Published September 13, 2012

Soil Fertility & Crop Nutrition

In-Season Canopy Reflectance-Based Estimation of Rice Yield Response to Nitrogen

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ABSTRACT

A sensor-based approach to derive N recommendation based on crop needs and seasonal variation in yield potential and plant-available soil N requires an estimate of in-season rice (*Oryza sativa* L.) response to applied N. The objectives of this study were to: (i) determine if normalized difference vegetation index (NDVI) readings can be used to predict rice grain yield response to applied N and (ii) establish the relationship between NDVI-estimated response index (RI-NDVI) and measured response index at harvest (RI-YIELD). Sensor and yield data were collected from multiple N-rate trials from different locations in Louisiana and Mississippi from 2008 to 2010. The NDVI readings were collected using a ground-based active sensor at panicle initiation (PI), one (PI + 1 wk) and 2 wk (PI + 2 wk) after PI. Two sets of RI values were computed: (i) the ratio of the highest yielding N-fertilized plot to the check plot and (ii) ratio of N fertilized plots to the check plot. Across sampling dates, significant linear relationships were obtained between RI-NDVI and RI-YIELD ($P < 0.01$). The highest coefficient of determination value (r^2) obtained between estimated and measured RIs was obtained at PI + 1 wk ($r^2 = 0.63$). The quality of the models was improved when RI values were computed by comparing all variable rate N-fertilized plots to the check plot. Our results showed that RI-YIELD can be predicted using RI-NDVI measured within a 3-wk period starting at PI which is in synchrony with the schedule of topdress N application in mid-southern United States rice production systems.

The application of N fertilizer based on crop needs while accounting for both spatial and temporal variability in soil-plant N dynamics constitutes a logical approach to increase nitrogen use efficiency (NUE) in cereal crops (Shanahan et al., 2008). The pre-sidedress soil nitrate test (PSNT) and the alkaline-hydrolyzable nitrogen (A-HN), are reported useful to guide N recommendations (Kwon et al., 2009; Lory et al., 1995; Magdoff, 1991; Roberts et al., 2009). However, the effectiveness and practicality of soil test-based N recommendations is limited in production areas where within-field spatial variability in soil properties is high. Even if homogenous soil attributes within- and among-fields are observed, Schepers et al. (2004) and Lambert et al. (2006) noted that the overall crop performance, yield potential, and crop N demand can be influenced by weather-mediated variability.

With these known limitations of soil test-based N recommendations, many studies have been oriented toward the development of in-season crop diagnostic tools to facilitate N management decisions. Close range sensors that measure chlorophyll content and crop canopy reflectance have been successfully used for in-season diagnosis of plant N status and N fertilizer management of crops like wheat (*Triticum aestivum* L.) and corn (*Zea mays* L.) (Raun et al., 2002, 2005; Scharf et al., 2006; Tubaña et al., 2008; Varvel et al., 1997). Most of these previous studies used active sensors which generate its own light source. Active remote sensors are not dependent on changing ambient illumination (Souza et al., 2010) thus they are more appealing when it comes to developing field-oriented, precision N management technologies. Biermacher et al. (2006) evaluated the performance of a variable-rate N application system in wheat using an active sensor (GreenSeeker, Trimble Navigation Ltd., Sunnyvale, CA) as outlined by Raun et al. (2002) vs. uniform N application. The economic analysis they conducted, using N valued at \$0.55 kg^{-1}, showed that significant N savings were achieved by the sensor/variable-rate application system across 65 sites in the southern Plains Region of the United States. This sensor and variable-rate application system for cereal grain production in Europe and elsewhere were also reported to improve NUE, crop harvest ability and quality (Berntsen et al., 2006; Olfs et al., 2005; Schroder et al., 2000; Tremblay and Belec, 2006; Zillmann et al., 2006).

In rice production, the concept of using spectral properties of leaves via leaf color charts (LCC) and leaves' light transmittance measurement by chlorophyll SPAD meters as tools to guide in-season N management decisions was introduced in the late 1980's and early 1990's (Furuya, 1987; Jund and Turner, 1990; Peng et al., 1993). Following this progress, a similar approach to LCC was established by Peng et al. (1996) using a preset threshold SPAD value as a basis for a topdress N recommendation. Peterson et al. (1993) introduced

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Published in Agron. J. 104:1604–1611 (2012)
Posted online 5 Sept. 2012.
doi:10.2134/agronj2012.0214

Abbreviations: NDVI, normalized difference vegetation index; PD, panicle differentiation; PI, panicle initiation; RI, response index.

the concept of sufficiency index value, [(SPAD value of the target plot/SPAD value of well-fertilized N plot) × 100], to estimate mid-season N rice requirement. This approach recommends a certain rate of N fertilizer when the sufficiency index value is below a preset critical level (95%). In the mid-southern U.S. rice production region, Wells et al. (1989) developed the concept of plant area measurement with a rice gauge to predict mid-season N need. A similar concept was adopted by Stevens et al. (2008) who developed thresholds with the use of visual and digital image measurement to address the concern of the intensive labor requirement of the rice gauge method. Later, research has evaluated the use of remote sensors for non-invasive characterization of the rice canopy to facilitate instant, real-time acquisition of data. The use of remote sensing in rice has been focused mostly in monitoring N status and field-based estimation of biomass, leaf area index, and grain yield (Casanova et al., 1998; Chang et al., 2005; Harrell et al., 2011; Lee et al., 2008; Tubaña et al., 2011; Xue et al., 2004).

The algorithm behind the remote sensor/variable-rate N application system developed by Raun et al. (2002) assesses crop N requirement based on two in-season canopy reflectance based-crop parameters: (i) yield potential projected after crop establishment, and (ii) estimate of crop response to N fertilizer introduced by Johnson and Raun (2003) as RI. Pre-plant or early-season establishment of an N-rich plot, a section in a field that is well fertilized with N (rates are typically higher than the N recommended for the crop in the region), is required to determine RI. To implement this system in rice, these two canopy reflectance based-crop parameters need to be established. While they are very limited, earlier works have already established the concept that rice grain yield can be predicted early in the season using canopy reflectance readings (Chang et al., 2005; Harrell et al., 2011; Shibayama and Akiyama, 1991; Swain et al., 2010). However, the use of an in-season estimate of RI, using canopy reflectance to predict actual grain yield increases due to applied N, has not been pursued in rice. In this context, we conducted this study to (i) determine if mid-season canopy reflectance readings can be used to predict rice grain yield response to applied N and (ii) establish the relationship between RI-mid-season estimate and measured RI at harvest.

MATERIALS AND METHODS

This study was conducted from 2008 to 2010 using yield and sensor data collected from multiple N-rate trials in Louisiana and Mississippi. The trials within the study period covered six locations and three rice cultivars. Table 1 provides detailed information of the N rate trials used for this study including the preflood N rate treatments, soil series, and classification. Table 2 contains the information on rice cultivars and dates of field operations which included planting, sensor data collection, and harvesting. Locations in Louisiana included the Louisiana State University Agricultural Center Rice Research Station near Crowley (30°14'48'' N, 92°21'7'' W), Lake Arthur (30°02'47'' N, 92°38'46'' W), and Rayville (32°33'08'' N, 91°43'19'' W). Three locations in Mississippi were Mississippi State University Delta Research and Extension Center in Stoneville (33°25'56'' N, 90° 54'08'' W), Leland (32°33'08'' N, 91°43'19'' W), and Boyle (33°40'41'' N, 90°44'10'' W). For each trial, four replications of preflood N treatments were laid-out using a randomized complete block design.

Before rice establishment, composite soil samples were collected and analyzed for soil pH in a 1:1 (soil/water) suspension and extractable nutrients using Mehlich-3 extraction procedure. Phosphorus, K, and Zn were applied at rates recommended by soil testing as triple superphosphate (0–46–0), muriate of potash (0–0–60) and zinc sulfate (36% Zn). The soil pH in Crowley and Rayville sites ranged from 6.8 to 7.3 while soil in Stoneville site had an average pH value of 8.0 across years. The soil in Lake Arthur was classified as acidic (pH value = 4.5). The rice was established under a drill-seeded, delayed-flood production system. Rice was planted approximately in mid-March in Crowley and Lake Arthur, from between mid- to late April at Rayville and all locations in Mississippi. A small-plot grain drill equipped with double-disc openers and press wheels was used to plant rice seeds to a depth of 4 cm at a rate of 300 seeds m^{-2}. In each plot, seeds were planted in seven 4.9 m long rows with 20-cm row spacing. Broadcast application of fertilizer N treatments in the form of urea (46–0–0), using a dry fertilizer spreader, was done when rice seedlings were at 4- to 5-leaf stage of development. Permanent flooding was initiated the following day and maintained at a depth of approximately 15 to 20 cm. The whole plot was harvested using a plot combine equipped with a computerized weigh and moisture system. Rough grain yield was adjusted to a moisture content of 120 g kg^{-1}.

Collection of sensor data at three sampling times was pursued to cover a period where topdress N is commonly scheduled in rice: at PI, PI+1 wk, and PI+ 2 wk using a GreenSeeker handheld sensor. The sensor measured canopy reflectance

Table 1. Soil and preflood N rates of all the trials in Louisiana and Mississippi, 2008 to 2010.

Year	Site	Soil series	Soil classification	Preflood N rates
				kg N ha^{-1}
2008	Crowley, LA	Crowley silt loam	fine, smectitic, thermic Typic Albaqualfs	0, 34, 67, 101, 134, 168, 202, 235
2008	Rayville, LA	Perry clay	very fine, smectitic, thermic Chromic Epiaquerts	0, 34, 67, 101, 134, 168, 202, 235
2008	Stoneville, MS	Sharkey clay	very-fine, smectitic, thermic Chromic Epiaquerts	0, 34, 67, 101, 134, 168, 202, 235, 269
2009	Rayville, LA	Perry clay	very fine, smectitic, thermic Chromic Epiaquerts	0, 67, 101, 134, 168, 202, 235, 302
2009	Stoneville, MS	Sharkey clay	very-fine, smectitic, thermic Chromic Epiaquerts	0, 34, 67, 101, 134, 168, 202, 235, 269
2010	Crowley, LA	Crowley silt loam	fine, smectitic, thermic Typic Albaqualfs	0, 34, 67, 101, 134, 168, 202, 235, 269, 302
2010	Lake Arthur, LA	Kaplan silt loam	fine, smectitic, thermic Aeric Chromic Vertic Epiaqualfs	0, 67, 101, 134, 168, 202, 235, 302
2010	Stoneville, LA	Sharkey clay	very-fine, smectitic, thermic Chromic Epiaquerts	0, 67, 101, 134, 168, 202, 235, 269
2010	Leland, LA	Forestdale silt loam	fine, smectitic, thermic Typic Endoaqualfs	0, 67, 101, 134, 151, 168, 196, 202, 235, 269
2010	Boyle, LA	Sharkey clay	very-fine, smectitic, thermic Chromic Epiaquerts	0, 67, 101, 134, 168, 202, 235, 269

readings at red (670±10 nm) and near infrared (NIR, 780±10 nm) wavebands of the spectrum and transformed these readings to NDVI values. The NDVI is computed as the difference between the reflectance reading at the NIR and red wavebands divided by sum of the reflectance readings at these two wavebands. Sensor readings were taken from the middle section of the plots with a scanned width of 61 cm. The sensor head was placed parallel above the rice canopy with a distance of 1 m. Sensing was performed at a constant speed to obtain an average of 45 readings for each plot.

Johnson and Raun (2003) determined RI by dividing the highest yielding N-fertilized plots with the yield of the check plot, a plot which did not receive N fertilizer. For this study, the ratio of N-fertilized plot with the highest mean grain yield to the check plot's mean grain yield was computed and hereafter is termed RI-YIELD. The corresponding NDVI reading of the selected N-fertilized plot was used to determine estimate of RI using NDVI readings as outlined by Mullen et al. (2003) and hereafter is termed as RI-NDVI. In addition, another set of RI-YIELD and RI-NDVI data were computed considering the ratios of responses obtained from each of all preflood N rate in reference to the check plot. This procedure computed increases in grain yield and NDVI due to applied N for all rates. Regression analysis was performed for RI-NDVI and RI-YIELD using PROC REG in SAS (SAS Institute, 2002). The intercept, slope, adjusted coefficient of determination (r^2), and root mean square error (RMSE) generated from this analysis were recorded. The significance of the model ($P < 0.05$), r^2, and RMSE are among the criteria used to determine the regression model that can be used to predict RI-YIELD using RI-NDVI as predictor for each sampling time. The ANOVA was performed using PROC MIXED in SAS to test the effect of preflood N rate on rice grain yield for each site-year. To compare treatment means, the least square means test was performed using the LSMEANS PDIFF option. The N rate from which rice grain yield was maximized was designated as the N rate recommendation for that particular site-year (Table 3).

RESULTS AND DISCUSSION

The effect of preflood N, optimal N rate, grain yield, and coefficient of variation (CV) for 0- and N-fertilized plots for each site-year, and RI-YIELD are reported in Table 3. The absence of a rice yield response to applied N was observed only in 2010 at Lake Arthur, LA. The check plot for this site-year had the highest grain yield across site-years (10,101 kg ha^{-1}) and had the least benefit from N fertilization. The N-fertilized plot obtained an average grain yield of 10,191 kg ha^{-1} which was only 90 kg ha^{-1} larger than the check plot's yield. This suggests that rice growth and development was limited by growth factors other than N. The varietal, temporal, spatial, and across-site variability in this study resulted in a wide range of maximum yields, as estimate of yield potential or limitation. Girma et al. (2007a, 2007b) noted that among the contributors to large yield variability among sites include temperature and relative humidity.

The non-uniformity of plant stand observed in plots without N (0-N) as reflected by higher CV values than the N-fertilized plots, both in grain yield (Table 3) and NDVI readings (Table 4), maybe possibly be due to limited supply of indigenous N. Tiller production and appearance are affected by nutrient deficiencies (Black and Siddoway, 1977). Buresh et al. (1993) noted that N is required in large quantities in lowland rice production. The reduced number of tillers could be attributed to the inability of the last tillers to compete for light and nutrients eventually resulting to death (Fageria et al., 1997). With N being dynamic and the most limiting nutrient in rice production, uneven distribution of available soil N within plots could explain the non-uniform size of individual rice plants hence larger CV values. An earlier study by Fageria and Baligar (2001) reported that rice tillering was significantly affected by N fertilization.

Except for Lake Arthur site in 2010, results from the other site-years demonstrated that grain yield can be maximized with N fertilization even if they have an inherently low yield potential, which was described by Raun et al. (2002) as the yield achievable without N fertilization. The N rate recommendation values reported in Table 3 represent the actual N rate applied which

Table 2. Cultivars and dates of field activities for all sites in Louisiana and Mississippi, 2008 to 2010.

Year	Site	Variety	Planting date	Sensing date† PI‡	PI + 1wk	PI + 2wk	Harvest date
2008	Crowley, LA	Catahoula	25 Mar.	26 May	9 June	16 June	11 Aug.
2008	Crowley, LA	CL151	25 Mar.	26 May	9 June	16 June	13 Aug.
2008	Rayville, LA	CL151	25 Apr.	10 June	17 June	24 June	10 Sept.
2008	Rayville, LA	Neptune	25 Apr.	10 June	17 June	24 June	10 Sept.
2008	Stoneville, MS	Catahoula	21 Apr.	18 June	24 June	1 July	15 Sept.
2009	Rayville, LA	Catahoula	23 Apr.	22 June	29 June	6 July	26 Aug.
2009	Rayville, LA	CL151	23 Apr.	22 June	29 June	6 July	26 Aug.
2009	Rayville, LA	Neptune	23 Apr.	22 June	29 June	6 July	26 Aug.
2009	Stoneville, MS	Catahoula	22 Apr.	19 June	26 June	2 July	28 Aug.
2010	Crowley, LA	Catahoula	14 Mar.	25 May	1 June	8 June	6 Aug.
2010	Crowley, LA	CL151	14 Mar.	25 May	1 June	8 June	6 Aug.
2010	Crowley, LA	Neptune	14 Mar.	25 May	1 June	8 June	6 Aug.
2010	Lake Arthur, LA	CL151	15 Mar.	25 May	1 June	8 June	2 Aug.
2010	Stoneville, LA	Catahoula	28 Apr.	9 June	16 June	21 June	23 Aug.
2010	Leland, LA	Catahoula	13 Apr.	8 June	15 June	21 June	18 Aug.
2010	Boyle, LA	Catahoula	16 Apr.	15 June	20 June	28 June	25 Aug.

† The interval among sensing dates was approximately 1 wk or 5 to 7 d.
‡ Panicle initiation.

achieved the highest grain yield for each site-year ($P < 0.05$). Across years, there was no discernable pattern between N rate recommendation and highest mean grain yield. Rice grain yield potential in 2008 Crowley (Catahoula) was maximized at 13,258 kg ha^{-1} with an application rate of 235 kg N ha^{-1}, while in 2009 Rayville and 2010 Crowley (planted both to Neptune), grain yield was maximized with 101 kg N ha^{-1} (Table 3). The respective grain yields of check plots at these site-years were 3666, 9582, and 4452 kg ha^{-1}: the magnitudes of the increase in yields due to applied N were approximately 2.7, 0.4 and 1.9 times that of the check plots for 2008 Crowley (Catahoula), 2009 Rayville (Neptune), and 2010 Crowley (Neptune), respectively. It is important to note that the increase in yield of 0.4 and 1.9 times for 2009 Rayville and 2010 Crowley, respectively were achieved with the same N rate applied at 101 kg ha^{-1}. Johnson and Raun (2003) summarized RI over time from a long-term non-irrigated winter wheat field study in Oklahoma. They noted that apart from the fact that the magnitude of wheat grain yield response to N had no association with the amount of N applied (ranged from 45–112 kg N ha^{-1}), the temporal variability in RI was large and lacked any discernible pattern. This suggests that RI prediction based on previous year's measured RI-YIELD

Table 3. Significance of preflood N effect on rice, optimum N rate, and grain yield and response to N of rice for all sites in Louisiana and Mississippi, 2008 to 2010.

Year	Site	Variety	N effect	N recommendation†	0-N Grain yield	0-N CV	N-fertilized‡ Grain yield	N-fertilized‡ CV	RI-YIELD§
			$P > F$	kg N ha^{-1}	kg ha^{-1}	%	kg ha^{-1}	%	
2008	Crowley, LA	Catahoula	<0.001	235	3,666	21.7	13,258	2.3	3.62
2008	Crowley, LA	CL151	<0.001	168	3,356	15.3	11,226	6.5	3.34
2008	Rayville, LA	CL151	<0.001	202	4,149	19.9	9,721	6.6	2.34
2008	Rayville, LA	Neptune	<0.001	168	6,606	18.1	12,813	4.9	1.94
2008	Stoneville, MS	Catahoula	<0.001	235	3,798	19.4	10,280	6.1	2.71
2009	Rayville, LA	Catahoula	<0.001	134	6,790	14.4	10,066	7.4	1.48
2009	Rayville, LA	CL151	<0.001	67	8,485	11.7	11,415	4.7	1.34
2009	Rayville, LA	Neptune	<0.001	101	9,582	8.8	13,078	6.4	1.36
2009	Stoneville, MS	Catahoula	<0.001	269	4,450	6.1	9,490	4.1	2.13
2010	Crowley, LA	Catahoula	<0.001	168	4,380	14.3	11,987	5.3	2.74
2010	Crowley, LA	CL151	<0.001	202	5,576	11.0	12,521	3.7	2.25
2010	Crowley, LA	Neptune	<0.001	101	4,452	17.2	13,070	3.1	2.94
2010	Lake Arthur, LA¶	CL151	0.2897	–	10,101	7.1	10,191	5.9	1.01
2010	Stoneville, LA	Catahoula	<0.001	235	4,153	10.5	10,265	4.5	2.47
2010	Leland, LA	Catahoula	<0.001	202	4,618	10.7	10,610	11.0	2.30
2010	Boyle, LA	Catahoula	<0.001	134	4,680	9.4	10,760	5.3	2.30

† Nitrogen rate with the highest significant grain yield.

‡ Highest yielding N-fertilized plot.

§ Actual rice response index computed as grain yield of N-fertilized plot divided by the grain yield of 0-N plot.

¶ Nitrogen rate recommendation was not determined since rice had no response to N.

Table 4. Coefficient of variation (CV) values of normalized difference vegetation index (NDVI) readings from the check and highest yielding N-fertilized plots across all sites in Louisiana and Mississippi, 2008 to 2010.

Year	Site	Variety	PI† 0-N	PI† N-Fertilized‡	PI + 1 wk 0-N	PI + 1 wk N-Fertilized	PI + 2 wk 0-N	PI + 2 wk N-Fertilized
			CV, %					
2008	Crowley, LA	Catahoula	30.33	22.19	60.89	4.95	38.18	2.21
2008	Crowley, LA	CL151	38.67	5.01	56.76	7.90	31.14	4.63
2008	Rayville, LA	CL151	38.39	12.41	7.88	3.78	9.00	3.26
2008	Rayville, LA	Neptune	25.11	18.27	7.31	3.95	9.46	3.78
2008	Stoneville, MS	Catahoula	17.71	2.34	42.05	12.56	50.21	6.26
2009	Rayville, LA	Catahoula	15.44	3.77	19.00	7.07	5.70	3.44
2009	Rayville, LA	CL151	16.81	5.45	24.45	8.87	12.00	8.67
2009	Rayville, LA	Neptune	12.53	4.27	22.65	13.93	22.62	6.06
2009	Stoneville, MS	Catahoula	10.31	2.34	13.14	1.99	4.88	1.80
2010	Crowley, LA	Catahoula	36.76	14.36	24.54	7.75	31.72	2.44
2010	Crowley, LA	CL151	19.78	2.72	25.78	4.31	25.01	2.03
2010	Crowley, LA	Neptune	20.55	6.71	23.24	3.14	21.08	3.50
2010	Lake Arthur, LA	CL151	3.70	2.51	14.20	1.32	–	–
2010	Stoneville, LA	Catahoula	–	–	36.76	13.79	16.70	2.88
2010	Leland, LA	Catahoula	5.98	1.35	14.14	1.05	12.30	1.23
2010	Boyle, LA	Catahoula	30.30	16.09	8.20	3.21	8.52	1.74

† Panicle initiation.

‡ NDVI reading from the significantly highest yielding N-fertilized plot.

would be unreliable. The variability in-field and in-season can be accounted with RI prediction computed from NDVI readings collected during the growing season (Mullen et al., 2003; Raun et al., 2005). This approach requires the establishment of a well-fertilized N plot within a target field every cropping season. Therefore, in principle, the RI computed from NDVI readings collected from a well-fertilized N plot and a target plot is calibrated for that specific growing season since a dynamic comparison is made between two plots within the same field condition. Peterson et al. (1993) reported similar advantage of using well-fertilized N strip as a point of reference for a preset SPAD threshold values to determine topdress N rates in rice.

The NDVI readings collected from the check plot (0-N) and the highest yielding N-fertilized plots at PI, PI + 1 wk, and PI + 2 wk are reported in Table 5. The RI-NDVI, the ratio of NDVI readings from the highest yielding N-fertilized plot to the check plot, was determined for each sampling date. For each sampling date, the RI-NDVI values across site-years were regressed with the RI-YIELD values. The results of the linear regression analysis for RI-NDVI and RI-YIELD using the highest yielding plot and all variable rate N-fertilized plots at different sensing times are presented in Fig. 1 and 2, respectively. The RI-NDVI for all sensing dates presented significant linear relationships with RI-YIELD ($P < 0.01$).

Using the highest yielding N-fertilized plot to compute RI, the variability in RI-YIELD can be best explained by RI-NDVI determined at PI + 1 wk ($P < 0.001$). When compared with PI + 1 wk ($r^2 = 0.59$), lower r^2 values were obtained by RI-NDVI determined at PI ($r^2 = 0.44$) and PI + 2 wk ($r^2 = 0.39$). In addition, considering the RMSE value, the overall quality of the regression model was also best achieved with RI-NDVI measured at PI + 1 wk (Fig. 1). The RMSE value measures goodness of fit of the linear line to the data points. The general interpretation follows that the lower the values, the better the quality of the model. When RI for each of all N-fertilized plots was used to establish the relationship of RI-YIELD and RI-NDVI (Fig. 2), similar r^2 values across sensing dates (0.52, 0.49, and 0.43) was obtained with lower RMSE values compared with RI computed from the highest yielding N-fertilized plot. While the RI-NDVI measured at all sampling times correlated with RI-YIELD ($P < 0.01$), it is important to note that there were also observable deviations of some data points from the regression models (Fig. 1 and 2). These represent those instances that RI-NDVI either over- or underestimated RI-YIELD as also reported by Chung et al. (2010). This is a recognized limitation of RI-NDVI as an estimate of RI-YIELD. The magnitude of difference between RI-NDVI and RI-YIELD is dependent on the occurrence of yield enhancing and limiting factors postsensing (Mullen et al., 2003).

The slopes and intercepts of the linear models between the two RI computations, that is, highest yielding N-fertilized vs. all variable rate N-fertilized plots, are similar. The RI-YIELD predictions were evaluated using a hypothetical RI-NDVI value of 2.0. With this RI-NDVI value at PI, the predicted RI-YIELD using the model established with RI computed from the highest yielding N-fertilized plot would be 2.3 (RI-YIELD = 0.913 × RI-NDVI + 0.449, Fig. 1a.). The model established with RI using all N-fertilized plots (RI-YIELD = 0.862 × RI-NDVI + 0.306, Fig. 2a.) would predict an RI-YIELD value of 2.0. Comparable estimates of RI-YIELD were obtained using the two groups of linear models for PI + 1 wk (2.1 vs. 1.9) and PI + 2 wk (2.4 vs. 2.2). Hypothetically, the estimate of RI-YIELD subtracted from 1 then multiplied by 100 is equivalent to the percentage increase in grain yield achievable with additional N. Thus for an RI-YIELD estimate of 1.9, the predicted increase in grain yield is 90%.

Overall, NDVI readings within the 3-wk period from the onset of PI were able to detect differences in rice biomass response to different preflood N application rates. An earlier study by Chang et al. (2005) showed that a predictive model for rice can be developed using canopy reflectance readings collected as early as the beginning of panicle formation. Bajwa et al. (2010) reported that plant N accumulation, tissue N

Table 5. Normalized difference vegetation index (NDVI) readings from check and N-fertilized plots, and response index values at panicle initiation (PI), 1 and 2 wk after PI across all sites in Louisiana and Mississippi, 2008 to 2010.

			NDVI at PI			NDVI at PI + 1 wk			NDVI at PI + 2 wk		
Year	Site	Variety	0-N	N-Fertilized†	RI‡	0-N	N-Fertilized	RI	0-N	N-Fertilized	RI
2008	Crowley, LA	Catahoula	0.268	0.583	2.18	0.210	0.824	3.92	0.378	0.794	2.10
2008	Crowley, LA	CL151	0.232	0.814	3.51	0.165	0.786	4.76	0.278	0.807	2.90
2008	Rayville, LA	CL151	0.267	0.720	2.70	0.536	0.756	1.41	0.491	0.758	1.54
2008	Rayville, LA	Neptune	0.417	0.680	1.63	0.557	0.730	1.31	0.508	0.742	1.46
2008	Stoneville, MS	Catahoula	0.362	0.827	2.28	0.210	0.808	3.85	0.245	0.865	3.53
2009	Rayville, LA	Catahoula	0.453	0.747	1.65	0.558	0.766	1.37	0.511	0.836	1.64
2009	Rayville, LA	CL151	0.465	0.790	1.70	0.465	0.773	1.66	0.536	0.832	1.55
2009	Rayville, LA	Neptune	0.517	0.746	1.44	0.490	0.749	1.53	0.577	0.808	1.40
2009	Stoneville, MS	Catahoula	0.523	0.878	1.68	0.498	0.872	1.75	0.658	0.869	1.32
2010	Crowley, LA	Catahoula	0.270	0.655	2.41	0.372	0.770	2.07	0.432	0.785	1.82
2010	Crowley, LA	CL151	0.338	0.794	2.35	0.329	0.813	2.47	0.394	0.781	1.98
2010	Crowley, LA	Neptune	0.323	0.597	1.85	0.407	0.744	1.83	0.352	0.733	2.08
2010	Lake Arthur, LA	CL151	0.723	0.833	1.15	0.694	0.852	1.23	–	–	–
2010	Stoneville, LA	Catahoula	–	–	–	0.286	0.804	2.81	0.420	0.806	1.92
2010	Leland, LA	Catahoula	–	–	–	0.280	0.792	2.83	0.458	0.846	1.85
2010	Boyle, LA	Catahoula	0.521	0.855	1.64	0.460	0.860	1.87	0.587	0.828	1.41

† NDVI reading from the highest yielding N-fertilized plot.

‡ Estimated response index computed as the NDVI readings of N-fertilized plot divided by NDVI readings of 0-N plot.

content, biomass, and chlorophyll had strong and significant responses to preflood N treatment within 3 wk of internode elongation. Further, these indicators of N status in rice were found to be related to several vegetation indices computed from canopy reflectance readings at 937 and 718 nm wavelengths. Xue et al. (2004) also attributed the observed spectral variations in rice canopy to differences in leaf N concentration, LAI, and biomass brought about by differences in N nutrition. Perhaps these previous findings can explain the moderate positive relationships observed between RI determined using estimate of green biomass (RI-NDVI) and measured response of rice using grain yield (RI-YIELD) across the three sampling dates. While our results showed that RI-NDVI can be a reliable estimate of in-season RI-YIELD, Mullen et al. (2003) noted that using RI-NDVI is not the sole basis to determine mid-season N. To calculate realistic in-season estimates of

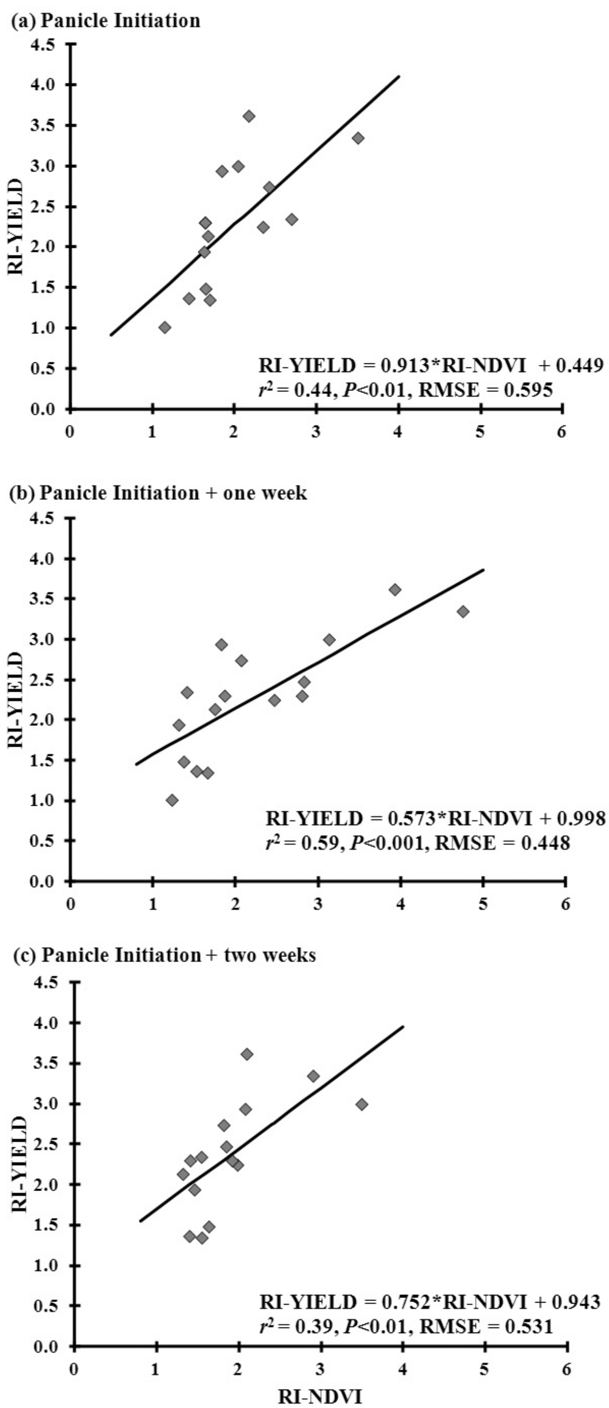

Fig. 1. Relationship between normalized difference vegetation index-estimated response index (RI-NDVI) and response index at harvest (RI-YIELD) at (a) panicle initiation, (b) 1 wk, and (c) 2 wk after panicle initiation using RIs determined by comparing the highest yielding N-fertilized plot to the check plot

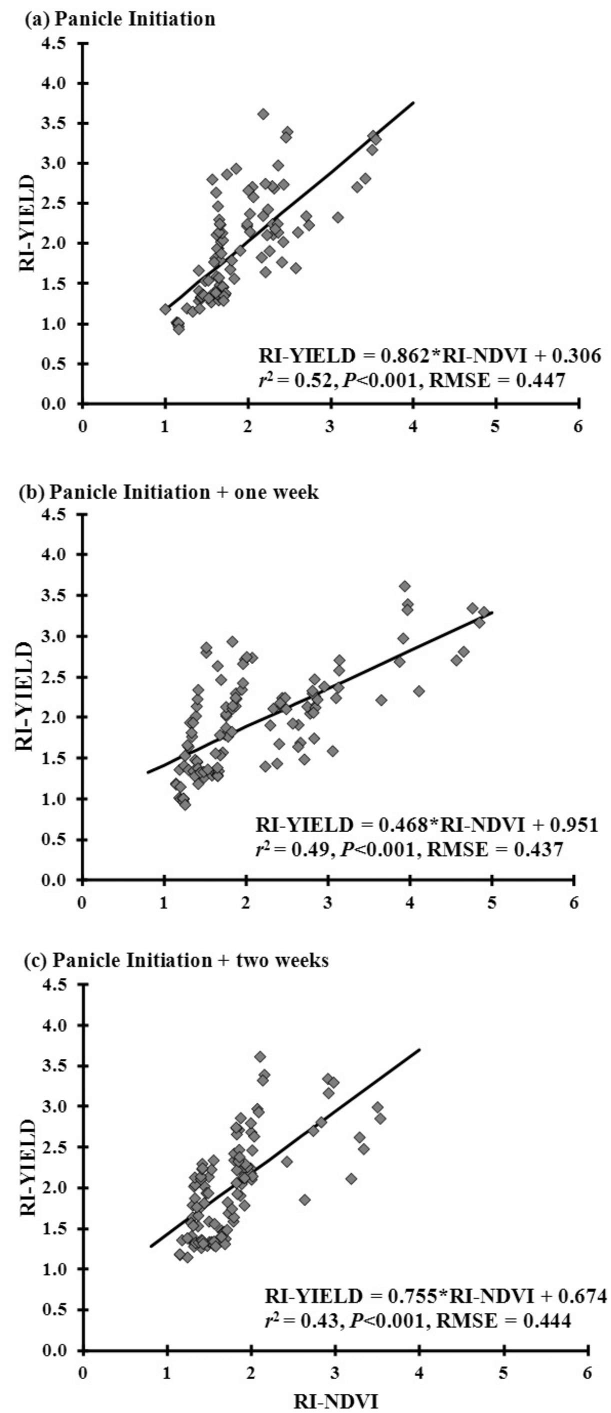

Fig. 2. Relationship between normalized difference vegetation index-estimated response index (RI-NDVI) and response index at harvest (RI-YIELD) at (a) panicle initiation, (b) 1 wk, and (c) 2 wk after panicle initiation using RIs determined by comparing each of all N-fertilized plots to the check plot.

N rate, both estimates of yield potential and RI should be considered in the computation (Lukina et al., 2001; Raun et al., 2002). The models for RI-YIELD predictions were established from RI-NDVI collected within 3 wk from the onset of PI. Early panicle formation is the most critical period that affects grain yield. In addition, this period also coincides with the time where topdress N is commonly applied in rice production. In the mid-southern United States, N is generally applied in two split applications; the first application is done before flooding and the second application, or topdress, is done when rice is at the PI to PD growth stages (Bollich et al., 1994; Wilson et al., 1998).

CONCLUSIONS

The present study demonstrated that RI-NDVI determined at PI and up to 2 wk after PI can be used to estimate RI-YIELD, defined as the actual response of rice grain yield to applied N. Two sets of RI values were computed: (i) ratio of the highest yielding N-fertilized plot to the check plot, and (ii) ratio of N-fertilized plots to the check plot. For both sets of RI values, the regression analysis showed that there were significant linear relationships between RI-NDVI and RI-YIELD across sensing timings. Using a hypothetical RI-NDVI value, the models that were established using the two sets of RI values generated comparable estimates of RI-YIELD. The quality of the linear models was improved when RI values were computed by comparing each of all N-fertilized plots to the check plot. Our study also showed that RI-YIELD predictions using RI-NDVI can be done within the 3-wk period from PI which is in synchrony with the schedule of topdress N application in the mid-southern U.S. rice production systems.

ACKNOWLEDGMENTS

This research was funded by the Louisiana Rice Research Board, Mississippi Rice Promotion Board, The Rice Foundation, and International Plant Nutrition Institute.

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