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Quantitative relationships between field-measured leaf area index and vegetation index derived from VEGETATION images for paddy rice fields

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Abstract. In an effort to develop the quantitative relationships between field-measured leaf area index (LAI) and VEGETATION-derived vegetation indices for paddy rice fields, we have measured LAI of paddy rice fields at 10-day intervals at five sampling sites in Jiangning County, Jiangsu Province of China during the rice growing season (July to October) of 1999, using a LI-COR LAI-2000 plant canopy analyser. Twenty-seven 10-day VEGETATION (VGT) synthesis products (VGT-S10) from 1–10 March to 21–30 November 1999 were acquired. Normalized difference vegetation index (NDVI) values were calculated for the VGT-S10 products, using ground surface reflectance values of VGT spectral bands (B3–near-infrared; B2–red). After rice transplanting in mid to late June, LAI increased rapidly and reached its plateau by early to mid August. There were similar temporal dynamics of NDVI and LAI among the five sampling sites over the growing season of paddy rice in 1999. Simple linear regression analyses indicate that there are statistically significant linear relationships between NDVI and LAI data over the growing season of paddy rice in 1999.

1. Introduction

Leaf area index (LAI, leaf area per unit ground area) of paddy rice fields is an important crop biophysical parameter. It provides information on crop growth dynamics and is highly correlated with crop biomass and productivity (Venkateswarlu *et al*. 1976, Dobermann and Pampolino 1995). A unique physical feature of paddy rice fields is that paddy rice is grown on flooded soils. The water background may significantly affect the spectral reflectance of rice and the sensitivity of spectral vegetation indices to LAI (Martin and Heilman 1986). Based on field-measured LAI data and spectral reflectance values at Landsat Thematic Mapper (TM) wavebands using a portable radiometer, Martin and Heilman (1986) found that spectral vegetation indices were highly correlated with LAI at small research plots. Other field studies at paddy rice fields also showed that there were statistically

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significant correlations between LAI and spectral vegetation indices derived from the NOAA Advanced Very High Resolution Radiometer (AVHRR) sensors (Lu 1997, Zhao *et al.* 1993, 1996).

The SPOT 4 satellite, which was successfully launched in March 1998, carries both the VEGETATION (VGT) instrument and the high-resolution visible and infrared (HRVIR) instrument. While the NOAA AVHRR sensors were originally designed for meteorological observations, the VGT sensor was designed for studying vegetation and the land surface. The VGT instrument has four spectral bands that are equivalent to spectral bands of Landsat TM/ETM+, i.e. B0 (blue, 430–470 nm), B2 (red, 610–680 nm), B3 (near-infrared, 780–890 nm) and MIR (mid-infrared, 1580–1750 nm). The VGT blue band is mostly used for atmospheric correction, and the VGT mid-infrared band is highly sensitive to soil moisture content, vegetation cover and leaf moisture content. The VGT instrument provides daily images of the global land surface at 1 km spatial resolution. Availability of VGT data offers new opportunities and greater potential for better mapping and monitoring of paddy rice agriculture, in comparison to the NOAA AVHRR sensors.

In 1999 we began a 3-year project to study paddy rice agriculture in Southern and Eastern China. One of the project objectives is to retrieve key rice crop biophysical parameters (LAI and above-ground biomass) using space-borne optical and synthetic aperture radar data. The project was designed to include intensive and extensive field surveys and image analysis across the scales of farm, landscape and region. In 1999 intensive field sampling at the farm level was conducted in Jiangning County, Jiangsu Province throughout the growing season (June to October) of paddy rice. Agriculture in this area is dominated by winter wheat/paddy rice and rapeseed/paddy rice double cropping rotations. In this paper we report on *in situ* field measurements of LAI in the rice growing season and the development curves of normalized difference vegetation index (NDVI) derived from multi-temporal VGT data for the corresponding field sites. Our objective is to develop a quantitative relationship between field-measured LAI and VGT-derived NDVI. Information on LAI dynamics is needed for rice agricultural ecosystem models (Wang *et al.* 1996, Gao *et al.* 1992, Miller *et al.* 1993) that aim to estimate rice production/yield at the landscape to regional scale. This site-scale analysis will provide the foundation for a VGT-based image analysis at the landscape scale.

2. Field study sites and field measurements

During an extensive field survey in 1999, five intensive sampling sites were selected and set up within Jiangning County (approximately 31°00′ N–32°00′ N and 118°30′ E–119°25′ E), Jiangsu Province, China (figure 1). Jiangning County is south of Nanjing city, the capital of Jiangsu Province. In Jiangning County, one farm family has about 3–5 mu (1 ha = 15 mu) of paddy rice field, dependent upon family size. Each of the five sampling sites belongs to one farm family. Each field site was selected to lie within a 2–3 km^2 landscape dominated by cropland (over 90% cropland area, figure 1). Agriculture in Jiangning County is dominated by double cropping systems that consist of either (1) winter wheat and paddy rice or (2) rapeseed (oilseed) and paddy rice crop rotations. Traditionally, winter wheat and paddy rice has been the dominant crop rotation system. However, during the last few years, because of a decline in wheat price in the national market, local farmers have cultivated more rapeseed in winter/spring seasons, and by 1999 there were approximately equal proportions between winter wheat and rapeseed cultivation in winter/spring seasons

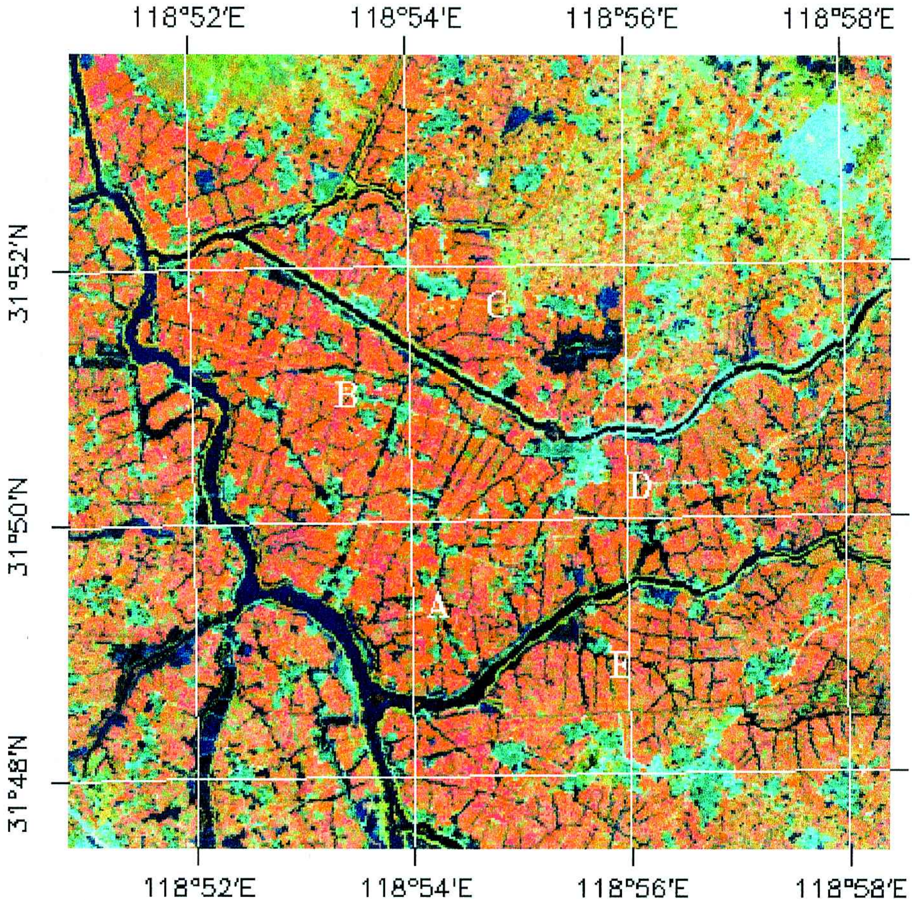

Figure 1. The locations of five intensive field sampling sites (A, B, C, D, E) in Jiangning County, Jiangsu Province, China. The background is a Landsat 5 TM image acquired on 22 April 1996, and is a false colour composite displayed with band 4 (red), band 5 (green) and band 3 (blue). Croplands in the image were mostly winter wheat crop in winter/spring seasons. The sampling sites are approximately 4–6 km away from each other.

in Jiangning County (Mr Libin Fu, personal communication, 1999). Winter wheat and rapeseed crops in Jiangning County are usually harvested in late May and early June. For all five field sampling sites (figure 1) the crop rotation system in 1999 was winter wheat and paddy rice rotation. Field sampling at the five sites was conducted at 10-day intervals from early July 1999 to late October 1999. The field measurements at the five sites include LAI, plant height, and above-ground biomass. A commercial LI-COR LAI-2000 plant canopy analyser (LI-COR, Inc., Lincoln, NE, USA) was used to measure LAI of paddy rice fields. At each sampling date, LAI measurements were conducted using one above-/four below-canopy readings at five locations within a sampling site. Average LAI values were calculated for each site on each sampling date to obtain a representative field mean LAI. Indirect, non-destructive measurement of LAI using the LAI-2000 instrument is a suitable alternative for measuring crop growth curves and within-field variability of rice (Dobermann and Pampolino 1995). In addition to intensive samplings at the five field sites, general field observations and surveys (e.g. interviews with farmers for information on rice crop varieties, dates of seeding and rice transplanting, fertilization) were also conducted for the larger areas surrounding the sampling sites. The general field observations confirmed that crop management and growth on the selected field sampling sites were representative of paddy rice in the vicinity and thus of paddy rice within a 1 km^2 VGT pixel. These five farm families kept records of the rice varieties they planted, dates of rice transplanting and harvesting, and fertilizer application in 1999 (table 1).

3. Remote sensing data and vegetation indices

SPOT Inc. provides three standard VGT products to users: VGT-P (Physical product), VGT-S1 (daily synthesis product) and VGT-S10 (10-day synthesis product). For each month there are three 10-day composites: day 1–10, day 11–20, day 21 to the last day of a month. The VGT-S10 data are generated using the composite approach that is based on the maximum NDVI values within a 10-day period for a pixel, which helps minimize the effect of cloud cover and variability in atmospheric optical depth. The values of the four spectral bands (B0, B2, B3, MIR) in the VGT-S10 products are the estimates of ground surface reflectance, as atmospheric corrections for ozone, aerosols and water vapour have already been applied to the VGT images using the SMAC algorithm (Rahman and Dedieu 1994). Twenty-seven VGT-S10 products from 1–10 March 1999 to 21–30 November 1999 for the study area were used in this study. For each of the VGT-S10 products, the NDVI was calculated using the ground surface reflectance values of spectral bands:

$$NDVI_{VGT} = (B3 - B2)/(B3 + B2) \tag{1}$$

We used a handheld global positioning system (GPS) receiver to collect geographical location information (latitude and longitude) of the five sampling sites. This geographical information is used to locate each sampling site within the VGT images and then to extract the NDVI time series data for the five sampling sites. According to the VEGETATION User Guide, the geometric accuracy of VGT data have an absolute location error <0.8 km, therefore, we expect that the selected VGT image pixels contain the field sampling sites.

4. Results and discussions

Immediately after the harvest of winter wheat and rapeseed in late May and early June, farmers in the Jiangning County begin paddy rice cultivation. Temporal development of paddy rice fields can be characterized by three main periods: (1) the flooding and rice transplanting period; (2) the growing period (vegetative growth stage, reproductive stage, and ripening stage); and (3) the fallow period after harvest (Le Toan *et al.* 1997). Rice transplanting dates varied from 12 June at site C to 22 June at site D (table 1). Field-measured LAI increased rapidly from early July to early August, and reached a plateau in late August, being in the range of 4–5 (figure 2). In a field study that assessed the suitability of the LI-COR LAI-2000 instrument for measuring LAI of paddy rice fields, Dobermann and Pampolino (1995) found that the instrument was capable of measuring reliable crop growth curves, but may underestimate LAI at higher absolute values (LAI $> \sim 4$–5). Dates of rice harvesting varied from 17 October at site C to 28 October at site E (table 1). There were similar seasonal dynamics of field-measured LAI among the five sampling sites over the growing season of paddy rice in 1999 (figure 2).

The seasonal dynamics of VGT-derived NDVI is similar to the temporal patterns

Table 1. Information collected in 1999 on seeding, rice transplanting, harvesting and fertilization for the five field sampling sites in Jiangning County, Jiangsu Province of China (also see figure 1).

	A	B	C	D	E
Longitude	118°54.519′	118°53.363′	118°54.76′	118°56.085′	118°55.861′
Latitude	31°49.623′	31°50.979′	31°51.613′	31°50.173′	31°48.68′
Farm size (mu*)	1.6	2.5	2.4	2.5	3.8
Seeding†	14 May	18 May	13 May	21 May	20 May
Transplanting	14 Jun	20 Jun	12 Jun	22 Jun	20 Jun
Harvesting	21 Oct	18 Oct	17 Oct	23 Oct	28 Oct
Fertilization	20 Jun, 30 Jul, 9 Aug	20 Jun, 26 Jun, 31 Jul	11 Jun, 19 Jun, 1 Aug	22 Jun, 27 Jun, 29 Jul	20 Jun, 26 Jun, 28 Jul

*1 ha = 15 mu (Chinese area unit).
†Seeding occurs in small seed-beds, where rice seeds germinate and grow up to 10–20 cm tall before transplanting.

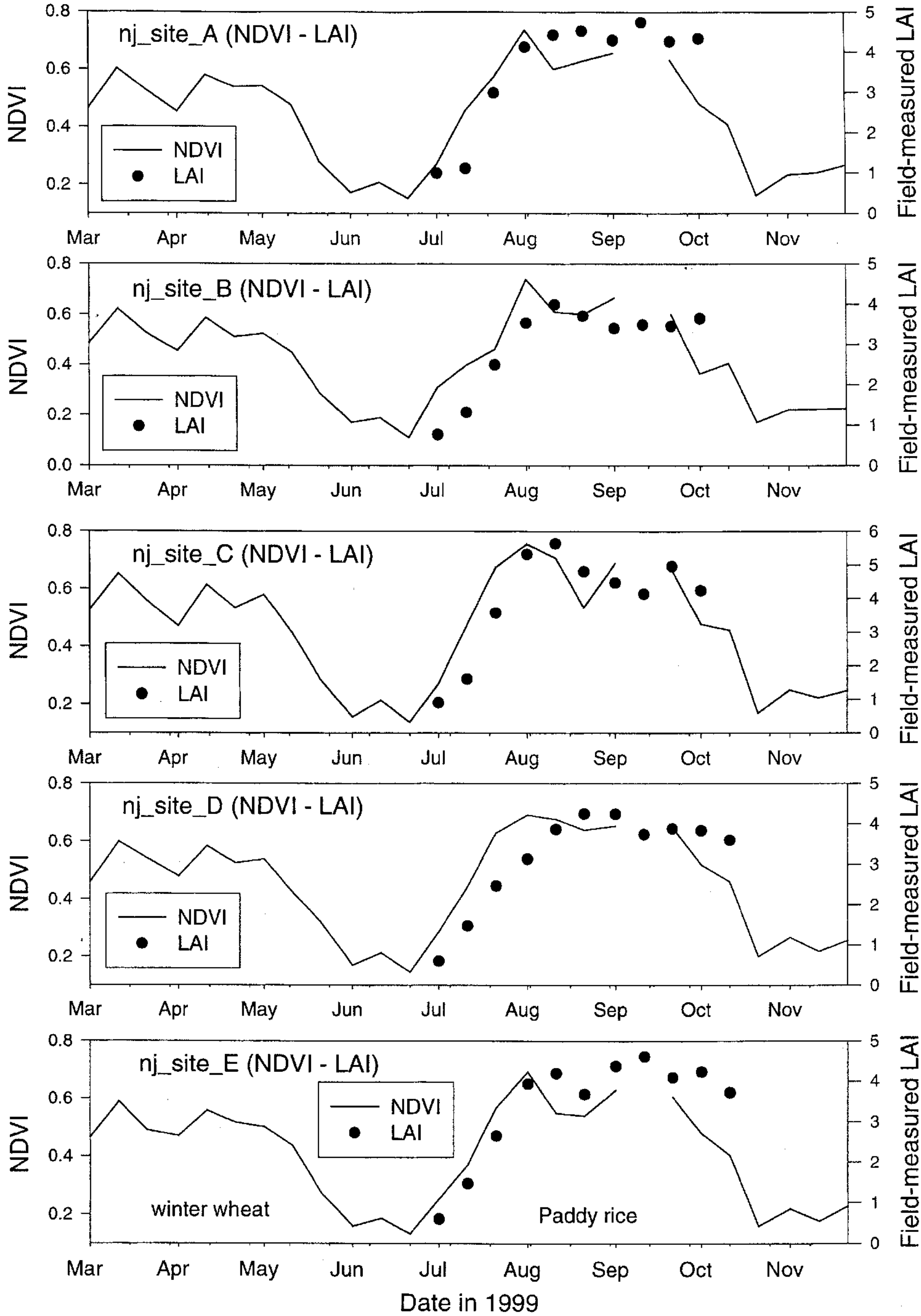

Figure 2. Seasonal dynamics of VGT-derived NDVI and field-measured LAI at 10-day intervals at the five intensive sampling sites in Jiangning County, Jiangsu Province of China. Note that there are no NDVI data in 11–20 September 1999 because of persistent cloud cover over a large area of Jiangning County, including these five sampling sites.

of the field-measured LAI of paddy rice fields (figure 2). NDVI values were very low in the period of land preparation and flooding, but increased rapidly after rice transplanting. NDVI reached a plateau by early to mid August, in the order of approximately 0.7 (figure 2), and remained at a high level until mid-September. As rice plants developed into the ripening phase (grain filling, milk and dough stages) in late September to early October, their leaves gradually turned yellowish/golden colour, due to a decrease of chlorophyll pigments. The rice ripening stage is also characterized by a decrease of the number of leaves and a drop in leaf and stem moisture (Le Toan *et al.* 1997). Correspondingly, NDVI values declined during the rice ripening stage, and dropped significantly following the rice harvesting in mid to late October (figure 2).

Earlier studies on crops grown on dry soils (e.g. wheat and cotton) showed that there is a non-linear relationship between LAI and NDVI (Asrar *et al.* 1984, Huete 1988). At wheat or cotton fields, the land surface is primarily composed of plants and soils. A number of studies have shown spectral vegetation indices are partially correlated with soil brightness over a certain range of vegetation density, and soil brightness influences are prevalent in partially vegetated canopies (Huete 1989). To minimize soil-brightness influences, Huete (1988) developed a soil adjusted vegetation index ($SAVI = \{(NIR - red)/(NIR + red + 0.5)\}/1.5$). The SAVI substantially reduces soil-induced variations, and improves the linearity between the SAVI and LAI (Huete 1989). Paddy rice fields are primarily composed of plants and water, and may have little or no soil brightness influences on spectral vegetation indices. The comparison of NDVI and LAI data at paddy rice fields in this study suggests a linear relationship between LAI and NDVI (figure 3).

All of the observations of LAI and NDVI from early July to early August among the five sampling sites were first lumped together (figure 3). This period is the most active vegetative period (tillering, elongation and booting). The vegetative phase is characterized by an increase of the plant height, an increase of the number of tillers, and a development of leaves (Le Toan *et al.* 1997). There is a strong linear relationship between field-measured LAI and NDVI among the five sites for the vegetative growth period (see equation (2)). We further transformed the raw LAI and NDVI data using the square-root transformation, and the resultant linear regression model shows a statistically significant linear relationship between the transformed LAI and NDVI data (see equation (3)).

$$LAI = -1.50 + 7.93\ NDVI \quad r^2 = 0.75,\ n = 25,\ p\text{-value} < 0.0001 \tag{2}$$

$$\sqrt{LAI} = -1.09 + 3.70\ \sqrt{NDVI} \quad r^2 = 0.81,\ n = 25,\ p\text{-value} < 0.0001 \tag{3}$$

During the field surveys in 1999, we did not measure LAI of paddy rice fields in other locations in Jiangning County, and thus there are no data for statistically assessing the accuracy of estimating LAI derived from spectral vegetation indices (Bouman 1992). As an alternative, cross-validation calculations of LAI estimates from NDVI for 1 July 1999–August 1999 were conducted, using equation (3) and the LAI and NDVI data for the five sampling sites. First, a simple linear regression between the square root of NDVI and the square root of measured LAI was calculated using LAI and NDVI data from four of the five sites. This regression was then used to generate estimates of LAI from NDVI of the fifth site, which were compared with the observed LAI data from the fifth site. The procedure was repeated

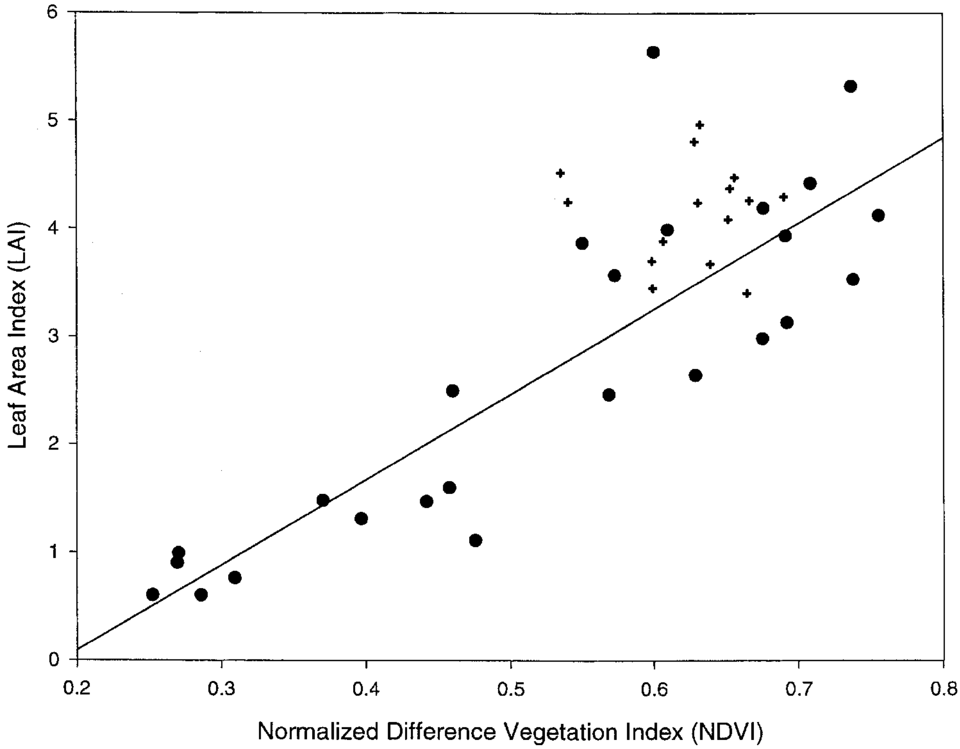

Figure 3. The comparison between VGT-derived NDVI and field-measured LAI in paddy rice fields over the period of 1 July to 31 September 1999 at the five sampling sites in Jiangning County, Jiangsu Province of China. The solid-circle symbols represent those observations from 1 July to 20 August (active vegetative growth phase of paddy rice life cycle), while the cross-hair symbols represent those observations from 21 August to 31 September 1999 (reproductive phases of paddy rice life cycle). The solid line indicates the regression for observations from 1 July to 20 August.

for the five sites and the results indicate a consistent relationship between LAI and NDVI among the five sites (figure 4).

Secondly, all of the observations of NDVI and LAI from early July to late September among the five sampling sites were lumped together (figure 3). These observations cover both the vegetative growth phase (tillering, elongation and booting) and reproductive phase (heading, panicle initiation, and flowering). The reproductive phase is characterized by a decrease in the number of tillers, the development of panicular leaves, and the panicle formation and development (Le Toan *et al.* 1997). This comparison of LAI and NDVI over most of the rice growing season also generated statistically significant linear relationships (see equation (4) for raw LAI and NDVI data; see equation (5) for the square-root transformed LAI and NDVI data), but with slightly lower correlation coefficients.

$$\mathrm{LAI} = -1.54 + 8.46\ \mathrm{NDVI} \quad r^2 = 0.68,\ n = 40,\ p\text{-value} < 0.0001 \tag{4}$$

$$\sqrt{\mathrm{LAI}} = -1.18 + 3.93\ \sqrt{\mathrm{NDVI}} \quad r^2 = 0.78,\ n = 40,\ p\text{-value} < 0.0001 \tag{5}$$

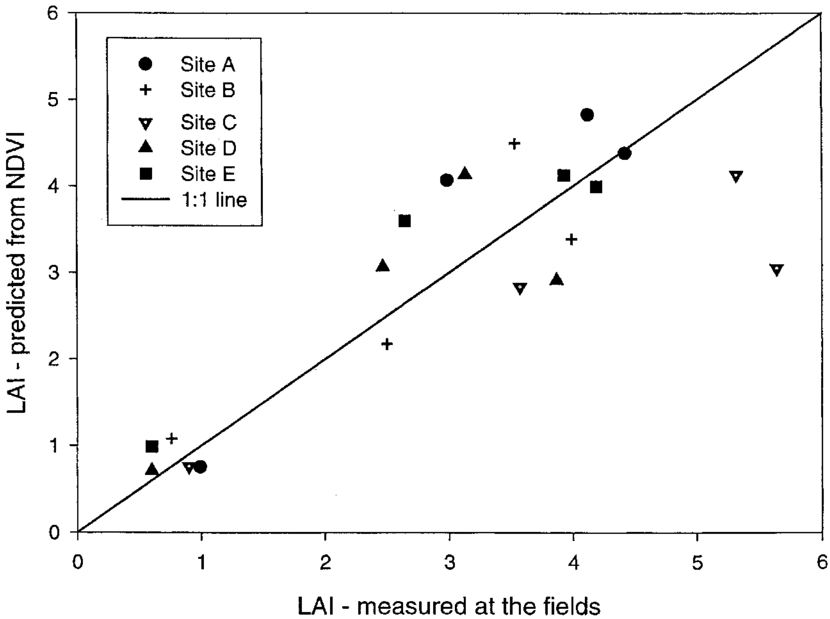

Figure 4. Cross-validation calculation of LAI estimates from NDVI data in comparison to field-observed LAI values for the period of 1 July to 20 August 1999 among the five sampling sites in Jiangning County, Jiangsu Province, China. Regression equation (3) in the text was used in calculating LAI from NDVI data.

5. Summary

A number of studies have demonstrated that spectral vegetation indices are highly correlated with LAI of crops growing in dryland conditions, such as wheat crops (Wiegand *et al.* 1979, Asrar *et al.* 1985). Our analysis of field LAI and VGT-derived NDVI time-series data at the site scale also suggested that there is a high correlation between NDVI and LAI for paddy rice fields over the growing season of paddy rice, which is consistent with other paddy rice studies (Martin and Heilman 1986, Zhao *et al.* 1993, 1996). This analysis of VGT-derived NDVI and field LAI measurements in 1999 at the site scale highlights the potential of using VGT-derived NDVI to estimate LAI of paddy rice fields across landscapes over time.

Acknowledgments

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References

Asrar, G., Fuchs, M., Kanemasu, E. T., and Hatfield, J. L., 1984, Estimating absorbed photosynthetic radiation and leaf area index from spectral reflectance in wheat. *Agronomy Journal*, **76**, 300–306.

Asrar, G., Kanemasu, E. T., and Yoshida, M., 1985, Estimates of leaf area index from spectral reflectance of wheat under different cultural practices and solar angle. *Remote Sensing of Environment*, **17**, 1–11.

Bouman, B. A. M., 1992, Accuracy of estimating the leaf area index from vegetation indices derived from crop reflectance characteristics, a simulation study. *International Journal of Remote Sensing*, **16**, 3069–3084.

Dobermann, A., and Pampolino, M. F., 1995, Indirect leaf area index measurement as a tool for characterizing rice growth at the field scale. *Communications on Soil Science and Plant Analysis*, **26**, 1507–1523.

Gao, L., Jin, Z., Wang, Y., Chen, H., and Li, B., (eds.) 1992, *Rice Cultivation Simulation-Optimization-Decision Making System (RCSODS)* (Beijing: Press of Agricultural Science and Technology) (in Chinese).

Huete, A. R., 1988, A soil adjusted vegetation index (SAVI). *Remote Sensing of Environment*, **25**, 295–309.

Huete, A. R., 1989, Soil influences in remote sensed vegetation-canopy spectra. In *Theory and Applications of Optical Remote Sensing*, edited by G. Asrar (New York: John Wiley & Sons), pp. 107–141.

Lu, D., (ed.) 1997, *Applications of Remote Sensing Technology in Agricultural Engineering* (Beijing: Qinghua University Press) (in Chinese).

Martin, R. D., Jr, and Heilman, J. L., 1986, Spectral reflectance patterns of flooded rice. *Photogrammetric Engineering and Remote Sensing*, **52**, 1885–1897.

Miller, B. C., Foin, T. C., and Hill, J. E., 1993, CARICE: a rice model for scheduling and evaluating management actions. *Agronomy Journal*, **4**, 938–947.

Rahman, H., and Dedieu, G., 1994, SMAC: a simplified method for atmospheric correction of satellite measurements in the solar spectrum. *International Journal of Remote Sensing*, **15**, 123–143.

Le Toan, T., Ribbes, F., Wang, L., Floury, N., Ding, K., Kong, J., Fujita, M., and Kurosu, T., 1997, Rice crop mapping and monitoring using ERS-1 data based on experiment and modeling results. *IEEE Transactions on Geoscience and Remote Sensing*, **1**, 41–56.

Venkateswarlu, B., Rao, P. K., and Rao, A. V., 1976, Canopy analysis on the relationships between leaf area index and productivity in lowland rice, *Oryza saliva*, L. *Plant and Soil*, **45**, 49–56.

Wang, Y., Gao, L., Jin, Z., and Chen, H., 1996, A software package for optimizing rice production management based on growth simulation and feedback control. *Agricultural Systems*, **4**, 335–354.

Wiegand, C. L., Richardson, A. J., and Kanemasu, E. T., 1979, Leaf area index estimates for wheat from Landsat and their implications for evapotranspiration and crop modeling. *Agronomy Journal*, **7**, 336–342.

Zhao, R., Dai, J., Jiang, N., and Wang, Y., 1993, Exploration on rice yield estimation by remote sensing in Wuxi. In *Experimental Research Article on Wheat, Maize and Cotton Production Estimation Using Remote Sensing Technology*, edited by S. Chen (Beijing: Press of Science and Technology), pp. 214–219 (in Chinese).

Zhao, R., Wang, Y., and Dai, J., (eds) 1996, *Dynamic Monitoring and Production Estimation of Paddy Rice Agriculture in China* (Beijing: Press of Science and Technology) (in Chinese).