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Correlations of Rice Grain Yields to Radiometric Estimates of Canopy Biomass as a Function of Growth Stage*

Hand-Held Radiometric Measurements of Two of the Thematic Mapper's Spectral Bands Indicate that the Forecasting of Rice Grain Yields is Feasible at Early to Mid Canopy Development Stages

Young-Kyu Yang
Remote Sensing Laboratory, Korea Advanced Institute of Science and Technology, Dongdaemoon P.O. Box 131, Seoul, Korea.

and

Lee D. Miller
Professor-University of Nebraska at Lincoln, Lincoln, Nebraska 68588-0517, USA.

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ABSTRACT

Considerable experience has been reported on the use of spectral data to measure the canopy biomass of dryland grain crops and the use of these estimates to forecast subsequent grain yield. These basic procedures were retested to assess the use of the general process to forecasting grain yield for paddy rice. The use of the ratio of a multiband radiometer simulation of Thematic Mapper band 4 (.76 to .90 μm) divided by band 3 (.63 to .69 μm) was tested to estimate the canopy biomass of paddy rice as a function of the stage of development of the rice. The correlation was found to be greatest ($R = .94$) at panicle differentiation about midway through the development cycle of the rice canopy. The use of this ratio of two spectral bands as a surrogate for canopy biomass was then tested for its correlation against final grain yield. These spectral estimates of canopy biomass produced the highest correlations with final grain yield ($R = .87$) when measured at the canopy development stages of panicle differentiation and heading. The impact of varying the amounts of supplemental nitrogen on the use of spectral measurements of

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canopy biomass to estimate grain yield was also determined. The effect of the development of a significant amount of weed biomass in the rice canopy was also clearly detected.

I. INTRODUCTION

Field spectrometry was used early in the development of agricultural remote sensing to establish a basic or fundamental relationship between the spectral reflectance characteristics of an "in situ" plant canopy and the biomass of the green portion of that canopy (Pearson and Miller 1972 and Tucker et al. 1975). Subsequently, the simple ratio of selected narrow band reflectances and radiances, originally found to be suitable for non-destructive canopy biomass estimates on the ground, gave rise to other types of transformations of these bands. These new transformations (ND6, TVI, VI, etc.) were more suitable for the analysis of agricultural canopy biomass from narrow band radiances measured from aircraft or satellite imagery (Tucker 1979). This improvement resulted from the fact that they were designed to compensate for the spatial variation in atmospheric extinction of the upwelling radiation and the lack of a white panel or other radiation reference level.

Over the intervening years, these techniques have been tested on the ground and in the "air" for a variety of crop canopies with varying degrees of success depending primarily upon the total amount of green biomass and the proportion of green versus brown leaf material present in the canopy (Tucker and Miller 1973; Pearson et al. 1976; Tucker et al. 1979a; and 1980). Thus, the use of spectral information as a basis for estimating green canopy biomass has been most successful in connection with wheat and other small grains which do not develop a heavy canopy biomass and tend to be almost all green biomass during the early through mid periods of canopy development. The subsequent yield of these small grains is a fuction of the growth or development curve with time of the green canopy. Thus, the periodic spatial mapping of green canopy biomass has been successfully used as a basis for forecasting subsequent grain yields (Colwell, *et al.* 1977). Based upon projections of the expectations for future improvements in the "siting" of the spectral bands, the frequency of the images required, their timely distribution, and their analysis on low cost processors; it is anticipated that the individual farm manager will ultimately be able to use aircraft and satellite derived canopy biomass maps and yield forecast maps as additional management information to adjust actual final yields.

Unfortunately, little attention has been given to the evolution of these techniques for the estimation of canopy biomass and grain yield for paddy rice (Ahn et al. 1980; Kim et al. 1981; LeToan and Megier 1978; and Miller *et al.* 1983). Paddy rice is well suited for assessment with these techniques as it has an appropriate low to medium range of canopy biomass which is green throughout all but the last two weeks of its cultivation. However, the spectral background for paddy rice is water with varying levels of turbidity. Thus it is not clear that the narrow spectral bands identified earlier for the biomass estimation of green, terrestrial vegetation versus soil background are optimally "sited" for this application. These reservation not withstanding, this experiment was designed to determine the value of the available Thematic Mapper spectral radiance bands to estimate green canopy biomass of rice as a function of it's development stage of growth. These spectral estimates of canopy biomass were in turn tested as a basis to estimate the final grain yield of paddy rice.

II. METHODS

II. 1. Site Description

The field measurement program was conducted at the Texas Agricultural Experiment Station at Eagle Lake, Texas approximately 60 miles due west of Houston, Texas. This field station is located in an area of several hundred square miles of surface irrigated rice fields of large field sizes. This field station is small, but adequately equipped for providing all the support measurements required such as large drying ovens, balances, mechanical harvesters, and so on. A large number of rice varietal and experimental treatment plots are cultivated on the site each year by a resident agronomist and his support staff. All the experimental plots which were used were on one soil type. All these plots occurred within 200 meters of the laboratory buildings allowing for concurrent processing of the canopy biomass samples for wet and dry weights. Under these excellent circumstances, it was not necessary to protect the field samples of canopy biomass from dehydration, as periodically, when several samples had been collected, they were immediately weighed for wet weights, labeled, and deposited in the drying ovens.

All field plots were maintained throughout the growing season by the support staff of the field station. This staff also harvested the test plots and processed the rice at the termination of the growing season using a motorized 4 row harvester (figure 1). This harvester was specially designed and constructed in Japan for harvesting rice test plots. After harvesting, the rice grain (variety Labelle) was shelled and dried to a standard moisture content and its yield determined in metric tons per hectare.

Fig. 1. RICE GRAIN HARVESTING USING 4 ROW HARVESTOR. A single, 7 meter yield sample test plot is about to be harvested on 21 August, 1980. The field crew member in the right foreground is pouring the rice grain from a tray to a cloth bag for subsequent drying and shelling. The field crew member in the right background is installing a second tray prior to the harvesting of a plot.

II.2. Radiometric Measurements

All field radiometric measurements were collected with two Mark II, three band radiometers (herein referred to as the triometer) provided by the Goddard Space Flight Center. This triometer efficiently measured the three spectral bands which correspond to bands 3, 4, and 5 of the Thematic Mapper on Landsat 4 (Tucker *et al*. 1981). Thus, the insights gained from this field radiometer measurment program may be applied in a practical sense using imagery collected by this new satellite imaging system. Both field instruments measured the same three spectral bands of red

(.63 to .69 μm), photo infrared (.76 to .90 μm) and, near infrared (1.55 to 1.75 μm). The two triometers provided very closely correlated readings and were thus used interchangeably and simultaneously. The instruments performed flawlessly without a single malfunction throughout the field experimental season yielding approximately 44,000 radiometric readings.

The triometer was easily handled in the field by the experimental observer. Its output could have been automatically recorded requiring only one field observer for each instrument. However, throughout the field measurement program the observer using the triometer was supported by a recorder who wrote down the measurements as called out (figure 2). Serendipitously, this combination of two people yielded significantly improved results over those achievable by a single observer using an automated data recording device. Several thousand small experimental test rice plots were present at the field station and within each experiment the replicas were laid out in a complicated fashion so as to minimize bias from soil variation, irrigation techniques, and so on. The observer operating the instrument was often so intent upon taking good measurements with the proper pointing of the device, and so on, under very adverse temperature conditions, that he would be in the wrong test plot or position in the plot.

(a) triometer observer

(b) data recorder between sample plots

Fig. 2. TRIOMETER OBSERVER AND RECORDER. Note safety line from triometer optical head to observers belt. The recorder in (b) is standing in the separation strip between the 6 row, 7 meter long yield test plots at the growth stage of panicle differentiation.

The second member of the team, the recorder, thus provided a needed and important check on the location of the current measurements as well as on the other measurement techniques such as pointing, height, etc.

Fig. 3. TWO FIELD CREWS USING TRIOMETERS TO MEASURE SPECTRAL BIOMASS RATIO (BSR). One crew is in the foreground and one in the background. The sample plots are the 6 row, 7 meter long yield test plots at the time of panicle differentiation. Springs in foreground were used as optical head pointing aids while moving along the length of plot for the 8 contiguous, observations.

The 1980 summer season was one of the hottest on record in the United States. Generally throughout the summer, during the appropriate daytime, cloud free periods of observation, the temperature encountered in these rice paddies was between 38 and 43°C with a relative humidity usually quite near 100%. Under these conditions a field measurement crew of at least 7 people was generally required so that the four people operating the two triometers could be spelled or rotated in and out of the fields (figure 3). The three people not involved in the actual triometer measurements also did all the canopy biomass harvesting, weighing, etc. The seventh team member laid out the plots and coordinated the experimental procedures. During the triometer measurements the optical head had to be tied to the wrist of the observer who moved about in boots from location to location. This safety measure prevented the dropping of the optical head into the water on several occasions (figure 2a). Approximately 25 full field days distributed over the mid to late summer were required for the 7 or more people to collect the radiometric and canopy biomass data base.

II. 3. Experimental Procedures for Canopy Biomass Estimation

The objective of this experiment was the determination of the suitability of TM bands 3 and 4 (.63 to .69 μm and .76 to .90 μm) for the estimation of rice canopy biomass as a function of growth stage (Miller et al. 1983; Pearson et al. 1976; Tucker et al. 1979b; and Pearson and Miller 1972). A large area of "sacrifice rice" (variety Labelle) was available in one plot immediately adjacent to the 200 plots used for the yield tests. The yield test plots could not be sampled directly for canopy biomass without disturbing their final yields. Thus, the convenient sacrifice plot maintained adjacent to the set of test plots was used for the canopy biomass experiment. The sacrifice area was maintained identically to the adjacent test plots except that no nitrogen (N=0) was applied to the area.

Areas of nominally .25 square meters were marked and measured with the triometer with three sets of three readings recorded for each sample area. The area observed was then marked with an aluminum ring of .25 square meters for subsequent clipping to determine the wet and dry canopy biomass. Initially the rice canopy was clipped at the water surface. However, it was quickly learned that the residual green stalk material left in the 5 to 10 cm of water below the surface was contributing to the total spectral response of the intact canopy.

Thus the experimental technique was adjusted so as to clip the biomass at the soil surface (i.e. mud surface) and precautions were taken to eliminate the water clinging to the surface of the stalk which might have increased the wet weight biomass. The biomass clipped from the plot was collected in one or more large brown kraft or grocery bags of approximately .05 cubic meters, labeled, weighed wet, held in a large drying oven for 48 hours at 100°C, and then reweighed for dry weights.

A total of 295 canopy biomass samples were collected at 7 growth stages using the techniques outlined (figure 4). It should be clearly noted that except for the two weeks prior to havrest (approximately the medium dough to harvest canopy development stages) that essentially no dead or brown canopy material exists in a properly cultivated wet rice plot or paddy. Thus, no consideration was given to dividing up the field sampled canopy biomass into a live and dead fraction (Tucker et al. 1980b).

All 295 sacrifice samples were observed three separate times with the triometer. The optical head was held at an height ranging from belt to chest level, dependent upon the height of the rice canopy, so that the area observed was a nominal .25 square meters for each of the three sets of measurements. Care was taken not to distrub the water or stir up sediment within the area being observed. All radiometric measurements were taken within ± 3 hours of local solar noon. An aluminum panel coated with barium sulphate ($BaSO_4$) was observed about every five minutes to be used as a radiance reference but was not used in the analyses to be reported upon herein.

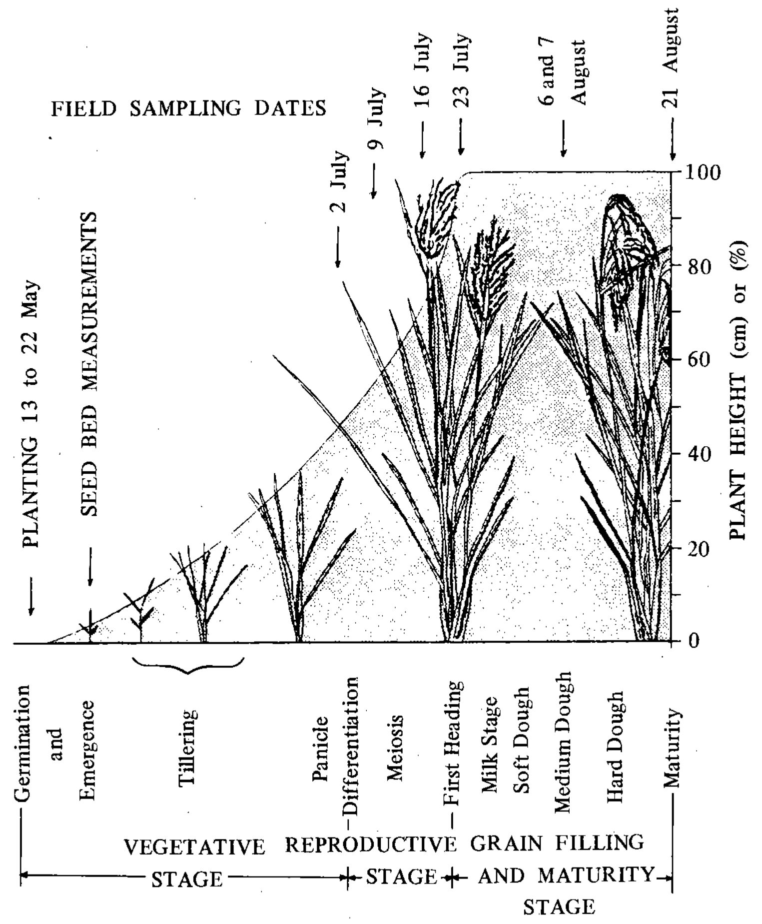


Fig. 4. DEVELOPMENT STAGES OF THE RICE PLANT. The field sampling dates are indicated at the top relative to the plant development stage. (Adapted from Stansel 1975)

II. 4. Experimental Procedures for Yield Estimation

A second rice grain yield experiment was conducted based upon the assumption that the canopy biomass could be accurately estimated from the two spectral bands represented by TM band's 3 and 4 (Miller et al. 1983 and Tucker et al. 1980). Two hundred plots of rice (variety Labelle) were available with 6 rows each, a spacing of 15 centimeters between rows or a total width of .75 meters and a length of 7 meters. Ninety of these plots were treated with 101 kilograms per hectare of nitrogen at the appropriate time near the beginning of the growing season. Ninety additional plots were similarly treated with 34 kilograms per hectare of nitrogen while the remaining 20 plots had 0 kilograms per hectare of nitrogen applied.

These test plots were measured four times during the growing season, specifically at the canopy development stages of panicle differentiation (July 2nd), heading (July 23rd), medium dough (August 6 and 7), and maturity (August 21). All the rice plots were harvested the day after the last set of spectral observations. Each plot was individually harvested using the 4 row mechanical harvester normally used on the test plots throughout the station (figure 1).

The triometer observations were identically taken on each of the 200 test plots for each of the 4 canopy development stages. Eight contiguous, circular areas of nominally .25 square meters were measured along the 7 meter length of the plot. Each of these eight observations or pointings yielded the 3 triometer measurements representing TM band's 3, 4, and 5 for a total of 24 measurements per plot and growth stage. The projected .25 square meter nominal field-of-view of the triometer, when held at belt height, nicely fit over the 4 center rows of the rice test plots. The outer two rows or guard rows of the 6 row plots were thus not generally observed by the triometer. Adequate space was available to walk between the 6 row plots so as to avoid disturbing the interior of the plot in any way. Considerable care was taken to work through the 200 plots in such an order that the sediment stirred up moved away from the plots being measured or awaiting measurement (Tucker and Miller 1974). The height of the optical head was adjusted upward slightly to chest height during the later growth stages so that the nominal .25 square meter area was subtended at about the mid-height of the taller rice canopy. Using these techniques the 200 plots with 24 radiometric measurements per plot yielded 4800 observations per development stage. Three rotating crews of 2 people each using 2 triometers completed these measurements within a period of ± 3 hours of solar noon for each development stage except when delayed to a second day by weather conditions during the medium dough stage (August 6 & 7).

III. RESULTS

III.1. Canopy Biomass Correlations

Simple ratios of the radiance of TM band 4 to TM band 3, the traditional photoinfrared to red ratio, were correlated with the actual field measurement of canopy biomass for each growth stage. Except for the two weeks prior to harvesting, when the field was being dried for machinery access and the canopy is senescing, all the wet rice occurred in fields containing standing water. Thus, one would expect that a high correlation exists between the wet and dry weights of the rice canopy. Since growing rice has essentially no dead canopy material this wet/dry weight correlation is quite high and linear and thus the observed radiance ratios correlated quite well with either the wet, fresh weight or the dry weight of the canopy.

III.2. Data Reduction for Canopy Biomass Estimation

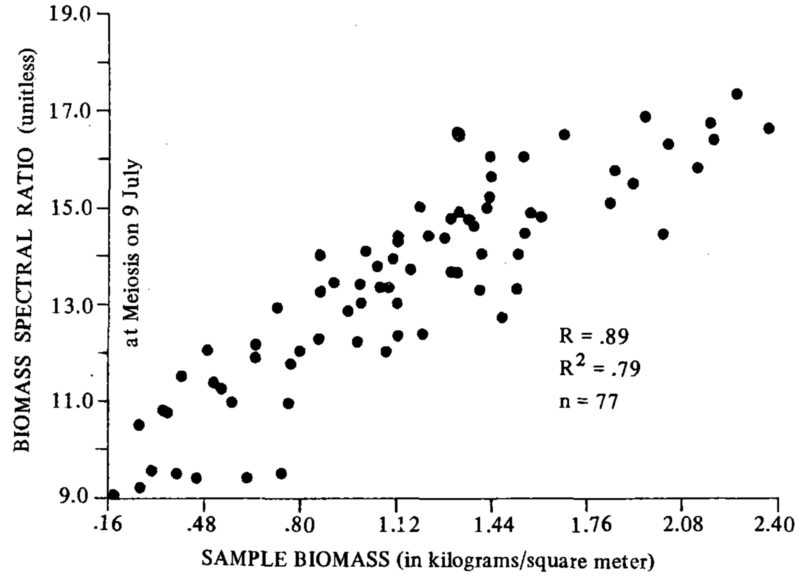
Each field plot was measured three times with the triometer to reduce the instrument and pointing errors. Biomass surrogates (biomass ratio, log biomass ratio, etc) were then computed individually for each observation and the three resulting measurement sets were averaged to yield a single mean observation. These mean, field observed, canopy biomass estimations for the sample plot were then regressed against the actual wet and dry biomass measured by clipping the plots.

The Biomass Spectral Ratio, hereafter referred to as the BSR, is the ratio of the observation of TM band 4 (.76 to .90 μm) divided by TM band 3 (.63 to .69 μm). The BSR has been established as one of the suitable green canopy biomass estimators for closely controlled ground radiometric measurements not involving atmospheric transmission variability from site to site. Thus, the use of the more complicated biomass estimators such as the Transformed Vegetation Index (TVI), ND6, VI etc., which are designed to mitigate the variation in atmospheric transmission from site to site with satellite observations, did not enhance the results. These types of estimators should be reevaluated if these field plot results are used in connection with actual Thematic Mapper imagery.

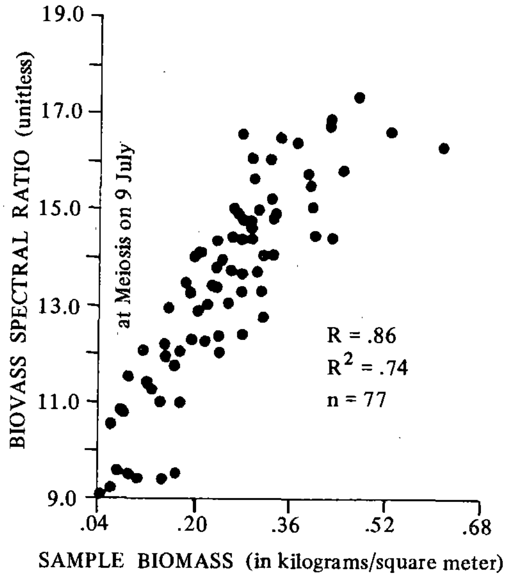
A linear regression of the BSR versus actual canopy biomass (and log BSR versus log canopy biomass) was computed for both wet and dry canopy biomass weights for each of the canopy development stages represented in the measurement sets (figure 5). The R^2 or correlation coefficients for each regression were organized into a table which illustrates the accuracy of the BSR as an estimator of actual canopy biomass as a function of the growth or developmental stage of the rice (table 1).

III. 3. Interpretation of Results

The observations in the middle period of the growth of the rice canopy during panicle dif-



(a) wet weight biomass



(b) dry weight biomass

Fig. 5. SIMPLE LINEAR REGRESSION OF BIOMASS SPECTRAL RATIO (BSR) VERSUS GREEN CANOPY BIOMASS AT TIME OF PLANT MEIOSIS (JULY 9). BSR is the ratio of TM band 4 to TM band 3 as measured by the triometer. Each value plotted is the mean of 3 observations. Actual canopy biomass was determined from samples clipped from .25 square meter, circular plots. The variety of the rice if Labelle.

ferentiation and meiosis produced the best correlations. The early development stages of seedling emergence through tilling represent canopies with relatively low biomass per unit area and can be radiometrically estimated but with reduced accuracy. As the canopy beginning to close, in a spatial sense, and to increase rapidly in green biomass (panicle differentiation through meiosis) the Biomass Spectral Ratio (BSR) provides significantly improved estimation of the actual canopy biomass present. The estimation of the total biomass is unreliable during medium dough through harvesting as a significant portion of the total canopy biomass begins to occur in the grain and the leaf material begins to senesce and lose chlorophyll.

Table 1. CORRELATION OF SPECTRAL BIOMASS RATIO (SBR) WITH WET AND DRY CANOPY BIOMASS MEASUREMENTS. Each set of radiometric observations was measured for a rice sample of .25 square meters. Three sets of readings were taken for each plot and a mean observation computed. The .25 square meters of rice canopy was then clipped at the surface of the soil (not the water surface) and weighed both wet and dry. The variety of rice is Labelle.

				SBR versus CANOPY WEIGHT		log (SBR) versus log (CANOPY WEIGHT)	
DEVELOPMENT STAGE	DATE (1980)	PLANT HEIGHT	SAMPLE SIZE	R^2 (wet wt.)	R^2 (dry wt.)	R^2 (wet wt.)	R^2 (dry wt.)
PANICLE DIFFERENTIATION	30 June	40%	n=10	.86	.88* R=.94	.87	.86
MEIOSIS	9 July	60%	n=77	.79	.74	.80	.76
MEIOSIS TO HEADING	16 July	70%	n=67	.61	.60	.66	.66
HEADING	23 July	80%	n=34	.30	.28	.33	.31
MEDIUM DOUGH	7 Aug.	100%	n=39	.10	.11	.12	.11
REGROWTH	3 Sept.	20% est.	n=33	.66	.6	.52	.67
REGROWTH	17 Sept.	30% est.	n=35	.77	.63	.87	.84

* $R^2 = .88$ or $R = .94$ is the highest correlation obtained.

SBR = Spectral Biomass Ratio is simulated Thematic Mapper band 4 divided by band 3.

The best developmental stage for the estimation of rice canopy biomass, determined from this discrete measurement set taken at 4 points in the development of rice, was at panicle differentiation. At this growth stage there is a fairly complete canopy, in a spatial sense, and a plant height of approximately 40% of final height. The resulting R^2 of .86 ($R = .93$) for wet canopy biomass and R^2 = .88 (R = .94) for dry canopy biomass indicate that successful mapping of the spatial variation of rice canopy biomass with TM spectral bands 3 and 4 could be conducted during the appropriate canopy development stage. The high correspondence between the results for wet and dry canopy biomass substantiates the earlier observation of the correlation between the water in the rice canopy with the amount of canopy biomass. This is the usual case with paddy rice where water is not normally a limiting factor incanopydevelopment until it is withheld prior to harvesting.

III. 4. Data Reduction for Yield Estimation

Each plot measured with the triometer with the procedures outlined earlier was observed as described at eight different contiguous locations along its length. The Biomass Spectral Ratio (BSR) of TM band 4 (.76 to .90 μm) divided by TM band 3 (.63 to .69 μm) and log BSR were computed for each of the eight contiguous sample areas. The eight BSR and log BSR values were then averaged to yield a mean BSR value for the plot which represented the spatial variation in canopy biomass normally found a rice paddy. One average value was measured of the yield of the rice canopy produced by the plot at the end of the season. Thus, an average of the spatially varying canopy biomass as estimated from the BSR was compared with an average of the spatially varying final grain yield. This procedure was designed to produce results more representative of actual grain yields of total rice paddies or of TM observation cells of 30 meters within which both canopy biomass and grain yields vary spatially.

The average BSR and log BSR were then regressed against the rice grains yields and log grain yields for each sample plot for each of the 4 canopy development stages observed (figure 6 and table 2). Ten of the 200 plots were omitted from this analysis as the field note sheets indicated that the plots contained very heavy weed infestations. These field observations were confirmed in the scatter diagrams of BSR versus grain yield which showed anomalously high biomass at earlier development stages with low final grain yields (figure 7). These 10 plots all occurred along one edge of the test plot layout where weeds were invading from a drainage ditch.

Intuition and earlier work with wheat indicated that the variation of canopy biomass with time would more accurately forecast yield than the canopy biomass observed at any one fixed point in time (Colwell et al. 1977). No growth/yield models appear to exist for rice which relate the final grain yield with the variation in canopy biomass as a function development stage (Wiegand et al. 1979). Thus, simple linear multiple regression was used to test all possible permutations of the BSRs of the 4 development stages observed to determine if their combination improved the ability to forecast final yield from canopy biomass estimations (table 2).

The impact of the variation in the application of nitrogen on the use of the BSR values to

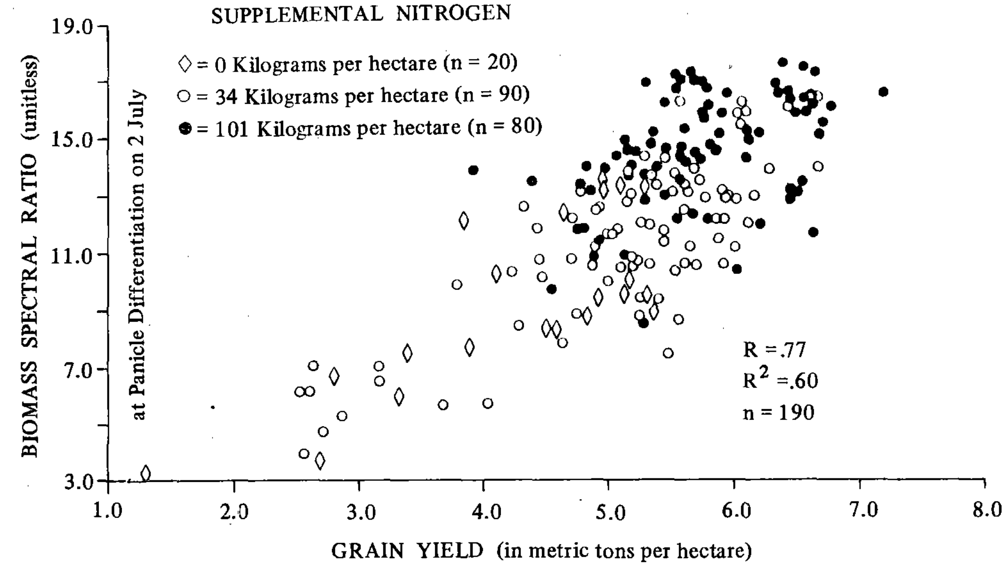


Fig. 6. FINAL GRAIN YIELD VERSUS BIOMASS SPECTRAL RATIO (BSR). This plot illustrates the correlation which exists and how it varies according to the supplemental nitrogen applied to the field. The variety of the rice is Labelle.

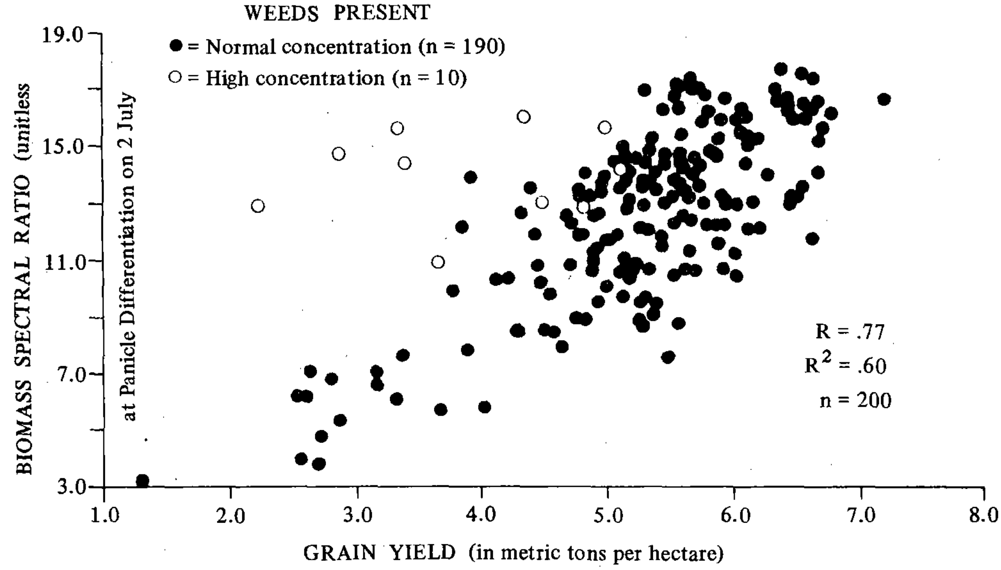


Fig. 7. FINAL GRAIN YIELD VERSUS BIOMASS SPECTRAL RATIO (BSR). This plot illustrates the lack of correlation between the BSR and final yield for sample plots containing significant weeds in the canopy. The 10 plots indicated as having weeds were the only plots noted to the field records to have this condition during the actual measurement of their radiometric values. The variety of the rice is Labelle.

forecast yield was also evaluated. Three different levels of nitrogen were applied over the 190 usable plots. This stratified the plots into 20 to which no supplemental nitrogen was applied, 90 plots to which 34 kg/ha of nitrogen was applied at the beginning of the growing season, and 80 plots to which 101 kg/ha of nitrogen was similarly applied. These three subpopulations were sufficiently large to enable the same single and multiple regression analyses to be repeated on them as described above for the total population of 190 test plots (table 3).

Table 2. CORRELATION OF SPECTRAL BIOMASS RATIO (SBR) WITH RICE GRAIN YIELD. Each observation regressed against the grain yield was a mean of a Spectral Biomass Ratio (SBR) for 8 contiguous .25 square meter circular areas along the length of the meter sample plots of rice with 6 rows of rice each separated by 24 centimeters. The rice variety is Labelle.

RICE DEVELOPMENT STAGE at the time of RADIOMETRIC FIELD OBSERVATION	SBR versus GRAIN YIELD R^2	log (SBR) versus log (GRAIN YIELD) R^2	ΣSBR versus GRAIN YIELD R^2
SIMPLE REGRESSION			
P	.60	.68	- - -
H	.65	.70	- - -
D	.29	.29	- - -
M	.13	.10	- - -
2 DATES IN MULTIPLE REGRESSION			
P H	.68	.75	.67
H D	.65	.70	.57
D M	.29	.30	.25
P D	.60	.68	.58
P M	.60	.68	.57
H M	.65	.71	.56
3 DATES IN MULTIPLE REGRESSION			
P H D	.69	.75	.64
H D M	.66	.72	.51
P H M	.69	.76*	.64
P D M	.60	.69	.55
4 DATES IN MULTIPLE REGRESSION			
P H D M	.69	.76*	.61

KEY: DEVELOPMENT STATE		*DATE OF OBSERVATION*	*PLANT HEIGHT*
P =	Panicle Differentiation	2 July 1980	40%
H =	Heading	23 July 1980	80%
D =	Medium Dough	6 and 7 Aug. 1980	100%
M =	Maturity	21 August 1980	100%

* R^2 = .76 or R = .87 is the highest correlation obtained.

SBR = Spectral Biomass Ratio is the simulated Thematic Mapper band 4 divided by band 3.

ΣSBR = sum of SBR values for all development stages measured.

Table 3. EFFECTS OF NITROGEN TREATMENT ON RICE YIELD FORECASTING. Each observation regressed against the grain yield was a mean of a Spectral Biomass Ratio (SBR) for 8 contiguous .25 square meter circular areas along the length of the 7 meter sample plots of rice with 6 rows of rice with 6 rows of rice each separated by 24 centimeters. The rice variety is Labelle.

	NITROGEN LEVEL (in kilograms per hectare)			
RICE DEVELOPMENT STAGE	N=0	N=34	N=101	N=all
at the time of	SAMPLE SIZE (number of plots)			
RADIOMETRIC FIELD OBSERVATION	n=20	n=90	n=80	n=190
SIMPLE REGRESSION				
P	.71	.70	.18	.68
H	.84	.72	.16	.70
D	.01	.35	.01	.29
M	.30	.16	.01	.10
2 DATES IN MULTIPLE REGRESSION				
P H	.88	.79	.20	.75
H D	.87	.74	.23	.70
D M	.40	.35	.01	.30
P D	.72	.72	.22	.68
P M	.72	.71	.21	.68
H M	.86	.72	.22	.71
2 DATES IN MULTIPLE REGRESSION				
P H D	.89*	.79	.27	.75
H D M	.87	.74	.25	.72
P H M	.88	.79	.25	.76
P D M	.72	.72	.22	.69
4 DATES IN MULTIPLE REGRESSION				
P H D M	.89	.80	.28	.76

KEY : DEVELOPMENT STAGE		DATE OF OBSERVATION	PLANT HEIGHT
P =	Panicle Differentiation	2 July 1980	40%
H =	Heading	23 July 1980	80%
D =	Medium Dough	6 and 7 Aug. 1980	100%
M =	Maturity	21 Aug. 1980	100%

* R^2 = .89 or R = .94 is the highest correlation obtained.

SBR = Spectral Biomass Ratio is the simulated Thematic Mapper band 4 divided by band 3.

III. 5. Interpretation of Results

Total grain yield from the 190 test plots, which varied widely in nitrogen treatment and thus in canopy biomass, could be reasonably forecasted from BSR observations made at the developmental stages of panicle differentiation (R^2 = .68, R = .82) or heading (R^2 = .70, R = .84) (table 2). At the stages of medium dough and maturity the use of BSR for forecasting grain yield would provide unusable accuracy. These results correspond quite closely with those described earlier for the verification of the relationships between the BSR and the actual canopy biomass for paddy rice. BSR was shown to be closely related to canopy biomass during the middle of the growth cycle (e.g. panicle differentiation, meiosis, and heading). Thus when BSR provides an acceptable estimate of the canopy biomass it can be used as a surrogate for canopy biomass to forecast grain yield. During the final canopy development stages (dough to maturity and harvesting - about 3 weeks) where the canopy is mature, the rice head is filling, and leaves are browning as water is withheld; the use of BSR to forecast yield is meaningless (table 2). During this period the canopy biomass measurement tests reported earlier also indicated that BSR could not be used to estimate rice canopy biomass.

Rice yield forecasting measurements were not made during the first 1/3 of the growth of the rice. It is reasonable to conjecture from the results of the canopy biomass estimation experiment that since BSR is marginally usable as an estimator of canopy biomass, marginally accurate forecasting of yield would be possible (Berg 1978). However, since the earlier the forecast is available the greater its value, similar yield experiments during earlier growth stages should be conducted. The marginal correlations of the early canopy development stages could become worse if a subsequent catch-up canopy growth occurs in the tardy portions of a field during the mid portion of the growth cycle (Robertson 1975). Thus, the spatial variation in the canopy biomass in the first 1/3 of the growth cycle is less meaningful, even if it can be reasonably estimated with BSR as the areas of low canopy biomass can catch up in the middle 1/3 of its growth and development.

The multiple regression results show that the combining of the canopy biomass estimations from more than one growth stage yield somewhat higher possible accuracy for forecasting final yield. When the measurements from all 4 developmental stages were combined the multiple regression yielded somewhat improved results ($R^2 = .76$ and $R = .87$) (table 2). More cooperative efforts between remote sensing specialists and agronomists should produce a more sophisticated mechanism to combine multidate BSR estimation of the canopy biomass at various development stages for forecasting final rice grain yield.

Examination of the results achieved by subsetting the rice yield experiment into nitrogen treatment level are quite revealing (table 3). Optimal applications of nitrogen to these plots is less than the 101 kg/ha applied to one of the strata ($n = 80$). Those plots with the overdose of nitrogen achieve substantially higher canopy biomass but do not significantly increase their grain yield over the nitrogen application of 34 kg/ha. This increased biomass is still within the range of accurate estimation of the BSR measurements as seen in the canopy biomass estimation experiment. However, overdriving the rice into canopy biomass production dramatically decouples the amount of final grain yield from the amount of canopy present at any of the 4 development stages of panicle differentiation, heading, medium dough and maturity. The highest single or multiple correlation achieved was $R^2 = .28$ using the measurements for all 4 growth stages together (table 3). These results show clearly that final grain yield at nitrogen applications of 101 kg/ha are almost independent of the canopy biomass present at any time. Thus, as was already known from other earlier agronomic experiments at this station, this excessive application of nitrogen drives the rice into producing foliar material and impairs its production of additional grain. Proper management of commercial rice paddies in the area would therefore not use high application without impairing yield, increasing costs and yielding potential nitrogen pollution of the return water.

The plots with applications of zero and 34 kg/ha of nitrogen yield improved correlations of BSR with grain yield. The highest correlation of $R^2 = .89$ or $R = .94$ occurred with 3 dates of observations used in multiple regression and a no application of supplemental nitrogen in the current year (nitrogen may have been carried over from the prior year's use of the plots) (table 3). Almost equally high were the results from 0 kg/ha and the simple regression at the time of heading where $R^2 = .84$ and $R = .92$ (table 3).

Examination of these results achieved with samples stratified by the amount of the supplemental nitrogen applied indicates that the use of BSR to forecast yield for real world rice paddies would be improved by the usual suboptimal applications of supplemental nitrogen. However, models attempting to relate final grain yield to spectral estimators of the canopy biomass, such as BSR, should also take into account that increasing canopy biomass at a given developmental stage may not indicate significant increases in grain yield. That is to say, the relationship of canopy biomass to yield is an asymtotic function which at the highest canopy values for a given plant development stage can become decoupled from final grain yield.

IV. DISCUSSION AND RECOMMENDATION FOR FUTURE WORK

IV. 1. Band Selection

The two bands tested in the BSR and the comparable bands available on the Thematic Mapper have been selected to optimize biomass assessment for terrestrial vegetation versus a soil background. All the earlier field spectrometer work which lead to the definition of these two bands and the subsequent development of image analysis techniques have dealt with the spectral contrast between vegetation and soils (Miller et al. 1976; Pearson and Miller 1971a and 1971b; Tucker and Miller 1973; and Tucker and Miller 1977). These earlier results cannot be arbitrarily extrapolated to rice where the vegetation occurs against a water background which can vary from clear to turbid. The optimal two spectral bands for the assessment of rice canopy biomass appear to be shifted from those used on the Thematic Mapper and triometer like devices. Whether or not this shift is significant should be determined in the field with a high resolution spectrometer and an experimental design similar to that employed here. Continued, expanded field measurement programs with radiometric devices may lead to incorrect conclusions due to the use of spectral bands optimized for terrestrial biomass assessment.

IV. 2. Turbid Water

During the early field portion of this experiment it was found that stirring up the water and increasing its turbidity significantly impacted on the triometer measurements for TM bands 3 and 4. This substantiates that the bands currently available may not be optimal and that the implications of varying turbidity should also be taken into account in the design of expanded experimentation to determine the optimal spectral bands. The under varying conditions of turbidity care should be exercised in the interpretation of the possible use of the results presented in this paper. Thus, the effects of turbid water which were excluded from the field experiment, should also be evaluated by a field spectrometer measurement program.

IV. 3. Earlier Dates

The spectral assessment of canopy biomass and its use in yield estimation during the early development stages of rice, prior to panicle differentiation, were not clearly examined in this effort (Tucker et al. 1979b and 1980a). A preliminary indication of the canopy biomass measurement results which might be achieved during the first 1/3 of the growing season are evident in a set of measurements made with the triometer in Korea (figure 8). One of the triometers was used in an actual paddy to estimate the canopy biomass of rice still in seed beds. The .25 square meters of rice canopy were then clipped and dried to provide the basis for computing the correlation of the SBR volume at low levels of this, sparse rice canopy biomass. A clear, useable relationship does exist but it is not linear over this light range of biomass (figure 9) (Park and Deering 1982). Further field measurements are needed to determine how soon after emergence from the soil, not the water, that reasonable canopy biomass and yield forecasting results could be expected.

Fig. 8. ILLUSTRATION OF ACTUAL FIELD MEASUREMENTS WITH TRIOMETER IN RICE SEED BEDS NEAR SEOUL, KOREA. Circular areas of .25 square meters whose rice canopy has been clipped for harvesting can be seen just below triometer's optical head and to the left of the observer.

IV. 4. Weed Infestations

The effects of weed infestations were clearly detected on the use of BSR type estimates of canopy biomass and yield. Further field research is needed to determine if these results are consistent and can be compensated for in yield forecast schemes or used in weed management schemes. Early emerging weeds show up as anomalous, high early green biomass and associated BSR values. This may be confused with the similar effects of over application of nitrogen, however, both produce lower final grain yields relative to the developmental history of the canopy biomass. Also, later weed infestations persist as measurable green biomass observable in the brown rice canopy after the field has been dried prior to harvesting.

IV. 5. Time of Day and Field Conditions

The time of observation did not affect the results achieved if the period of measurement was restricted to plus or minus about 4 hours relative to local solar noon. However, a wind of suffi-

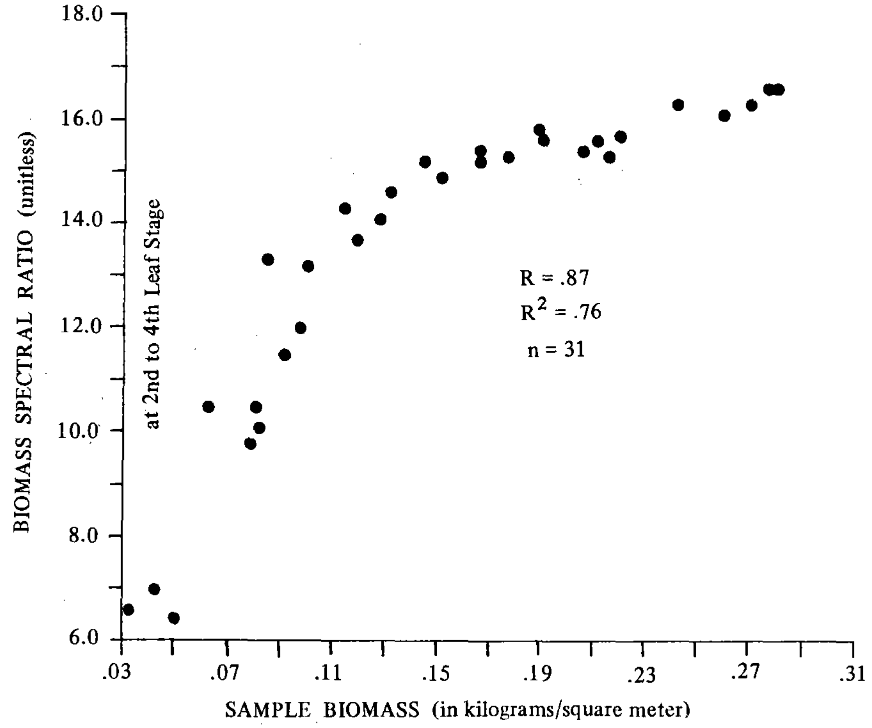


Fig. 9. BIOMASS SPECTRAL RATIO (BSR) VERSUS DRY GREEN CANOPY BIOMASS FOR SEED BED RICE. These field measurements made near Seoul, Korea illustrated the consistent but non-linear relationship between the measured BSR values and the very low levels of canopy biomass present in early stages of development of rice seedlings (2nd to 4th leaf stage). Figure 5 illustrates field setting.

cient velocity to ripple the water surface within the rice canopy has a very significant impact on the BSR values measured. This is due to the occurrence of sun glint back into the radiance path at almost any angle from the wavelets. Generally, however, this was not a problem in light winds where the rice canopy was large enough to protect the water surface from ripplings. Observations in the initial 1/3 of the canopy's development, where insufficient canopy is available to provide such shielding, might be much more significantly polluted by this phenomena which never occurs during the measurement of terrestrial vegetation.

V. CONCLUSIONS

Estimation and improvement of the forecasting of rice grain yield is a very important objective to the United States. The over or under abundance of rice in the international market place directly impacts on the demands for other grainstocks such as wheat or corn (Hammond 1975). Its production, or lack thereof, is more directly connected with the loss or preservation of human life than any of the other major grains. Relative to other crop types, very little U.S. research has been sponsored or conducted on the use of remote sensing in the management of rice or in its yield forecasting. It has been assumed that the approaches developed for other crops, especially wheat, can be directly extrapolated to rice. Unfortunately, this is not true as rice differs in significant ways which requires that several of our earlier research efforts be repeated. The factors which need to be closely reexamined are as follows:

1. paddy rice canopies must be spectrally contrasted with water and not with soil backgrounds,
2. the water background can range from highly turbid to clear,
3. the physical surface of the water can ripple causing spectral glint,
4. agronomic practices used with rice are unique, and
5. rice commonly occurs in numerous small fields.

These preliminary investigations have indicated that rice canopy biomass can be estimated from spectral measurements. These canopy estimates can then be used to forecast final grain yield. Cultural practices such as the application of nitrogen or weed control impact on the use of these techniques (LeToan and Megier 1978). Conditions of these experiments were optimal and practical utilization of the results will yield less significant correlations. However, the correlations achieved in these closely controlled experiments were sufficiently high so as to provide encouragement that acceptable results would be achieved in the practical application of hand-held, aircraft, and satellite devices for forecasting of rice grain yields.

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