ were obtained. The $\mathrm{LAI}_{\mathrm{measured}}$ was replaced by either $\mathrm{LAI}_{\mathrm{NB}}$ or $\mathrm{LAI}_{\mathrm{FORMOSAT\text{-}II}}$ to accumulate the values in the optimal periods for comparing the differences between predicted yields and measured yield.

STATISTICS

The statistical analyses and graphics were carried out using Statistical Analysis System (SAS) version 8.1 (SAS Institute 1998) and Sigmaplot 2000 (SPSS ASC BV, the Netherlands). The dummy-variable was used to compare differences in spectral data between different years of the same cropping season as well as between cropping seasons. Data from two years or two seasons were pooled for statistical analyses if the tests were non-significant. The root mean square error (RMSE) was calculated as $RMSE = \sqrt{\frac{1}{k}\sum_{i=1}^{k}(X_i - \hat{X}_i)^2}$, and was used to compare the precision of estimation between the measured values (X_i) and the estimated values ($\hat{X}_i$).

RESULTS AND DISCUSSION

The information content of satellite images and radiometric data may be useful in a field or regional scale quantitative assessment of biophysical parameters of a crop canopy. The LAI, a key input in many growth models, is especially important for such assessment by which growth behavior may be properly described and biological and physical processes associated with vegetation may be characterized (Bonan 1993; Liu *et al.* 1997; Running *et al.* 1999). Thus, many studies have been carried out to investigate the relationship between the measured LAI and spectral vegetation indices derived from various remote sensing platforms (Chen & Cihlar 1996; Chen & Yang 2002; Fassnacht *et al.* 1997; Nemani *et al.* 1993; Su & Yang 1999; Yang & Chen 2004).

The values of NDVI were computed both from ground-based high-resolution canopy reflectance data and simulated FORMOSAT-II data obtained during the experimental periods (Fig. 1). It indicated that $NDVI_{NB}$ and $NDVI_{FORMOSAT\text{-}II}$ change curvilinearly during rice growth with $NDVI_{FORMOSAT\text{-}II}$ being lower than $NDVI_{NB}$. Thus, on the same sampling date, $NDVI_{FORMOSAT\text{-}II}$ computed from the simulated satellite data was lower than $NDVI_{NB}$ computed from ground-based remotely sensed data.

The relationship between $LAI_{measured}$ and $NDVI_{NB}$ is shown in Fig. 2 as an exponential function. The determination coefficients (R^2) are greater than 0.53, suggesting that LAI is a good indicator for NDVI and in turn NDVI is a good parameter to estimate LAI. Incorporated with the visual observations, $NDVI_{NB}$ was found sensitive to changes in LAI under fractional vegetation cover until a full cover is reached, beyond which a further increase in LAI results in only small and asymptotic increase in NDVI. As changes in LAI as a function of NDVI show a positive correlation, with a fairly high coefficient of determination, it indicated that the LAI-NDVI relationship appears adequate for estimating and monitoring rice growth during the growing period. This is consistent with findings in other reports (Carlson *et al.* 1990; Chen & Cihlar 1996; Myneni *et al.* 1997; Su & Yang 1999).

However, there is the need to use the exponential function with caution especially at the upper end of the curve because of the saturation problem. Moreover, large scatter was observed by the mixing of heterogeneous data from different years. The observed degree of uncertainty would greatly compromise the use of the relationship and hence the NDVI-LAI relationship established for the first crops may not be adequate for mapping LAI in the second crops. With similar management practices, the relatively high scattering of the NDVI-LAI relationship implies that there probably exists a high internal heterogeneity due mainly to the morphological variations caused by different environmental conditions between years. Such variations in LAI suggest that there is much space for precision farming by which data of LAI variation may be incorporated as inputs. Areas with low LAI could be potentially improved through a differentiated treatment and LAI maps could be used to formulate management strategies or recommendations, especially during the early stages of rice growth. Using high spatial resolution imagery such as FORMOSAT-II data, a better LAI-NDVI relationship should be retrieved as compared to low resolution imagery where each

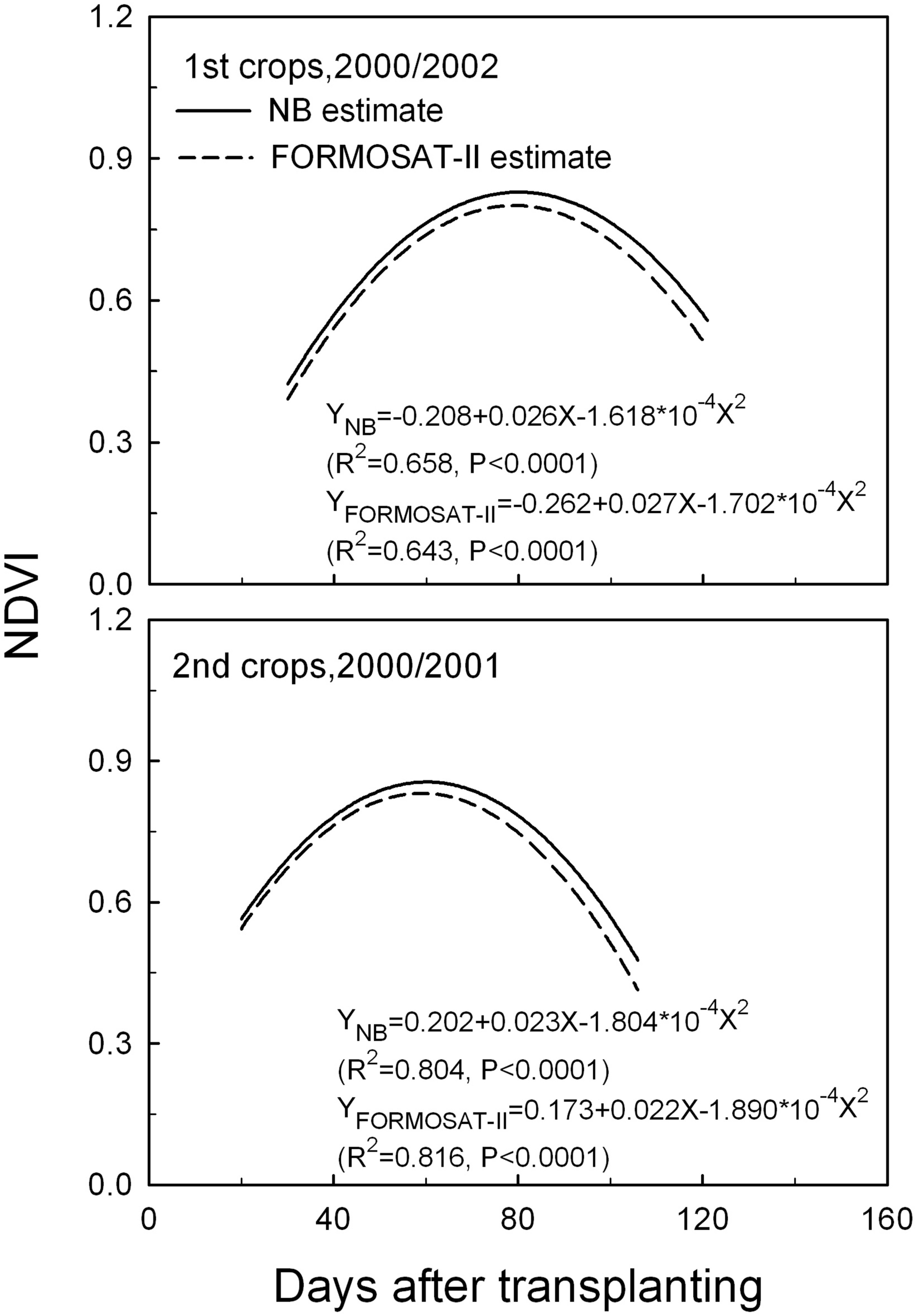

Fig. 1. Changes in $NDVI_{NB}$ and $NDVI_{FORMOSAT-II}$ through the growth stages of rice (*Oryza sativa* L. cv. TNG 67) grown in the first cropping seasons of 2000 and 2002 and the second cropping seasons of 2000 and 2001.

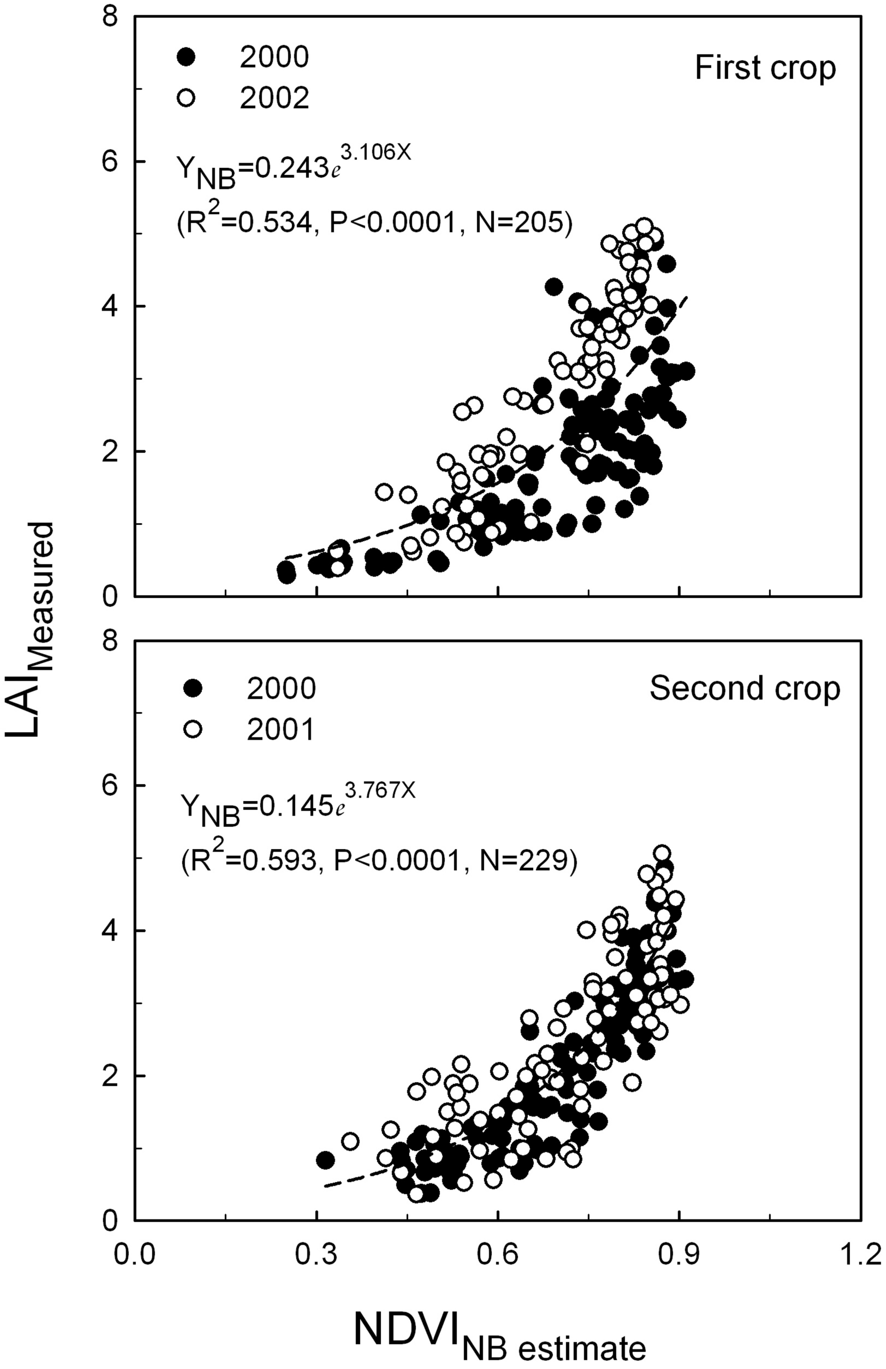

Fig. 2. Relationship between $LAI_{measured}$ and $NDVI_{NB}$ for rice (*Oryza sativa* L. cv. TNG 67) grown in the first cropping seasons of 2000 and 2002 and the second cropping seasons of 2000 and 2001.

pixel may have made up of many land cover types (Chen & Cihlar 1996). The scatter effect caused by a mixture of different land cover classes on the spectral data may be greatly reduced. Thus, in a mixing vegetation types, stratifying the land cover would improve the relationships as well as the mapping of LAI (Colombo *et al*. 2003).

With the LAI-NDVI regression equation, the estimates of LAI_{NB} and $LAI_{FORMOSAT-II}$ can be obtained by using $NDVI_{NB}$ and $NDVI_{FORMOSAT-II}$ as equation inputs. It showed that changes in $LAI_{measured}$, LAI_{NB} and $LAI_{FORMOSAT-II}$ were all quadratic during the growing periods. The values of $LAI_{FORMOSAT-II}$ were lower than values of LAI_{NB} along plant development, while these estimated LAIs were lower than values of $LAI_{measured}$ after approximately 55 days after transplanting (Fig. 3). Compared to $LAI_{measured}$, the estimates of both LAI_{NB} and $LAI_{FORMOSAT-II}$ appeared to be under-estimated, especially using reflectance of larger bandwidths as that employed in FORMOSAT-II data (Fig. 4). However, these estimates of LAI did not significantly

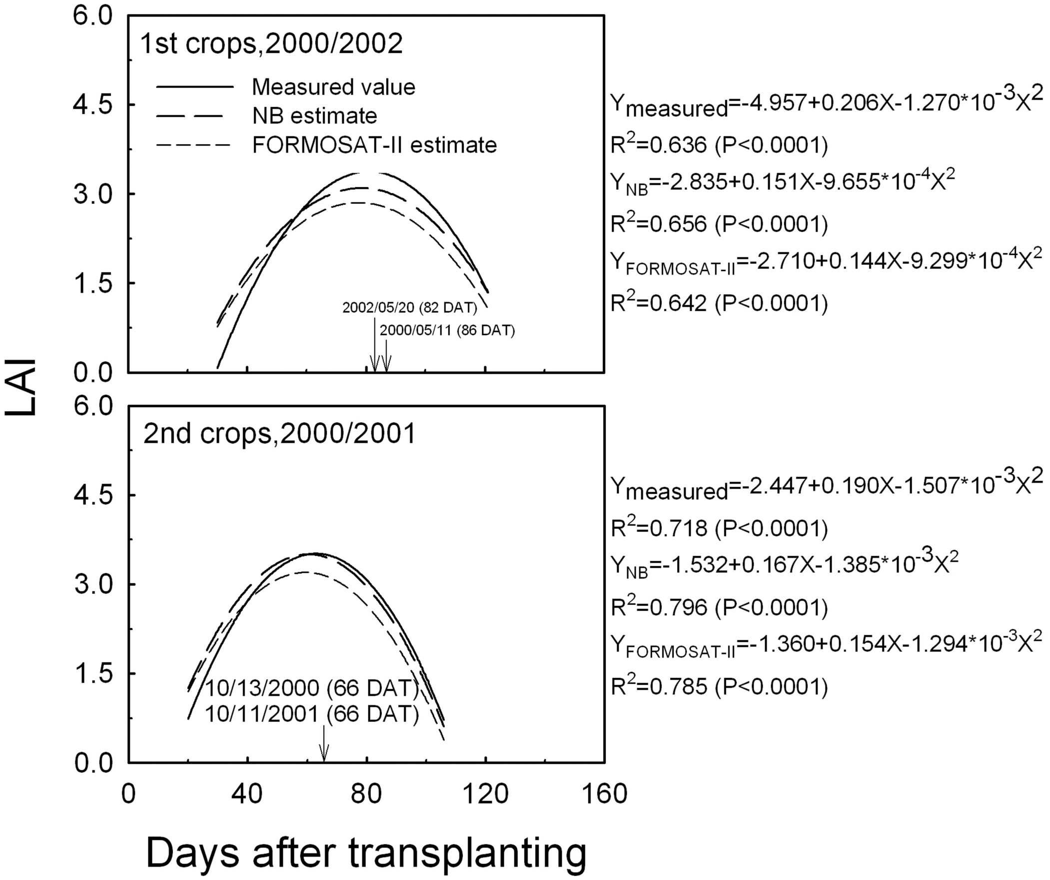

Fig. 3. Changes of $LAI_{measured}$, LAI_{NB} and $LAI_{FORMOSAT-II}$ through the growth stages of rice (*Oryza sativa* L. cv. TNG 67) grown in the first cropping seasons of 2000 and 2002 and the second cropping seasons of 2000 and 2001. Arrows indicate the dates of 50% of heading at the respective growing weasons.

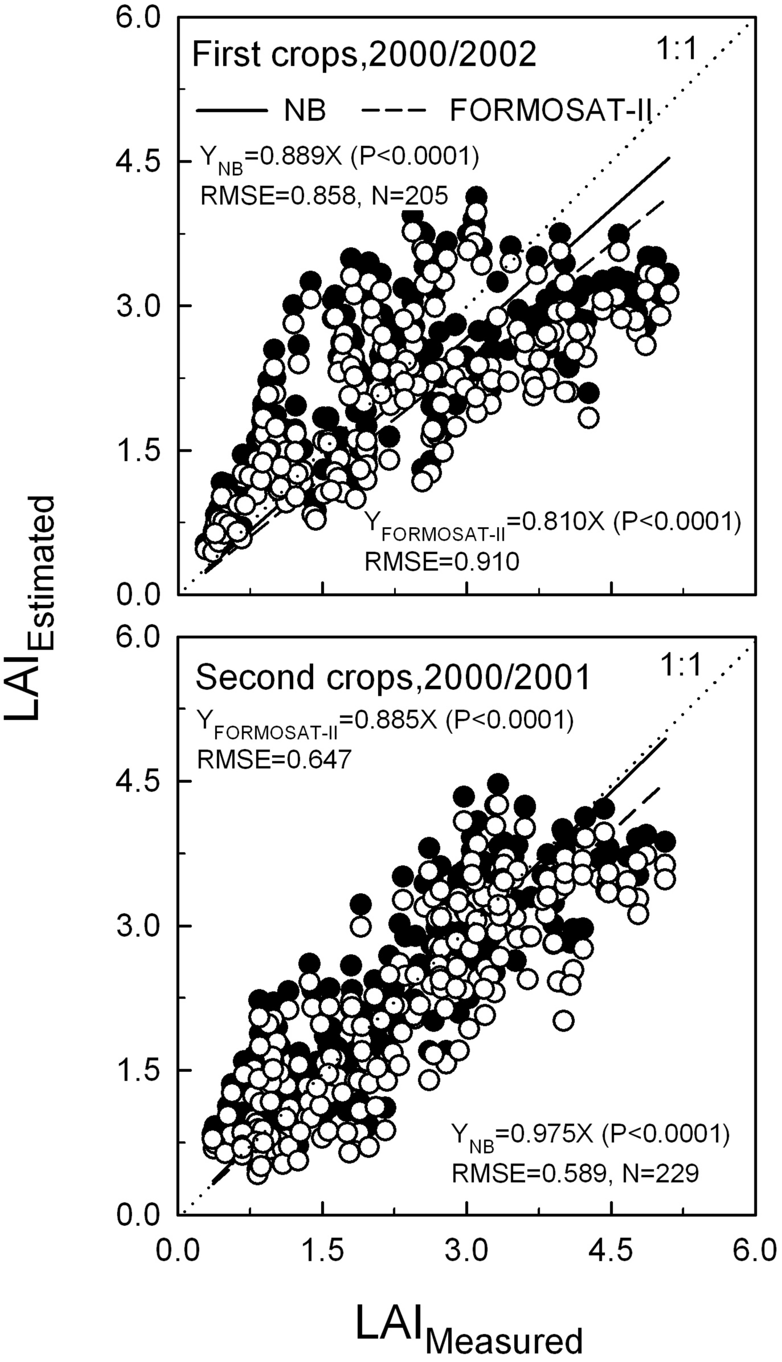

Fig. 4. Comparisons of the estimated values of LAI from $NDVI_{NB}$ (●) and $NDVI_{FORMOSAT-II}$ (○) to values of $LAI_{measured}$ for rice (*Oryza sativa* L. cv. TNG 67) grown in the first cropping seasons of 2000 and 2002 and the second cropping seasons of 2000 and 2001.

change the LAI-NDVI relationship, with a slope greater than 0.81 ($P<0.0001$). Given the relationship, NDVI derived from satellite FORMOSAT-II spectral data may be used for monitoring spatial and temporal distribution of LAI and evaluating growth status of rice crop as indicated in other studies (Chen & Cihlar 1996; Colombo *et al*. 2003; Fassnacht *et al*. 1997; Nemani *et al*. 1993; Spanner *et al*. 1990).

Variation in yield of a crop could be related to one or a combination of the following; nutrient balance, weed and pest control, water management, and capacity of biomass production problems (Moran 2000). Besides environmental effects, the magnitude of photosynthetic capacity, which determined by multiplying mean photosynthetic rate of single leaf, LAI and the extinction coefficient of incident solar radiation, is the major factor deciding biomass production (Murata 1975). Of the three components, LAI plays the key role in determining the source capacity (Yoshida 1981). Shieh (1978) pointed out that rice yield was positively correlated with total biomass and LAI near heading, so that keeping larger leaf area duration (LAD) before heading until harvest would improve grain yield.

Regression analysis between grain yield and LAI showed that yield and LAI were closely correlated from about 50 DAT to near harvest, with R^2 greater than 0.72 (Chen & Yang 2005). The accumulated values of LAI from 15 days before heading (DBH) to 15 days after heading (DAH) provided the best prediction of yield for the first crops, while the accumulated values from 15 DBH to 10 DAH were the most suitable duration to predict yield for the second crops (Chen & Yang 2005). Based on these relationships, this study used LAI_{NB} and $LAI_{FORMOSAT\text{-}II}$ obtained from LAI-NDVI relationship with $NDVI_{NB}$ and $NDVI_{FORMOSAT\text{-}II}$ as inputs and cumulated the values during the optimal time periods previously mentioned for yield prediction. Results showed that predicted yields from the accumulated values of LAI_{NB} and $LAI_{FORMOSAT\text{-}II}$ were lower than the measured yields, especially yields from $LAI_{FORMOSAT\text{-}II}$ prediction (Fig. 5). As aforementioned that values of $NDVI_{FORMOSAT\text{-}II}$ were lower than values of $NDVI_{NB}$ on the same sampling dates after transplanting and hence obtained a lower estimated values of $LAI_{FORMOSAT\text{-}II}$. Thus, under the same optimal periods to predict yields, yields predicted by the $LAI_{FORMOSAT\text{-}II}$ would be lower than yields predicted by the LAI_{NB} and the measured yields.

This paper provides a case study in which ground-based canopy reflectance spectra of high resolution were used to simulate spectral data sensed by broad-band sensors of satellite FORMOSAT-II. The data were then to calculate NDVI for monitoring changes in LAI during rice growth, and to use LAI as a predictor for predicting yield production at harvest. Results demonstrate the potential for using NDVI extracted from canopy reflectance data to reasonably estimate growth and predict yield by transforming NDVI into LAI based on the established LAI-NDVI relationship. It has also been reported that light reflectance measurements prior to flowering may predict grain yield response in corn and provide in-season indications of N deficiency (Ma *et al*. 1996). With the quadratic pattern of NDVI during the growth and the exponential function between LAI and NDVI, transforming NDVI for LAI and accumulating LAI for yield prediction should be used with caution. The scattering effect on LAI-NDVI relationship caused by environmental influences between cropping seasons and years also imposes constraints in using NDVI and limits the accuracy for predicting yield. Also, bad weather conditions occurring prior to harvest may cause dramatic influence on yield too. Due to the nature of broad-band sensors in averaging reflectance, LAI estimated by $NDVI_{FORMOSAT\text{-}II}$ and yield predicted by $LAI_{FORMOSAT\text{-}II}$ will be under-estimated. Nevertheless, the

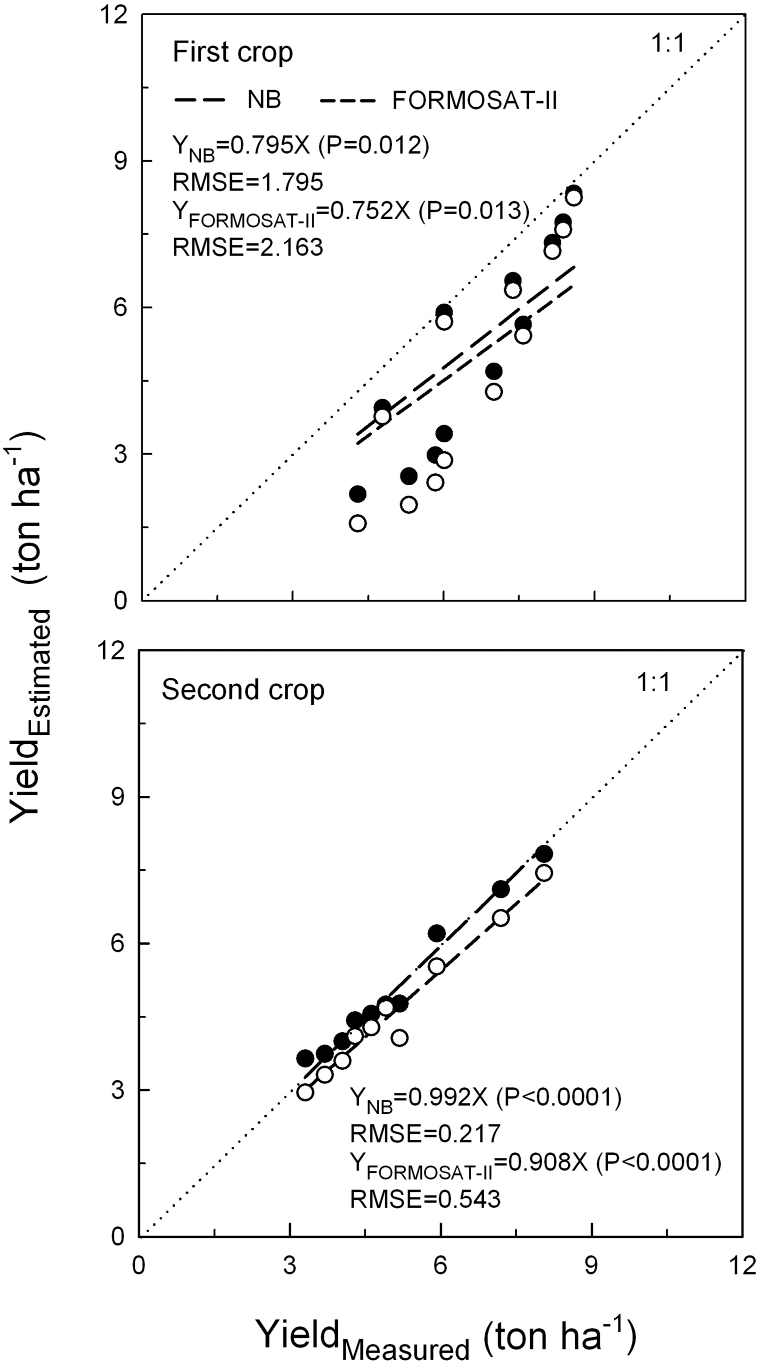

Fig. 5. Comparisons of the predicted yields from accumulated values of LAI_{NB} (●) and $LAI_{FORMOSAT-II}$ (○) to the measured yields of rice grown in the first cropping seasons of 2000 and 2002 and the second cropping seasons of 2000 and 2001.

availability of NDVI on such applications provides not only non-destructive real time information for evaluating growth status of a crop, but also means to be applied in precision farming activities from remote sensing data.

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以高解析反射光譜模擬福衛二號衛星資料估測水稻生長及預測產量之潛力[1]

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摘要

楊純明、陳榮坤。2004。以高解析反射光譜模擬福衛二號衛星資料估測水稻生長及預測產量之潛力。台灣農業研究 54:54-69。

本研究旨在利用近地面高解析植被反射光譜模擬福衛二號衛星(FORMOSAT-II)光譜測值以評估應用於水稻(*Oryza sativa* L. cv. TNG 67)生長估測與產量評估之潛力。田間試驗係在臺中縣霧峰鄉農委會農業試驗所農場進行，以量測 2000-2002 年兩期稻作之植被光譜、葉面積指數及產量等。福爾摩沙二號衛星承載之紅光(630-690 nm)及近紅外光(760-900 nm)寬頻波段測值由高解析光譜之相對累積窄波段測值平均值模擬，並以計算窄波段及寬波段之標準差植被指數($\mathrm{NDVI}_{\mathrm{NB}}$ 及 $\mathrm{NDVI}_{\mathrm{FORMOSAT\text{-}II}}$)。結果顯示 $\mathrm{NDVI}_{\mathrm{NB}}$ 及 $\mathrm{NDVI}_{\mathrm{FORMOSAT\text{-}II}}$ 在水稻生育期間呈現曲線分佈，而 $\mathrm{NDVI}_{\mathrm{FORMOSAT\text{-}II}}$ 概低於 $\mathrm{NDVI}_{\mathrm{NB}}$。實際量測之葉面積指數($\mathrm{LAI}_{\mathrm{measured}}$)與 $\mathrm{NDVI}_{\mathrm{NB}}$ 之間為一指數函數關係，並據以輸入 $\mathrm{NDVI}_{\mathrm{NB}}$ 及 $\mathrm{NDVI}_{\mathrm{FORMOSAT\text{-}II}}$ 而估算出 $\mathrm{LAI}_{\mathrm{NB}}$ 及 $\mathrm{LAI}_{\mathrm{FORMOSAT\text{-}II}}$。又發現生育期間估測之 $\mathrm{LAI}_{\mathrm{FORMOSAT\text{-}II}}$ 均小於 $\mathrm{LAI}_{\mathrm{NB}}$，且這些估值自移植後 55 天起皆低於 $\mathrm{LAI}_{\mathrm{measured}}$。結果也顯示，產量可由生育某段期間 $\mathrm{LAI}_{\mathrm{measured}}$ 累加值預測，當由 $\mathrm{LAI}_{\mathrm{NB}}$ 及 $\mathrm{LAI}_{\mathrm{FORMOSAT\text{-}II}}$ 取代時，產量預測值將低於實測值。顯然地，模擬福爾摩沙二號衛星寬波段測值將獲得小於地真(ground truth)資料之生長估測與產量預測。

關鍵詞：福衛二號衛星、高解析反射比、水稻生長估測、產量預測、模擬。

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