Predicting Rice Yield Response to Midseason Nitrogen with Plant Area Measurements

G. Stevens,* A. Wrather, M. Rhine, E. Vories, and D. Dunn

ABSTRACT

A simple method is needed to aid farmers with midseason nitrogen (MSN) decisions in dry-seeded, delayed flood rice (*Oryza sativa* L.). This study was conducted to develop thresholds using visual and digital image measurements for predicting rice yield response to MSN. 'Francis' and 'Cheniere' rice were drill seeded on 19-cm row spacing from 2004 to 2006 on silt loam and clay soils at Glennonville and Portageville, MO. Preflood N (PFN) was applied at rates of 0, 39, 78, 118, and 157 kg urea-N ha^{-1} with and without two MSN applications of 34 kg N ha^{-1} at panicle differentiation (R1) and at R1 + 7d. Plant area observations were made 1 to 2 d before R1. In each plot, a yardstick was floated on floodwater positioned between two center rows. Visible inch numbers were counted while standing above the rows. A number was not counted when rice leaves obstructed the view of one or more digits in the whole number. Plant height was measured, and digital images of canopy were analyzed to determine percent green pixels. Highest rice yields on both soils were most often achieved with 78 kg N ha^{-1} with MSN or 118 kg N ha^{-1} without MSN. The PFN significantly affected visible yardstick numbers, plant height, and percent green pixels. Height was the least reliable indicator of rice N status. Using regression analysis, no rice yield increase from MSN was produced when fewer than 13 yardstick numbers were showing or more than 64% of image pixels were green.

Managing nitrogen fertilization in dry-seeded, delayed flood rice production can be a challenge due to potential N losses from urea volatilization before flooding and denitrification after flooding. Extension recommendations for PFN rates in rice are usually based on empirical N field tests and adjustments are made for specific cultivars, crop rotation, and soil texture (Guindo et al., 1994; Norman et al., 1997; Dunn and Stevens, 2006). To help reduce rice N deficiency stress from early season N losses and supply N needs during grain-filling growth stages, midseason aerial topdressing of N on rice can be applied near panicle differentiation (R1) growth stage (Wells and Johnston, 1970; Counce et al., 2000). Measurements such as leaf area index, biomass accumulation, Y-leaf (most recently fully expanded leaf) N concentration, and whole-plant N concentration have been used to estimate midseason plant N sufficiency for determining whether topdressing is likely to increase rice yields (Mills and Jones, 1996; Ntamatungiro et al., 1999).

Collecting leaf chlorophyll readings with a lightweight, portable instrument developed by the Soil-Plant Analyses Development unit (SPAD) of Minolta Camera Company[1] (Tokyo, Japan) is a nondestructive method for predicting rice need for midseason N (Stevens and Hefner, 2001). Currently, few U.S. rice farmers and crop consultants use SPAD meters for managing midseason N because of the purchase cost (>$1300 U.S. for a Minolta SPAD 502 m) and the need to establish high N reference strips. The SPAD meter estimates the amount of chlorophyll present by measuring the amount of light that is transmitted through a rice leaf. Meter readings are based on wavelength measurements in the red area where adsorption is high and the infrared area where adsorption is extremely low (SPAD-502, Owner's Manual). Turner and Jund (1994) reported that a SPAD chlorophyll meter used during late tillering (V8) predicted 62% of the rice yield response to topdress MSN for 'Lemont' rice. Carreres et al. (2000) investigated rice yields and N efficiencies with six preflood N rates and three topdressing patterns. A significant relationship was found between rice tissue N content and chlorophyll content (SPAD) values. Regression equations based on rice yields and SPAD showed a high coefficient of determination for predicting a need for N topdressing at mid-tiller, but not at R1 growth stage. Other stress factors besides N deficiency influence rice leaf chlorophyll content and grain yield. Hussain et al. (2000) found good N yield response predictions in rice using critical chlorophyll meter sufficiency indices from readings adjusted relative to well-fertilized reference plots.

Scientists at the International Rice Research Institute in the Philippines developed a leaf color chart for measuring rice leaf green color intensity (Shukla et al., 2004). This tool is being used with good results around the world (Alam et al., 2005). However, the need to use high N reference strips also applies to this method and for red–green color blind individuals, matching a rice leaf to green color plates on a chart is not possible. In the

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[1]Mention of trade names or commercial products in this publication is solely for the purpose of providing information and does not imply recommendation or endorsement by the USDA or the University of Missouri.

Abbreviations: PD, panicle differentiation; PFN, preflood N; MSN, midseason nitrogen; YLD, yield change from midseason N application (kg ha^{-1}); %PIXEL, percent green pixels in digital image; SHOW, number of readable inch numbers on yardstick placed between rice rows; SPAD, Soil-Plant Analyses Development unit.

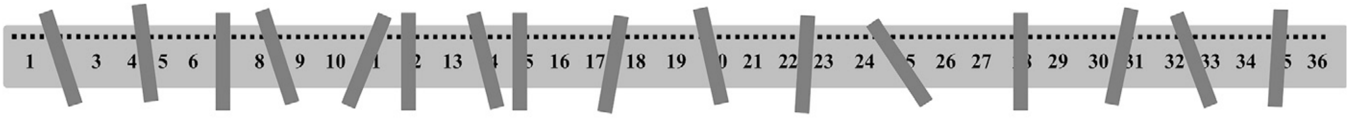

Fig. 1. Illustration of rice leaves blocking the overhead view of inch numbers on a yardstick floating in floodwater parallel and halfway between two rice 19-cm spaced drill rows. In this example, 2, 7, 11, 12, 14, 15, 20, 25, 28, 31, and 35 would not be counted as showing.

United States, 8 to 10% of men have inherited protan and deutan defects of the human eye, collectively termed red–green color vision defects (Neitz and Neitz, 2000).

Plant area measurements with a rice gauge have also been used to predict midseason N need (Wells et al., 1989). The rice gauge has two main components: (i) a vertical wooden board (4 cm wide by 100 cm tall) with centimeter digits for measuring plant height and (ii) a height adjustable inverted trapezoid (40 cm across the top) with centimeter digits along the top edge for measuring canopy spread. The vertical board is positioned in the center of a rice drill row, and the trapezoid slid to the top of the canopy. Then a person visually estimates the rice plant height and width at the sample location. These numbers are used in a formula to calculate plant area. Ntamatungiro et al. (1999) found that plant area values from a rice gauge were a good estimator of rice dry matter and a more reliable estimator of total N accumulation than Y-leaf N concentrations and SPAD readings. Although use of the rice gauge for predicting rice need for midseason N has been widely promoted by state extension services in the upper Mississippi Delta region, very few rice consultants or farmers use it because of the labor required. Much of the rice in the Delta region is scouted by a single person walking across a field checking for disease, insect, weed, and nutrient problems. For monitoring rice plant midseason N status with a rice gauge, one person must carry a clip board and pencil to record numbers, slide and lock the trapezoid in place, prevent the vertical shaft from falling over in the mud while backing away to estimate height and width, and then move to another sample location in a field.

The objective of this study was to develop thresholds using visual and digital image measurements for predicting rice yield response to MSN applications at R1 growth stage. In 2004 to 2006, we conducted experiments to determine if plant area estimates based on plant height or numbers visible on a yardstick floating on floodwater between rice rows were reliable predictors of rice need for MSN applications. In 2005 to 2006, percent green pixels in digital images from rice plots recorded with a digital camera were evaluated as a predictor of rice need for MSN.

MATERIALS AND METHODS

Rice field experiments were conducted at Glennonville, MO on a Dewitt silt loam soil (fine, smectitic, thermic, Typic Albaqualf) that overlay a thick silty clay loam argillic horizon, and at Portageville, MO on a Sharkey clay soil (very-fine, smectitic, thermic Chromic Epiaquert). Plots were shifted to a new location each year to maintain a soybean [*Glycine max* (L.) Merr.]–rice rotation. Rice plots were drill seeded (19-cm row spacing) with Francis and Cheniere cultivars at a rate of 330 seeds m^{-2}. A split-plot design with four replications was used with rice cultivars in main plots and N treatments in subplots. Nitrogen treatments were urea N applied 0, 39, 78, 118, and 157 kg N ha^{-1} before flooding at V4 to V5 growth stage with no additional N at midseason and the same PFN rates with MSN applied 34 kg N ha^{-1} urea at R1 growth stage followed by 34 kg N ha^{-1} urea again at R1 +7d. Each subplot was 3.7 m wide by 8 m long.

In this study, MSN rates of 34 kg N ha^{-1} at R1 growth stage followed by 34 kg N ha^{-1} 1 wk later were used because this topdressing program has been the standard practice in the Delta region for many years. Recently, some rice farmers have begun making a single midseason application of 50 to 70 kg N $ha^{-1}$to reduce aerial application costs. This system may change the magnitude of yield change from midseason N, but in-season diagnostic indicators predicting rice response to additional N will continue to be needed.

Clomazone herbicide [2-(2-chlorophenyl) methyl-4,4-dimethyl-3-isoxazolidinone] (0.56 kg a.i. ha^{-1}) was applied premergence for weed control at each site. Quinclorac (3,7-dichloro-8-quinoline-carboxylic acid) (0.33 kg a.i. ha^{-1}) and propanil (3',4'-dichloropropionalilide) (2.8 kg a.i. ha^{-1}) were applied postemergence before flooding grass and broadleaf control. In 2005 on the Dewitt silt loam, an infestation of duck salad [*Heteranthera limosa* (Sw.) Willd] developed after flooding and bensulfuron methyl (0.06 kg a.i. ha^{-1}) was applied for control.

Plots were mechanically harvested with a combine and adjusted to 13% moisture. Rice yields for each PFN rate subplot without midseason N were subtracted from yields in PFN rate subplots with midseason N.

Three methods of measuring midseason plant area per plot were evaluated 1 to 2 d before R1 growth stage. For the first method, a yardstick was floated on floodwater between two center drill rows and the numbers visible were counted. Inch digits on the yardstick were approximately 2.0 mm tall. Standing between adjacent rows and leaning over the sampling rows, we counted the inch numbers showing on the yardstick (not hidden by rice leaves) out of 36 numbers possible (Fig. 1). When a rice leaf obstructed the view of one digit in a two-digit number to the point that the whole number was not recognized, we did not count that number. For the second method, plant height was measured at the same sample location in each plot. One location per plot was sampled.

For the third method, digital images were collected 1 to 3 d before midseason N applications with a camera mounted on 1.5-m rod held above the plot in 2005 and 2006. This method was not used in 2004. The camera was positioned level with the soil surface and recorded a plot area of 80 by 115 cm (Fig. 2). A computer macro program developed at the University of Arkansas was used with Sigma Scan Pro 5.0 image software (Aspire Software International, Asburn, VA) to determine the percentage of green pixels in each photo (Purcell, 2000). We defined green color in Sigma Scan as 52 to 110° hue on the color wheel and a saturation range of 35 to 100%.

The statistical analyses of plant height, yardstick numbers showing, percent green pixels, and rice yield were performed using Proc Mixed from Statistical Analysis System Version 8.0 (SAS Institute Inc., Cary, NC). This procedure provided Type III *F* values but did not provide mean square values for each source of variation within the analysis or the error terms. Mean separation was evaluated through a series of pair-wise contrasts among all treatments (Saxton, 1998). Probability levels >0.05 were categorized as nonsignificant. Excel 2000 (Microsoft Corp., Redmond, WA) spreadsheet software was used to graph and develop regression equations

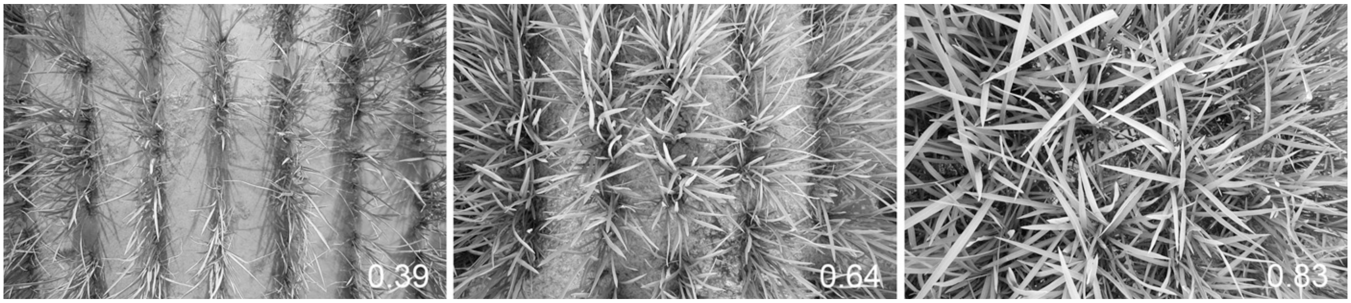

Fig. 2. Example images (left to right- low preflood nitrogen [PFN] to high PFN,) collected at R1 growth stage with a digital camera from 80 by 115 cm areas in rice plots. Values in the lower right corner of photos were the proportion of green pixels in images.

for yardstick number showing and percent green pixels relative to rice yield changes from midseason N.

RESULTS AND DISCUSSION

All main factors (year, soil, cultivar, PFN, and midseason N) had significant effects on rice yields (Table 1). Significant interactions for yield occurred between PFN and MSN and both factors also interacted with year, cultivar, and soil. The general yield trend was for progressively lower yield responses from MSN applications as PFN rates increased (Table 2). In most cases, MSN did not result in a significant yield increase and in two cases MSN caused a significant decline in rice yield. Rice yields on both soils were most often greatest with 78 kg N ha^{-1} PFN with midseason N or 118 kg N ha^{-1} without midseason N.

Although Francis cultivar rice plants grew taller and matured 3 to 5 d later than Cheniere, we found no consistent rice yield pattern indicating that one cultivar should be fertilized with more or less N than the other cultivar on a specific soil. However, as indicated in the interactions, cultivars did not always respond the same to N treatments in different weather and soil environments. Only in 2 out of 12 cases (Francis, Sharkey clay, 2004; and Francis, Dewitt silt loam in 2006), did a cultivar with 118 kg N ha^{-1} PFN produce statistically lower yields than the same rice cultivar with 157 kg N ha^{-1} PFN.

In this study, soil and weather conditions were typical of growing seasons in the upper Mississippi Delta region except the Sharkey clay soil (Portageville) in 2005. The test site was regraded in 2005 with laser land leveling equipment in the fall of 2004, and the plots were located in an area which had been filled with 15 cm of moved soil. This soil disturbance may have stimulated microbes to mineralize more N from organic matter than normal and contributed to less positive yield response to N fertilizer. Weather was also a factor at this site in 2005. The remnants of Hurricane Katrina, downgraded to a tropical storm, passed through West Tennessee and Kentucky and parts of Southeast Missouri on 30 August. This produced high winds after rice heading and 40 to 60% of the plants lodged in some plots (Table 3). The lodging problem was greatest in rice that had received MSN. Although the intake header on the plot combine was positioned close to the soil to pull in as much rice as possible, some rice grain was lost in lodged plots. The lowest yields were in Cheniere plots with 157 kg N ha^{-1} PFN followed by MSN applications (Table 2). On the Dewitt silt loam soil at Glennonville, lodging was not a problem in 2005. Glennonville is located 56 km west of Portageville and received less intense wind when the storm tracked northeast.

The wind conditions on 30Aug. 2005 at Portageville provided a unique opportunity to study the effect of MSN fertilization on rice lodging. Although applying MSN is an important management tool for relieving N-deficiency stress in rice, plants may be more likely to lodge. By chance, the rice drill rows in plots were planted east to west because of the field grade. Weather records indicate the wind gusts were strongest from 0300 to 0600 h CDT when wind was blowing straight from the east in the row direction. Rice plants prone to lodge fell toward the alleys rather than an adjoining plot on the right or left. We observed plots without midseason N that were completely standing from border to border. Often these plots were immediately adjoining plots with high PFN rates and MSN that sustained 60 to 80% lodging. One explanation for the high lodging in MSN plots is that midseason N fertilization may have produced plants with

Table 1. Summary of tests of fixed effects of years (2004, 2005, 2006), soils (Dewitt silt loam, Sharkey clay), culivar (Francis, Cheniere), preflood N (PFN) (0, 39, 78, 118, and 157 kg N ha^{-1}) and midseason N (MSN) (0, 34 + 34 kg N ha^{-1}) on rice grain yield at Glennonville and Portageville, MO.

Effect	Significance
Year	**
Soil	**
Year × soil	**
Cultivar	**
Year × cultivar	ns†
Cultivar × soil	ns
Year × cultivar × soil	**
PFN	**
Year × PFN	ns
Soil × PFN	ns
Year × soil × PFN	**
Cultivar × PFN	**
Year × cultivar × PFN	ns
Cultivar × soil × PFN	ns
Year × cultivar × soil × PFN	ns
MSN	**
Year × MSN	ns
Soil × MSN	**
Year × soil × MSN	**
Cultivar × MSN	ns
Year × cultivar × MSN	ns
Cultivar × soil × MSN	ns
Year × cultivar × soil × MSN	**
PFN × MSN	**
Year × PFN ×MSN	ns
Soil × PFN × MSN	ns
Year × soil × PFN × MSN	ns
Cultivar × PFN × MSN	ns
Year × cultivar × PFN × MSN	ns
Cultivar × soil × PFN × MSN	ns
Year × cultivar × soil × PFN × MSN	ns

** Significant at the 0.01 probability level.

† ns, not significant at $P < 0.05$.

Table 2. Rice grain yields from Francis and Cheniere cultivars grown on Dewitt silt loam and Sharkey clay with preflood and midseason N treatments in 2004 to 2006.

Soil	Year	Cultivar	Midseason N	Preflood N, kg N ha^{-1} 0	39	78	118	157
			kg N ha^{-1}	kg rice grain ha^{-1}				
Dewitt silt loam	2004	Francis	0	7156 ij †	8666 efg	9319 bcdef	10197 abc	10643 a
			34 + 34	8246 gh	9647 abcde	10118 abc	10264 ab	9772 abcd
		Cheniere	0	7081 j	7594 hij	8804 defg	9169 cdefg	8827 defg
			34 + 34	8279 fgh	8734 defg	9038 defg	8816 defg	8164 ghi
	2005	Francis	0	6282 f	7441 def	8680 abcd	9374 abc	10421 a
			34 + 34	7568 cdef	8643 abcde	9937 ab	8783 abcd	10240 a
		Cheniere	0	6753 ef	7366 def	8334 bcde	8537 abcde	9765 ab
			34 + 34	8211 bcde	9114 abcd	9562 ab	9978 ab	8911 abcd
	2006	Francis	0	5291 h	6847 defg	6910 cdefg	7596 bcde	8438 a
			34 + 34	6963 cdefg	7892 abcd	7650 bcd	7574 bcde	7490 bcdef
		Cheniere	0	6160 fgh	7359 bcdef	8250 ab	7352 bcdef	7152 bcdefg
			34 + 34	6279 efgh	7503 bcdef	7902 abcd	7472 bcdef	6478 efgh
Sharkey clay	2004	Francis	0	5489 ef	5419 f	5795 def	6188 cdef	7231 abc
			34 + 34	6086 cdef	5738 def	6458 bcdef	6747 abcde	7821 a
		Cheniere	0	5542 ef	6513 bcdef	6739 abcde	6965 abcd	7320 abc
			34 + 34	6566 abcdef	7473 ab	7307 abc	7228 abc	6544 bcdef
	2005	Francis	0	8538 ab	9649 a	10609 a	10468 a	10166 a
			34 +34	9075 a	10016 a	10059 a	9276 a	9262 a
		Cheniere	0	8803 a	9764 a	10073 a	10317 a	9312 a
			34 + 34	9169 a	9434 a	9111 a	8459 ab	6263 b
	2006	Francis	0	8075 fg	9505 cd	10585 abc	11034 a	10534 abc
			34 + 34	8186 efg	9599 bcd	10737 ab	10470 abc	10469 abc
		Cheniere	0	7150 g	9276 de	10314 abcd	9869 abcd	9832 bcd
			34 + 34	9220 def	9635 bcd	9889 abcd	10098 abcd	9752 bcd

† Within soils and years, rice yield values followed by the same letter were not significantly different at the 0.05 probability level.

heavier panicles which is desirable for increasing grain yields but makes the plant top heavy and more likely to lodge in high winds.

Preflood Nitrogen

An important factor to consider before applying MSN is the amount of N that was applied preflood. The small plots in this study were managed with ideal cultural practices for minimizing N losses from urea volatilization. We were able to completely flood plots within 4 h of applying preflood urea and maintained the flood for the rest of the season. Unfortunately, farmers may need several days to flood a field and they may be uncertain of how much PFN was lost due to N volatilization. Nevertheless, PFN remains one of the best predictors of whether yield increases are likely to occur from MSN.

Regression analysis was done on the complete dataset (two cultivars and two soils across 3 yr) with PFN as the independent variable. A linear regression equation for MSN response, ignoring cultivar and year interactions, showed a coefficient of determination of $R^2 = 0.405$ for rice yield change (yield with MSN− yield without MSN) based on each PFN rate (Table 4). Solving for zero yield increase from MSN application, the equation reduced to PFN = 98 kg N ha^{-1}. This indicated that at PFN rates > 98 kg N ha^{-1}, MSN applications were not predicted to produce higher rice yields based on the entire dataset.

A second group of regression analyses was performed after removing Sharkey clay 2005 yields from the dataset (Table 4). This was done because of the problems with soil disturbance from land leveling and high winds at harvest. The coefficient of determination was slightly higher ($R^2 = 0.478$) without the 2005 clay data. Solving for zero yield increase from MSN application (YLD = 0), we found that 120 kg N ha^{-1} preflood was predicted to produce rice yields with no additional response to midseason N topdressing. This is 28% less N than the current University of Missouri total N recommendation to farmers for Francis and Cheniere cultivars (168 kg N ha^{-1}), but is much closer than predictions with Sharkey clay 2005 results included in the analyses. On an actual rice farm in the Delta, more urea N may be required than our predictions to compensate for N losses from volatilization and denitrification. Since it is difficult to know how much N is lost in a given field, developing one or more in-season plant indicators for predicting N response to MSN is needed.

Table 3. Visual estimation of plant lodging in Sharkey clay plots in 2005 following winds from tropical storm Katrina.

Preflood N	No midseason N	With midseason N
kg N ha^{-1}	———plant lodging, %—	
0	3 e †	16 cd
39	5 de	20 c
78	5 de	38 b
118	6 de	43 b
157	3 e	62 a

† Lodging values followed by the same letter were not significantly different at the 0.05 probability level.

Plant Measurements

Plant height, yardstick number counts, and green pixel digital image analyses were done before MSN applications were made. In

Table 4. Summary of regression analyses for predicting rice yield change (YLD, kg rice ha^{-1}) from applying midseason N based on preflood N rates (PFN, kg N ha^{-1}), and yardstick numbers showing (SHOW, 0–36), and rice plant height (HT, cm).

Independent variables†	Regression equation	R^2
All soils and all years		
Preflood N	YLD = 1038.3 – 10.59PFN	0.405
Yardstick digits showing	YLD = 2736.6 + 237.5 SHOW – 3.96 SHOW^2	0.365
Rice plant height	YLD = 1833.8 – 27.285 HT	0.082
Excluded clay 2005‡		
Preflood N	YLD = 1143.3 – 9.4563PFN	0.478
Yardstick digits showing	YLD = –1814.2 + 174.75 SHOW – 2.814 SHOW^2	0.318
Rice plant height	YLD = 1691.7 – 21.818 HT	0.085

† Equations using percent preflood, yardstick numbers showing, and plant height variables are from results with Francis and Cheniere cultivars on Sharkey clay in 2004, 2005, and 2006 and Dewitt silt loam in 2004, 2005, and 2006.

‡ Data from Sharkey clay in 2005 was excluded from regression analyses because of land leveling soil disturbance and plant lodging from tropical storm Katrina.

Table 5. Summary of tests of fixed effects of years (2004, 2005, 2006), soils (Dewitt silt loam, Sharkey clay), cultivar (Francis, Cheniere), preflood N (PFN) (0, 39, 78, 118, and 157 kg N ha^{-1}) and midseason N (0, 34 + 34 kg N ha^{-1}) on plant height (HT) and numbers showing on a yardstick (SHOW) at PD stage in Glennonville and Portageville, MO. Summary for tests with percent green pixels (%PIXEL) in digital images were from Francis and Cheniere in 2005 on Sharkey clay and Dewitt silt loam soil in 2005 and 2006.

Effect	HT	SHOW	%PIXEL
Year	**	**	**
Soil	**	ns†	**
Year × soil	**	ns	**
Cultivar	**	ns	**
Year × cultivar	**	**	**
Cultivar × soil	ns	ns	ns
Year × cultivar × soil	*	ns	*
PFN	**	**	**
Year × PFN	**	**	**
Soil × PFN	**	**	**
Year × soil × PFN	**	**	**
Cultivar × PFN	**	ns	ns
Year × cultivar × PFN	**	ns	ns
Cultivar × soil × PFN	ns	ns	ns
Year × cultivar × soil × PFN	ns	ns	ns

*** Significant at the 0.05 probability level.**

**** Significant at the 0.01 probability level.**

† ns, not significant at *P* < 0.05.

this study, all three plant measurements indicated highly significant effects from PFN rates (Table 5). However, each system also showed other significant main factor effects and multiple interactions between factors. The greatest number of significant effects other than PFN occurred with plant height (11 factors or interactions), and the second greatest interactions occurred with percent green pixels. The least number of interactions occurred with yardstick numbers showing.

Although plant height is used as an input for estimating rice crop canopy with the rice gauge, we found little value for this measurement for predicting rice N status at midseason. Regression coefficients of determination for plant height and rice yield change from midseason N applications were very low as shown in Table 4.

Most modern rice cultivars have been selected for vertical leaf orientation for the uppermost leaves (Ort and Long, 2003). This change in leaf orientation improves light penetration into the canopy compared to the more horizontal leaf position of older cultivars. Cheniere and Francis are high-yielding rice cultivars bred to maximize photosynthesis using vertical leaf orientation. Yardstick numbers showing and percent green pixels in digital images are indicators of crop leaf canopy closure and can be influenced by leaf orientation. Cultivar main effect had a significant effect on green pixel percentages but did not significantly affect yardstick numbers showing (Table 5). Yardstick numbers visible and % green pixels were significantly affected by preflood N rates but did not have a cultivar × preflood N interaction. This is important because it indicates that the systems might be used for N management with both Cheniere and Francis, and perhaps across other cultivars with vertical leaf orientation, without major adjustments. Plant height measurements produced a significant three-factor interaction between cultivar, PFN, and year.

Plant area measurements were made with yardstick and digital image systems on the Dewitt silt loam in 2005 and 2006 and Sharkey clay in 2005 and 2006. We found that an inexpensive

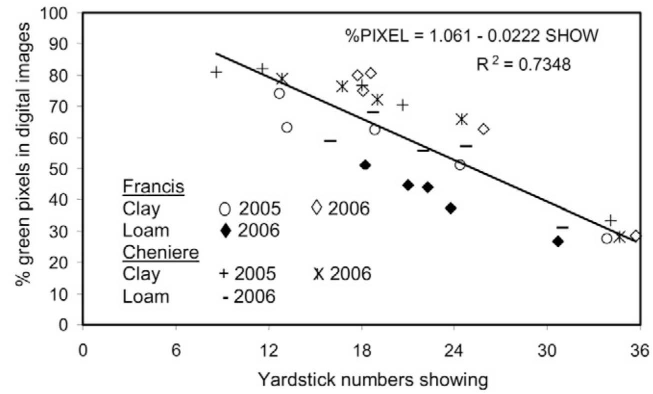

Fig. 3. Relationship between visible numbers showing on yardstick and percent green pixels in digital images measured at R1 growth stage before midseason N was applied in 2005 and 2006 on Francis and Cheniere cultivars.

low-resolution digital camera (640 × 480 pixels) produced similar green pixel percentages as more expensive digital cameras. Also low resolution images from a cheap camera can be processed faster in Sigma Scan than large high resolution files. As expected, a strong coefficient of determination ($R^2 = 0.73$) was found between the two monitoring systems (Fig. 3). The main difference between the systems is that yardstick numbers indicate the outward overlapping of rice leaves from rows into the center of row middles in contrast to the green pixel method which evaluates the entire rice leaf area including the rows. Sunlight glare and plant shadows can produce errors in green pixel measurements. In digital images, bright reflections off of rice leaves are counted as white color and shaded leaf areas deep in the canopy are black. The values from yardstick and green pixel methods were inversely related because %green pixels are greatest in images from plots with dense leaf canopy, and total yardstick numbers showing are smallest in dense canopy rice plots because more inch numbers are blocked from view by overhanging leaves into the row middles.

An infestation of aquatic weeds developed after the permanent flood was established on the silt loam soil at Glennonville in 2005. Digital images on the loam site in 2005 were not useable and were excluded from Fig. 4 because of small duck salad weeds growing between the drill rows after flooding. An application of bensulfuron methyl herbicide killed the weeds but Sigma Scan software could not distinguish between green pixels produced by rice plants and green pixels from the slowly dying aquatic weeds at the water surface. Fortunately, the duck salad was small enough that the plants did not interfere with our ability to place the yardstick between rice rows and collect visual inch-number-showing data.

Yardstick number showing, used as an independent variable with regression analysis did not perform as well as PFN rate for predicting yield change from topdressed MSN application (Table 4). The best fit equation correlating yield change from MSN with yardstick digits was a quadratic equation (Fig. 5). Although MSN can help reduce deficiency, it is only a supplement to a good PFN program. Rice rows with 30 to 35 yardstick numbers showing were severely deficient of N, and tillering was poor. Applying N at R1 growth stage on these plots was often too little N applied too late.

Using the regression equation for yardstick numbers in Table 4 with Sharkey clay 2005 data excluded, no yield response to MSN was produced when <13 inch numbers were showing on a yardstick. The regression equation shown in Fig. 4 is based on a smaller data set (clay 2005 and 2006 and loam 2006) than the yardstick

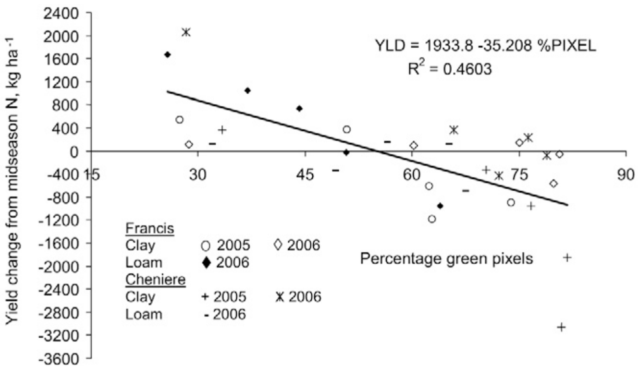

Fig. 4. Rice yield response to midseason N applications relative to percentage of green pixels in digital images recorded at R1 stage from Francis and Cheniere cultivars in 2005 and 2006 on Sharkey clay and 2006 on Dewitt silt loam soil.

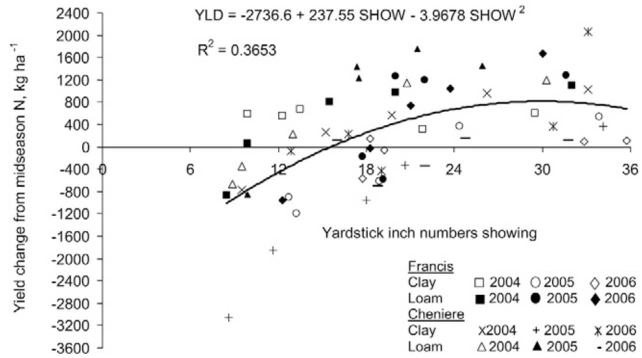

Fig. 5. Rice yield response to midseason N applications relative to visual number of numbers showing on yardstick at R1 growth stage from Francis and Cheniere cultivars in 2005 and 2006 on Sharkey clay and 2006 on Dewitt silt loam soil.

equation. From these results, we found that MSN should not be applied when >55% of the pixels in an image of a rice plot are green. When the clay 2005 data were removed from the regression analysis because of the lodging problem, 64% pixels was the critical level for no yield response to MSN (YLD = −25.38%PIXEL + 1630.3, $R^2 = 0.418$).

Coefficient of determination values of the yardstick and green pixel methods for predicting rice N need at R1 growth stage did not surpass most SPAD chlorophyll meter results reported in the literature. Costs for equipment, software, and labor will influence which plant N-monitoring system are used by rice farmers, crop consultants, or scouts. Commercial cost for Sigma Scan Pro 5.0 image software is approximately $1375. A wooden yardstick can be purchased for less than $5. A yardstick is lighter to carry than a pole and camera across muddy rice fields. Also, when using digital photography, image file names and field names must be matched, images processed later with a computer, and aquatic weeds can make results unusable. However, using aerial digital photography of whole fields combined with scouting for weeds would minimize some of these problems.

SUMMARY

No significant yield increase was produced from MSN when 118 kg N ha^{-1} was applied preflood with small plot water management. However, in large rice grower fields managing to reduce volatilization and denitrification losses is more difficult. Critical plant area thresholds values for R1 growth stage rice were developed using visual and digital image measurements for predicting rice yield response to MSN. No yield response was produced from MSN when fewer than 13 numbers were showing on a yardstick floating between drill rows or more than 64% of the pixels in digital images of plots were green.

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REFERENCES

Alam, M.M., J. K. Ladha, S.R. Khan, Foyjunnessa, Harun-ur-Rashid, A.H. Khan, and R.J. Buresh. 2005. Leaf color chart for managing nitrogen fertilizer in lowland rice in Bangladesh. Agron. J. 97:949–959.

Carreres, R., J. Sendra, R. Ballesteros, and J.G. de la Cuadra. 2000. Effects of preflood nitrogen rates and midseason nitrogen timing on flooded rice. J. Agric. Sci. 134:379–390.

Counce, P.A., T.C. Keisling, and A.J. Mitchell. 2000. A uniform, objective, and adaptive system for expressing rice development. Crop Sci. 40:436–443.

Dunn, D., and G. Stevens. 2006. University of Missouri soil test recommendations for rice production. p. 64–65. *In* C. Dickens and D. Beighley (ed.) Missouri rice research update 2005. Spec. Rep. 001–2005. Southeast Missouri State Univ., Cape Girardeau, MO.

Guindo, D., B.R. Wells, and R.J. Norman. 1994. Cultivar and nitrogen rate influence on nitrogen uptake and partitioning by rice. Soil Sci. Soc. Am. J. 58:840–845.

Hussain, F., K.F. Bronson, Y. Singh, B. Singh, and S. Peng. 2000. Use of chlorophyll meter sufficiency indices for nitrogen management of irrigated rice in Asia. Agron. J. 92:875–879.

Mills, H., and J. Jones. 1996. Plant analysis handbook II. MicroMacro Publ., Athens, GA.

Neitz, M., and J. Neitz. 2000. Molecular genetics of color vision and color vision defects. p. 691–700. *In* L. Levin (ed.) Mechanisms of ophthalmic disease. Vol. 118. Am. Medical Assoc. Chicago, IL.

Norman, R.J., C.E. Wilson, Jr., B.R. Wells, S. Ntamatungo, N.A. Slayton, K.A. Gravois, and K.A.K. Moldenhauer. 1997. Management of agronomic factors in rice production. p. 169–177. *In* R.J. Norman and T.H. Johnston (ed.) B.R. Wells rice research studies. Res. Ser. 456. Arkansas Agric. Exp. Stn., Fayetteville.

Ntamatungiro, S., R.J. Norman, R.W. McNew, and B.R. Wells. 1999. Comparison of plant measurments for estimating nitrogen accumulation and grain yield by flooded rice. Agron. J. 91:676–685.

Ort, D., and S. Long. 2003. Converting solar energy into crop production. p. 262–264. *In* M. Chrispeels and D. Sadava (ed.) Plant, genes, and crop biotechnology. 2nd ed. Jones and Bartlett Publ., Sudbury, MA.

Purcell, L.C. 2000. Soybean canopy coverage and light interception measurements using digital imagery. Crop Sci. 40:834–837.

Saxton, A.M. 1998. A macro for converting mean separation output to letter groupings. p. 1243–1246. *In* Proc. Mixed. Proc. 23rd Annual SAS Users Group Int. Conf., Nashville, TN. 22–25 March. SAS Inst., Cary, NC.

Shukla, A.K., J.K. Ladha, V.K. Singh, B.S. Dwivedi, V. Balasubramanian, R.K. Gupta, S.K. Sharma, Y. Singh, H. Pathak, P.S. Pandey, A.T. Padre, and R.L. Yedav. 2004. Calibrating the leaf color chart for nitrogen management in different genotypes of rice and wheat in a systems approach. Agron. J. 96:1606–1621.

Stevens, G., and S. Hefner. 2001. Use of portable chlorophyll meter to manage crop nitrogen in rice. Ext. Bull. MP 729. Univ. of Missouri, Columbia.

Turner, F.T., and M.F. Jund. 1994. Assessing the nitrogen requirements of rice crop with a chlorophyll meter. Aust. J. Exp. Agric. 34:1001–1005.

Wells, B.R., and T.H. Johnston. 1970. Differential response of rice cultivars to timing of midseason nitrogen applications. Agron. J. 62:608–612.

Wells, B.R., R.J. Norman, R.S. Helms, and R.E. Baser. 1989. Use of plant measurement as a indication of midseason nitrogen fertilization. p. 45–48. *In* W.E. Sabbe (ed.) Arkansas soil fertility studies. 1988. Res. Ser. 385. Arkansas Agric. Exp. Stn., Fayetteville.