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Recommendation of Nitrogen Topdressing Rates at Panicle Initiation Stage of Rice Using Canopy Reflectance

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Abstract

The response of grain yield (GY) and milled-rice protein content (PC) to crop growth status and nitrogen (N) rates at panicle initiation stage (PIS) is critical information for prescribing topdress N rate at PIS (Npi) for target GY and PC. Three split-split-plot experiments including various N treatments and rice cultivars were conducted in Experimental Farm, Seoul National University, Korea in 2003-2005. Shoot N density (SND, g N in shoot m^{-2}) and canopy reflectance were measured before N application at PIS, and GY, PC, and SND were measured at harvest. Data from the first two years (2003-2004) were used for calibrating the predictive models for GY, PC, and SND accumulated from PIS to harvest using SND at PIS and Npi by multiple stepwise regression. After that the calibrated models were used for calculating N requirement at PIS for each of nine plots based on the target PC of 6.8% and the values of SND at PIS that was estimated by canopy reflectance method in the 2005 experiment. The result showed that SND at PIS in combination with Npi were successful to predict GY, PC, and SND from PIS to harvest in the calibration dataset with the coefficients of determination (R^2) of 0.87, 0.73, and 0.82 and the relative errors in prediction (REP, %) of 5.5, 4.3, and 21.1%, respectively. In general, the calibrated model equations showed a little lower performance in calculating GY, PC, and SND in the validation dataset (data from 2005) but REP ranging from 3.3% for PC and 13.9% for SND accumulated from PIS to harvest was acceptable. Nitrogen rate prescription treatment (PRT) for the target PC of 6.8% reduced the coefficient of variation in PC from 4.6% in the fixed rate treatment (FRT, 3.6g N m^{-2}) to 2.4% in PRT and the average PC of PRT was 6.78%, being very close to the target PC of 6.8%. In addition, PRT increased GY by 42.1 g m^{-2} while Npi increased by 0.63 g m^{-2} compared to the FRT, resulting in high agronomic N-use efficiency of 68.8 kg grain from additional kg N. The high agronomic N-use efficiency might have resulted from the higher response of grain yield to the applied N in the prescribed N rate treatment because N rate was prescribed based on the crop growth and N status of each plot.

Key words: Nitrogen, canopy reflectance, rice, yield, protein, prescription

Introduction

Nitrogen fertilizer requirement, N-use efficiency, and grain yield (GY) were reported to be highly dependent on crop growth and nutrition status of rice before N application (Feibo et al. 1998; Hussain et al. 2000; Miyama 1998; Nguyen 2005; Singh et al. 2002; Yang et al. 2003). The variation in growth and nutrition status at various growth stages of cereal crops was caused by spatial and temporal variation in soil properties (Casanova et al. 1999; Dobermann 1994, Dobermann et al. 1995; Nguyen 2005; Yanai et al. 2000) and crop population and management (Casanova et al. 2002; Dobermann 1994). As a result, uniform N application for rice without consideration of crop growth and N nutrition status in a field may result in over-fertilizer application in some locations but nutrient deficiency in others. Excessive N fertilization has been reported as a cause of environmental pollution (Booltink et al. 2001; Verhagen 1997) while N deficiency restricted crop growth and yield (Kim 2004; Miyama, 1998; Nguyen 2005; Yang et al. 2003).

Spatial variation in soil properties has been studied and considered for prescribing N topdressing amount in upland crops,

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for example, corn and potatoes (Delin et al. 2005; Verhangen 1997) and lowland rice crop (Miyama 1998; Nguyen 2005). However, some authors indicated that soil properties, even some stable properties such as soil organic mater, texture, bulk density, and CEC varied considerably from season to season of a year, and from year to year (Cassman et al. 1996a, 1996b; Dobermann 1994; Mohanty et al. 2004). In similar perspective, climate conditions (Kroff et al. 1994) and crop management techniques (Casanova et al. 2002; Dobermann 1994) significantly affecting crop growth and nutrition varied unavoidably from year to year in the same field. Therefore, crop growth and nutrition status could be an ideal indicator for the fertilizer prescription reflecting both spatial and temporal variation in soil, climate, and management techniques (Dobermann et al. 2002; Peng et al. 1996).

Recently, the real-time prescription of N requirement based on crop growth and N status have received a great deal of attention in rice production (Dobermann et al. 2002; Peng et al. 1996; Singh et al. 2002; Yang et al. 2003). They found that the higher rice yield and N recovery efficiency were obtained in the plant-based N prescription treatment by chlorophyll meter (SPAD meter) than in the fixed N rate treatment (Dobermann et al. 2002; Feibo et al. 1998; Hussain et al. 2000; Singh et al. 2002). However, characterizing crop N status by chlorophyll meter was a simple but time-consuming method and difficult to extend to a large scale.

So far various crop variables related to crop physiology and biochemistry such as LAI, plant N concentration, N uptake, and chlorophyll content have been reliably predicted by remote sensing techniques (Casanova et al. 1998; Diker and Bausch 2003; Hansen and Schjoerring 2003; Hinzman et al. 1986; Takebe et al. 1990). These techniques have provided a fast, non-destructive and relatively inexpensive characterization of crop status and have had a high benefit when applied at regional levels. Therefore, over the past several decades, remote sensing techniques have been used increasingly for crop monitoring and yield prediction. Studying hyperspectral remote sensing technique with hand-held equipment for crop characterization at field scale would lend support for extending to a large-scale application by using satellite or aerial remote sensing image (Casanova et al. 1998).

Relationship between milled-rice protein content (PC) and grain quality has been reported by Ishima et al. (1974) and Taira (1995). Chikubu et al. (1985) measured PC and palatability of cooked rice by five parameters (appearance, aroma, taste, stickiness, and hardness) and found that PC had a negative correlation coefficient with appearance (-0.42), aroma (-0.35), taste (-0.43), and stickiness (-0.44), and a positive correlation coefficient with hardness (0.41). Similarly, Ishima et al. (1974) found a high negative correlation between PC in polished rice and taste evaluation score. In general, the higher the PC, the lower the rice-eating quality.

The effect of applied N rates at PIS (Npi) in relation to crop growth and N nutrition status at PIS on grain yield (GY) and PC have been reported by Kim (2004) and Nguyen (2006). They found that applied N rates up to 7.2 g m^{-2} at PIS highly significantly increased rice GY and PC significantly while high SND at PIS showed a positive correlation with GY but a negative correlation with PC due to dilution effect. Therefore, our objectives were (1) to calibrate models for N rate prescription based on SND at PIS for target GY and PC and (2) to test the prescribed N rate at PIS for target GY and PC by the calibrated models in combination with the predicted SND at PIS by hyperspectral canopy reflectance.

Materials and methods

Site description and experimental design

Three experiments, in 2003, 2004, and in 2005, were conducted on a paddy field of 3,000 m^2 at the Experimental Farm (37°16'N, 126°59'E) of Seoul National University, Suwon, Korea. The field had a soil texture of sandy clay loam, CEC of 11.9 cmol$^{(+)}$ kg^{-1}, organic matter of 14.4 mg g^{-1}, total N of 0.75 mg g^{-1}, and pH of 5.4. The experiment in 2003 included ten nitrogen (N) treatments and four rice cultivars; the experiment in 2004 included 12 N treatments and two rice cultivars, and the

Table 1a. Design of the 2003 experiment.

Treatment	N rates[a] at transplanting	N rates at tillering stage	N rates at PIS	Rice cultivar[b]
1	0	0	0	V1, V2, V3, V4
2	4.8	0	0, 3.6, 7.2	V1, V2, V3, V4
3	4.8	36	0, 3.6, 7.2	V1, V2, V3, V4
4	4.8	72	0, 3.6, 7.2	V1, V2, V3, V4

[a]Applied N (g m^{-2}), [b]V1-V4 were Hwaseongbyeo, SNU-SG1, Juanbyeo, and Surabyeo, respectively

Table 1b. Design of the 2004 experiment.

Treatment	N rates[a] at transplanting	N rates at tillering stage	N rates at PIS	Rice cultivar[b]
1	4.8	0, 3.6, 7.2	0	V1, V5
2	4.8	0, 3.6, 7.2	3.6	V1, V5
3	4.8	0, 3.6, 7.2	Variable N rates[c]	V1, V5
4	4.8	0, 3.6, 7.2	Variable N rates	V1, V5

[a]Applied N (g m^{-2}), [b]V1 and V5 were Hwaseongbyeo and Daeanbyeo, respectively.
[c]N rate at PIS for treatment 3 and 4 was 1.5 1± 1.67 and 1.50 ± 1.38 g m^{-2}, respectively.

Table 1c. Design of the 2005 experiment.

Treatment	N rates[a] at transplanting	N rates at tillering stage	N rates at PIS	Rice cultivar[b]
1	4.8	0, 3.6, 7.2	0	V1, V5
2	4.8	0, 3.6, 7.2	3.6	V1, V5
3	4.8	0, 3.6, 7.2	Prescribed N rate[c]	V1, V5

[a]Applied N (g m^{-2}), [b]V1 and V5 were Hwaseongbyeo and Daeanbyeo, respectively.
[c]Details for prescribed N rate at PIS for treatment 3 by canopy reflectance are presented in the next section.

experiment in 2005 included nine N treatments and two rice cultivars. The details of experimental design are presented in Tables 1a-c.

It is noted from Table 1b that the purpose of variable N rate treatments (3 and 4) in the 2004 experiment was to make the testing N rate wider and more variable for calibrating models to calculate crop variables in the 2005 experiment. The word PIS here was defined as a common date for N application at PIS in Korea (24 days before heading). The experiment was a split-split-plot design in which N rates at tillering stage and PIS, and rice varieties were randomly assigned into main plots, sub plots, and sub-sub plots, respectively. Plot size was 24 m^2 in 2003 and 30 m^2 in 2004 and 2005. Rice was transplanted manually at hill spacing of 0.15 x 0.30 m with three seedlings per hill on the 20th May in 2003, the 23rd May in 2004, and the 30th May in 2005. The whole experimental field was applied with the same amount of 8.0 g P_2O_5 + 4.8 g K_2O m^{-2} at transplanting and 2.4 g K_2O m^{-2} at panicle initiation stage. The other management techniques for the whole field such as land preparation, weeding, water supplies, etc. were applied homogenously based on the standard cultivation practices in Korea.

Measurement of canopy reflectance and crop variables

At PIS, canopy reflectance of the rice crop was recorded using a GER 1500 spectroradiometer (GER 1500, GER Inc. USA) with a field of view (FOV) of 15° in 2003 and 20° in 2004 and 2005. The reason for changing FOV from 15° to 20° was due to the fact that FOV of 20° was potentially better but not available in 2003. The spectral measurement range was from 300 to 1100 nm with spectral resolution of 1.55 nm. For each measurement, eight scans were performed and the spectral data were averaged over the scans. The sensor was held approximately 2.0 m above the ground by hand in year 2003 and by frame in years 2004 and 2005 at nadir position. The spatial coverage on the ground was about 2,170 cm^2 for the sensor with FOV of 15° (in 2003) and 3,900 cm^2 for the sensor with FOV of 20°. The measurements were conducted under a clear and cloudless sky between 11:00 to 13:00 local time (GMT + 9) at the time estimated as close to the panicle initiation stage of each year as possible. The real dates of canopy reflectance measurement were 19 July in 2003, 22 July in 2004, and 21 July in 2005. Prior to each plant reflectance measurement, reflectance of a white standard panel coated with $BaSO_4$ was taken. The spectroradiometer automatically calculated the percent canopy reflectance by dividing the canopy sample reflectance by the reflectance of white standard panel. Immediately after canopy reflectance measurement, five rice hills at the location for canopy reflectance measurement were sampled on the same day of canopy reflectance measurement. The sampled plants were dried at 70 °C to a constant weight. The dried samples were weighed, ground, and analyzed for total N by Kejeltec Auto 1035 System (Tecator, Sweden). The values obtained were then used for calculating SND (g N in shoot m^{-2}).

At harvest dates (12 October in 2003, 16 October in 2004, and 9 October in 2005), one sample of 72 rice hills per plot was collected for GY (g m^{-2}) and shoot dry weight (g m^{-2}), shoot and milled-rice N concentration (Kejeltec Auto 1035 System, Tecator, Sweden) measurements. Shoot N concentration and shoot dry weight were used for SND calculation while milled-rice N concentration (%) was converted into milled-rice protein content (%) by multiplying the conversion factor of 5.95.

Data pretreatment

Before data analysis, the whole data from three years were pretreated for outlier detection. Because sampling size for plant growth and N status measurement at PIS was small (5 hills per plot), it was expected to contain a significant source for noises and outliers. To detect outliers from the dataset, we used stepwise multiple regression models for yield prediction by applied N rates (linear and quadratic) and SND measured at PIS (linear and quadratic). Because grain yield was measured from a big sample (72 hills per plot) so as to be reliable and N rates at PIS was carefully controlled, 12 observations with a missing values or high studentized residual values (higher than 3 or smaller than -3) were excluded from the dataset as outliers.

Model calibration for variable nitrogen rate prescription

Data collected from three years (2003-2004) were pooled by block for reducing noise before quantifying the relationship between crop variables at PIS and grain yield and protein content using PROC STEPWISE default of 0.05 probability level for independent variable selection in SAS 8.1 version (SAS Institute Inc., 1999-2000). Shoot N density accumulated from PIS to harvest was predicted by SND and applied N rates at PIS while GY and PC were predicted by SND measured at PIS and SND accumulated from PIS to harvest. The close relationship between GY and PC with SND measured at PIS (Cui and Lee 2002; Kim 2004; Nguyen 2005; Nguyen 2006) and shoot biomass and N accumulation from PIS to harvest (Ishii 1995; Kumura 1995; Nguyen 2006) was intensively reported. After that SND measured at PIS before N application and applied N rates at PIS was used as independent variables for prediction of SND accumulated from PIS to harvest. Shoot N density at PIS could be precisely predicted by canopy reflectance methods (Hansen and Schjoerring 2003; Nguyen and Lee 2004) while the intercept and the parameter estimate of applied N rate in the predictive equation of SND accumulated from PIS to harvest could be considered as the natural N supply from PIS to harvest and the recovery efficiency of the applied N, respectively, enabling the extension of the equation to the other environment if its natural soil supply and N recovery efficiency were known. After this step, the calibrated models by data from years 2003 and 2004 were ready for N topdressing rate prescription at PIS in year 2005.

Model validation and application for N topdressing rate prescription at PIS in 2005

Model validation

The calibrated model equations were used for calculating GY, PC, and SND accumulation from PIS to harvest using crop parameters measured at PIS of year 2005 experiment. The per-

Table 2. Crop statistics and correlation among crop variables in the calibration dataset (n = 81).

Crop variables[a]	Crop statistics					Correlation coefficient (r)			
	Unit	Mean	CV (%)	Min	Max	Yield[b]	Protein	HSND	PHSND
Yield	g m^{-2}	645	15.6	359	846	1			
Protein	%	6.8	8.5	5.9	8.3	0.11^{NS}	1		
HSND	g m^{-2}	10.5	21.0	5.4	14.7	0.88***	0.42***	1	
PHSND	g m^{-2}	5.2	49.6	0.2	10.5	0.39***	0.78***	0.63***	1
PSND	g m^{-2}	5.3	39.2	1.7	9.4	0.46***	-0.52***	0.27**	-0.57***
Npi	g m^{-2}	2.4	100.0	0.0	7.2	0.49***	0.82***	0.70***	0.81***

[a] Yield, protein, and HSND were grain yield, milled-rice protein content ,and shoot N density measured at harvest. PHSND was shoot N accumulation from PIS to harvest. PSND and Npi were shoot N density and applied N rate at PIS.

[b] NS, *, **, *** indicated non-significant, significant at probability levels of 0.05, 0.01, and 0.001, respectively.

formance of the calibrated models was evaluated by the coefficient of determination (R^2) and the root mean square error in prediction (RMSEP) that is an indicator of the average error in the analysis expressed in original measurement unit. RMSEP was calculated by Eq. (1):

$$\text{RMSEP} = \left[\frac{1}{n} \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \right]^{0.5} \tag{1}$$

where y_i and $\hat{y}_i$ were actual and calculated values of crop parameters at harvest (GY, PC, and SND accumulation from PIS to harvest), respectively, and n was number of samples in the dataset. Another useful parameter was the relative error of prediction (REP) that shows the predictive ability of the model and calculated by Eq. (2):

$$\text{REP}\,(\%) = \frac{100}{\bar{y}} \left[\frac{1}{n} \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \right]^{0.5} \tag{2}$$

Similar to Eq. 1, y_i and $\hat{y}_i$ were actual and calculated values of crop parameters, respectively, and n was number of sample in dataset and $\bar{y}$ was mean of the actual values of crop variables.

Model application for N topdressing rate prescription

The calibrated models which showed the interrelationship among crop parameters at PIS and harvest and rates of applied N at PIS were used for calculating required N rate for target GY and PC of a rice cultivar, Hwaseongbyeo (V1) at given values of SND that was calculated by canopy reflectance at PIS. The performance of N prescription treatment was evaluated by comparing the treatment means of GY and PC with those of the fixed N rate of 3.6 g m^{-2} applied at PIS as commonly recommended in Korea and control treatments with no N.

The SND at PIS was predicted by hyperspectral canopy reflectance and partial least square regression (PLS) as proposed by Nguyen and Lee (2006). Briefly, the PLS regression model for SND calculation by hyperspectral canopy reflectance data was formulated using the SND and corresponding canopy reflectance data measured from each plot at PIS in 2003 and 2004. The SND of each plot in 2005 was calculated by the formulated PLS model with hyperspectral canopy reflectance measured from the same plot.

Results and Discussion

Descriptive crop statistics and correlation among crop variables in calibration set

Descriptive statistics of crop variables in year 2003 and 2004 (Table 2) indicated that the average GY and PC over two years (2003 and 2004) were 645 g m^{-2} and 6.8%, respectively. The variation in PC was smaller (8.5%) compared to the variation in GY (15.6%). There was higher variation in SND at PIS and SND accumulation from PIS to harvest than the variation in SND at harvest. Although SND at harvest had the highest correlation with grain yield (r = 0.88), it had low correlation with protein content (r = 0.42). The lower linear correlation between SND at PIS with GY and PC may result from their nonlinear relationship and different response of GY and PC to SND at PIS at different N rates applied at PIS (Fig. 1). We may obtain high linear correlation (r = 0.78) between PC and SND accumulated from PIS to harvest that was calculated by subtracting SND at PIS from SND at harvest (Table 2). Low linear correlation between the applied N rates at PIS and GY may also result from the quadratic effect of N fertilizer rates on GY as discussed by Kim (2004) and Nguyen (2006).

Model calibration

Because grain yield and milled-rice protein content and nitrogen accumulated from PIS to harvest responded curve-linearly to SND at PIS but differently at different N rates applied at PIS as discussed in the previous section, we used stepwise multiple linear regression procedure to quantify interrelationship among crop variables and predict GY, PC, and SND accumulation from PIS to harvest by SND and the applied N rates at PIS (Table 3). In general, multiple regression model using SND and the applied N rates at PIS explained 82% of the variation in SND accumulation from PIS to harvest and multiple regression models using SND measured at PIS and SND accumulation from

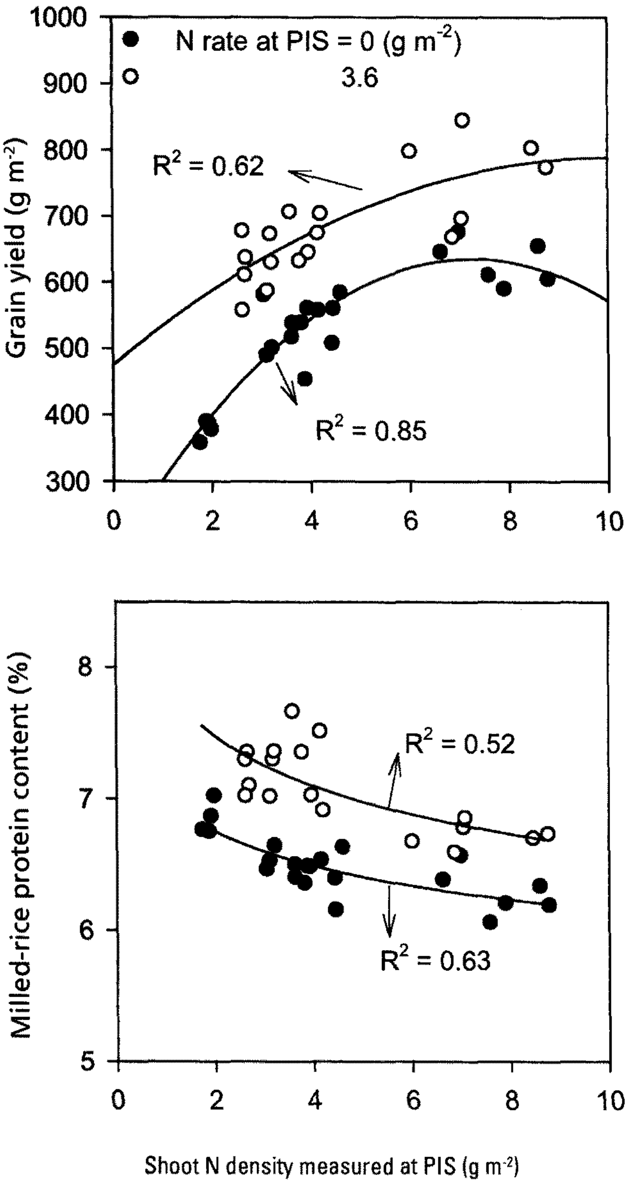

Fig. 1. Non-linear relationship between shoot N density measured at PIS and grain yield and milled-rice protein content in 2003 and 2004.

PIS to harvest explained 87 and 73% of the variation in GY and PC, respectively. The predictive model for SND accumulation from PIS to harvest (Eq. 3) indicated that shoot N accumulation from PIS to harvest responded curve-linearly to SND measured at PIS. The average N recovery efficiency of the applied N at PIS was about 69.2% and the natural soil N supply rate (N uptake from soil) from PIS to harvest was about 3.31 g m^{-2}. The average N recovery efficiency of 69.2% and the natural soil supply of 3.31 g m^{-2} from PIS to harvest determined by multiple stepwise regression in our two-year experiment (2003-2004) were quite similar to those of 66.3% and 3.60 g m^{-2} determined from the experiment conducted in the same field in year 2001-2002 with Hwaseongbyeo rice cultivar as reported by Kim (2004). The average N recovery efficiency of the applied N at PIS from our experiment was also higher than that ranging from 33 to 61% in Bangladesh as reported by Timsina et al. (2001) and 57.1% in Thailand as reported by Ohnishi et al. (1999). Timsina et al. (2001) found that N recovery efficiency was different from two rice cultivars and higher under irrigation than rainfed.

Table 3. Stepwise multiple regression models to predict grain yield, milled-rice protein, and shoot N accumulation from PIS to harvest.

Equations for yield[a], protein and PHSND prediction		R^2
$PHSND = 3.31 + 0.692Npi + 0.678PSND - 0.105PSND^2$	(Eq. 3)	0.82
$Yield = 75.4 + 82.57PSND - 2.96PSND^2 + 56.31PHSND - 1.92PHSND^2$	(Eq. 4)	0.87
$Protein = 7.09 + 0.016PHSND^2 - 0.347PSND + 0.029PSND^2$	(Eq. 5)	0.73

[a] Yield: grain yield (g m^{-2}), Protein: milled-rice protein (%), PHSND: N accumulation from PIS to harvest (g m^{-2}), Npi: N applied at PIS (g m^{-2}), PSND: shoot N density at PIS (g m^{-2}), R^2: coefficient of determination.

From Eq. 4, we found that GY had a quadratic relationship with both SND at PIS and SND accumulation from PIS to harvest. The maximum yield (1064 g m^{-2}) would be expected at the optimum SND of 13.95 g m^{-2} at PIS and SND of 14.66 g m^{-2} accumulation from PIS to harvest. This may indicate the potential grain yield at given climate conditions at the experimental site. However, to obtain the maximum yield as calculated from Eq. 4, we should apply a large N fertilizer amount of 26.8 g m^{-2} (calculated from Eq. 3 with values of SND of 13.95 g m^{-2} at PIS and 14.66 g m^{-2} accumulation from PIS to harvest) and milled-rice protein content would increase to 11.3% (calculated from Eq. 5 with the values of SND of 13.95 g m^{-2} at PIS and 14.66 g m^{-2} accumulated from PIS to harvest). This was not applicable in normal rice production because high N rate application brought about not only low N recovery efficiency and high environmental risk (Booltink et al. 2001; Verhagen 1997) but also high milled-rice protein content that is detrimental to eating quality of cooked rice (Chikubu et al. 1985; Ishima et al. 1974; Taira 1995). It was also noted that all of the calculated values for the maximum grain yield from Eq. 4 (maximum grain yield, optimum SND at PIS and SND accumulation from PIS to harvest) were out of the range of the actual values of those indicators used for the model formulation presented in Table 2. Therefore, the calculated optimum values of SND at PIS and SND accumulation from PIS to harvest may not be reliable for application

Equation 5 indicated that milled-rice protein content had a quadratic relationship with SND at PIS but positive correlation with square of SND accumulation from PIS to harvest. The dilution effect of N content at PIS on milled-rice protein content was also visible by plotting N content at PIS versus milled-rice protein content (Fig. 1) and the high positive effect of N accumulation from PIS to harvest on PC was discussed by Kim (2004), Murayama (1995), and Nguyen (2006). Murayama (1995) indicated that N absorbed from late N application could be translocated directly into grain, resulting in much higher PC in comparison to the earlier N application. From Eq. 5 the optimum N content at PIS for minimum PC content was calculated as 5.99 g m^{-2}. Because milled-rice protein content was positively correlated with square of SND accumulation from PIS to harvest which was in turn positively correlated with N rates applied at PIS (Table 2), it was difficult to obtain high GY and low PC by only adjusting N rates at PIS.

Validation of the calibrated model

Using models to predict GY, PC, and SND accumulation from PIS to harvest that were calibrated by data in 2003 and 2004, we calculated those variables in year 2005 experiment. Comparing the calculated and measured values of GY, PC and SND from PIS to harvest in both calibration data set (data of 2003-2004 experiments) and validation data set (data from year 2005 experiment), three parameters for model performance were calculated by Eq. 1 and Eq. 2 and presented in Table 4.

Table 4. Performance parameters of models for grain yield, milled-rice protein content, and nitrogen accumulation from PIS to harvest.

Crop variables	Descriptive statistics				Model quality parameters		
	Mean	CV(%)	Min	Max	R^2	RMSEP[b]	REP (%)
			Calibration dataset (n = 81)				
Yield[a] (g m^{-2})	645.0	15.6	358.8	845.8	0.87	35.6	5.5
Protein (%)	6.76	8.5	5.86	8.34	0.73	0.29	4.3
PHSND (g m^{-2})	5.20	49.6	0.18	10.54	0.82	1.10	21.1
			Validation dataset (n = 24)				
Yield[a] (g m^{-2})	683.7	12.4	525.4	858.0	0.52	68.5	10.0
Protein (%)	6.68	4.6	6.21	6.99	0.38	0.22	3.3
PHSND (g m^{-2})	6.35	22.0	3.38	7.97	0.85	0.89	13.9

[a] yield, protein, and PHSND were grain yield, milled-rice protein conten,t and N accumulation from PIS to harvest, respectively.

[b] RMSEP and REP were root mean square error in prediction and relative error in prediction calculated by Eq. 1 and Eq. 2, respectively

Comparing the performance parameters of the models in the calibration data set to those in the validation data set, R^2 of the models for GY and PC reduced from 0.87 and 0.73 to 0.53 and 0.38, respectively while the relative error in prediction (REP) was higher (10.0%) for GY and lower (3.3%) for PC in the validation than set than those of 5.5 and 4.3%, respectively, in the calibration set. The low precision (R^2) of the models in validation data set might have resulted from the narrower range of GY and PC in the validation data set than the calibration data set (Table 4 and Fig. 2). Although model R^2 for milled-rice protein content prediction was low (R^2 = 0.38), the relative error in prediction of 3.3% was within an acceptable accuracy for milled-rice protein content prediction in 2005. In contrast, the calibrated equation (Eq. 3) for SND accumulation from PIS to harvest by data from 2003 and 2004 had a high model performance in calculating this plant indicator in 2005.

Model application for N topdressing rate prescription at PIS

In principle, we may prescribe N rate requirement at PIS for target GY and PC using Eq. 3 in combination to Eq. 4 or Eq. 5, respectively. However, we decided to choose Eq. 5 and Eq. 3 to prescribe N topdressing rate requirement at PIS for target PC because of the recent attention on production of high quality rice with low protein content of 6.0-6.5 % (14% moisture) as guideline by Korean Rural Development Administration. The palatability of cooked rice has been reported to decrease linearly with the increase of milled rice protein content (Chikubu et al. 1985; Ishima et al. 1974; Taira, 1995). Moreover, because the result from year variation analysis using data from this study (Nguyen 2006) indicated that year variation significantly affected grain yield but not protein content and both of them were significantly affected by the applied N rates at PIS. It is also noted from the previous section that some of calculated values from Eq. 4 for GY prediction were out of the range of the actual values of those indicators used for the model formulation. Therefore, in prescribing the N rate at PIS the equation for protein prediction would be more adaptable from year to year and more reliable than the equation for yield prediction.

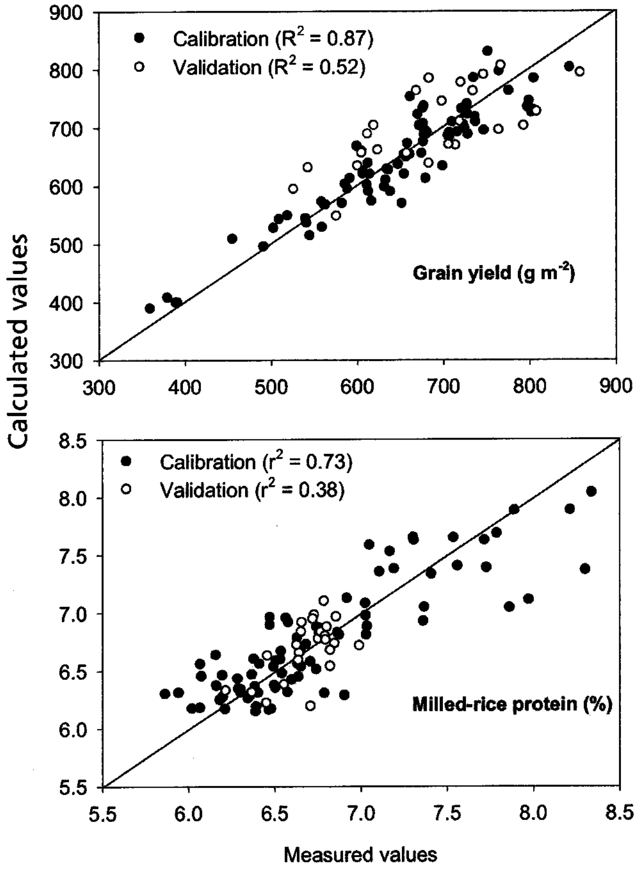

Fig. 2. Measured versus calculated values of grain yield and milled-rice protein content by Eq. 4 and Eq. 5, respectively. Solid line was 1:1 line.

Although the recent guideline by Korean Rural Development Administration was set as PC of 6.0-6.5 % (14% moisture) for high quality rice, there was no specific guideline on PC for cv. Hwaseongbyeo. We set the target PC as 6.8% (0% moisture) that was equal to 6.0% (14% moisture) for cv. Hwaseongbyeo in our experiment in 2005. The procedures calculating the required N rate in the prescribed nitrogen rate treatment (PRT) based on SND at PIS measured by canopy reflectance methods (Nguyen and Lee 2006) using Eq. 3 to Eq. 5 were as follows:

- Calculate the required SND accumulation from PIS to harvest for the target PC based on the predicted SND at PIS and the target PC of 6.8% (0% moisture) by Eq. 5. As a result, variable values of SND at PIS of different plots resulted in variable SND accumulation from PIS to harvest for the target PC of 6.8%.
- From the required SND accumulation from PIS to harvest of each plot for the target PC of 6.8% (calculated by Eq. 5), we calculated the required N amount that should be applied at PIS for obtaining the given values of SND accumulation from PIS to harvest by Eq. 3. Based on Eq. 3 to calculate N requirement for each plot, we assumed that all plots in the experiment had similar natural soil N supply of 3.31 g m^{-2} from PIS to harvest and N uptake recovery of 69.2% that were average natural soil N supply and N recovery efficiency determined from two-year experiments (2003-2004).

The calculated values for prescribed N rate treatment are presented in Table 5.

Table 5. Parameters of the prescribed N treatment at PIS for target milled-rice protein content of 6.8% of Hwaseongbyeo rice cultivar.

N rate at tillering (g m^{-2})	Calculated PSND[a] (g m^{-2})				Prescribed N rate[b] (g m^{-2})			
	Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max
0	4.32	38.2	2.96	6.16	3.02	54.3	1.58	4.81
3.6	5.43	28.9	3.76	6.90	4.11	34.8	2.57	5.40
7.2	7.24	22.2	5.38	8.19	5.56	21.9	4.15	6.27
Average	5.66	28.8			4.23			

[a] PSND was shoot N density at PIS measured by canopy reflectance method.

[b] Prescribed N rate were calculated by Eq. 3 and Eq. 5 for target milled-rice protein content of 6.8%.

The coefficient of variation in the calculated SND at PIS was quite high ranging from 22.2% for the treatment with 7.2 g N m^{-2} applied at tillering stage to 38.2% for the treatment without N applied at tillering stage. The high variation in SND at PIS among plots of the same N treatment at tillering stage might have resulted from the high variation in soil properties among blocks. The variation in SND at PIS among plots might also have been caused by the variation in N residuals from high and low N treatments design and application from the last year's experiment that was conducted in the same field. The high variation in SND at PIS among plots resulted in large differences in N requirements at PIS for the target PC of 6.8% calculated by Eq. 3 and Eq. 5. The calculated minimum N requirement at PIS was 1.58 g N m^{-2} and the highest was 6.27 g N m^{-2} with a mean of 4.23 g N m^{-2} (Table 5). The mean of calculated N for the target PC of 6.8% was higher than the currently recommended N of 3.6 g m^{-2} in Korea. The measured rice grain yield and milled-rice protein content of the prescribed N rate treatment in comparison to the fixed N rate treatment and the control treatments with no N are presented in Table 6.

Table 6. Descriptive statistics of grain yield and milled-rice protein content of the prescribed N rate treatment (PRT), the fixed N rate treatment (FRT, 3.6 g N m^{-2}), and no N treatment at PIS of Hwaseongbyeo rice cultivar.

N rate at tillering (kg/10a)	Treatment	Grain yield (kg/10a)				Milled-rice protein content (%)			
		Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max
0	No N	525.4	6.5	486.8	550.4	6.55	2.3	6.44	6.73
0	FRT	618.3	8.4	559.5	656.4	6.65	6.0	6.27	7.09
0	PRT	610.9	8.0	560.7	658.0	6.85	2.9	6.62	6.98
3.6	No N	542.2	9.2	492.6	592.7	6.37	4.9	6.02	6.65
3.6	FRT	667.8	5.3	627.7	695.3	6.64	5.7	6.23	7.00
3.6	PRT	718.2	6.9	666.2	764.3	6.73	2.4	6.58	6.91
7.2	No N	604.3	11.8	524.1	661.5	6.45	2.9	6.25	6.65
7.2	FRT	682.7	1.3	675.8	692.5	6.84	3.2	6.71	7.10
7.2	PRT	766.0	5.2	738.8	811.3	6.75	2.4	6.60	6.92
Pooled	No N	557.2	10.6	486.8	661.5	6.46	3.3	6.02	6.73
	FRT	656.3	6.6	559.5	695.3	6.72	4.6	6.23	7.10
	PRT	698.4	11.4	560.7	811.3	6.78	2.4	6.58	6.98

Results from Table 6 showed that variation in milled-rice protein content among plots in the PRT was significantly reduced at most of the treatments with different N rates (0, 3.6, and 7.2 g N m^{-2}) applied at the tillering stage and on an average the variation in PC was reduced from 4.6% in the FRT to 2.4% in the PRT. The range of PC was from 6.58 to 6.98% in the PRT that was also smaller than that from 6.23 to 7.10% in the FRT. The average of PC of the PRT was 6.78%, being very close to the target PC of 6.8% in our experiment. This revealed a potential of the prescribed N rates at PIS for target PC in rice production. The results indicated that mean of grain yield of the PRT was higher than that of the FRT at plots with 3.6 and 7.2 g N m^{-2} applied at tillering stage but lower at plots without N application at tillering stage. This suggested that grain yield of the PRT for target PC was highly dependent on shoot N accumulation until PIS and, the PRT for target PC would get high GY if only rice growth and N nutrition status at PIS were sufficient.

Data from Tables 5 and 6 indicated that the application of the PRT for target PC of 6.8% increased grain yield by 42.1 g m^{-2} while the applied N increased by 0.63 g m^{-2} in comparison to the FRT, resulting in high agronomic N-use efficiency of 68.8 kg grain from each kg of additionally applied N. The high agronomic N-use efficiency in the PRT might have resulted not only from the effect of additionally applied N amount but also from the higher response of grain yield to applied N in the PRT because applied N amount was calculated based on crop N demand of each plot.

Possible error sources in N topdressing rate prescription

at PIS

As compared to the FRT of 3.6 g N m^{-2} applied at PIS, the PRT reduced the coefficient of variation in milled-rice protein among plots from 4.6% in the FRT to 2.4% in PRT (about 50%) but a large proportion of variation of milled-rice protein content in the PRT for target PC of 6.8% indicated that some sources of errors in N topdress rate using SND at PIS and from PIS to harvest existed.

Error sources from calculating SND at PIS by canopy reflectance method

Plotting the measured SND versus the calculated SND by canopy reflectance measurement at PIS (Fig. 3), we may see that the R^2 between the measured and calculated SND was 0.74 and linear regression equation without intercept had a slope of 1.02 and relative error in prediction (REP) of 16.3%. Relative error in calculating SND at PIS (16.3%) could be considered to be large in comparison to 28.8% of the coefficient of variation among nine plots with N rate prescription (Table 5). For the success of N topdressing rate prescription at PIS, improvement of precision and accuracy in model to calculate shoot N content at PIS by canopy reflectance was needed.

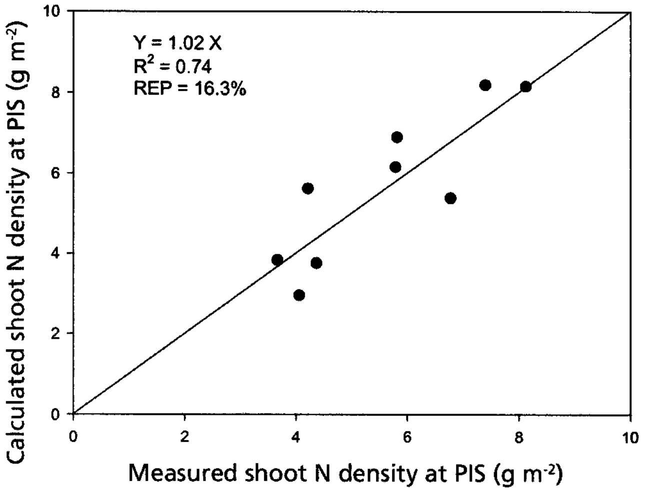

Fig. 3. Measured versus calculated shoot N density by canopy reflectance at PIS of the prescribed N rate treatment with Hwaseongbyeo rice cultivar.

Error sources from calculation of Shoot N accumulation from PIS to harvest

To examine the error in the calculation of SND accumulation from PIS to harvest, we used actually measured SND at PIS in combination with N rates applied at PIS for calculating SND accumulation from PIS to harvest by Eq. 3. Plot of the actual SND from PIS to harvest versus the calculated SND accumulation from PIS to harvest was presented in Fig. 4. It can be seen from Fig. 4 that SND accumulation from PIS to harvest was underestimated by Eq. 3 and low correlation between the two variables was detected. The error in estimating SND accumulation from PIS to harvest result from two main error sources: error of calibration model equation 3 and different response of SND accumulation from PIS to harvest in 2005 in comparison to those in 2003 and 2004.

As stated in the above section, the calculation of SND accumulation from PIS to harvest using Eq. 3 with the assumption that natural N soil supply from PIS to harvest and recovery efficiency of N applied at PIS were the same for all of nine plots in the experiment and similar to average values of 3.31 g m^{-2} for natural soil N supply and 69.2 % for recovery efficiency of N applied at PIS as determined in 2003-2004. Nguyen (2005) measured spatial variation in the natural soil N supply rate in a field of 6500 m^2 in Korea and indicated that the average of the natural soil N supply was 1.37 g m^{-2} from transplanting to PIS with coefficient of spatial variation of 20.4%. Kim (2004) estimated natural soil N supply and recovery efficiency of various N rates applied at PIS in 2001 and 2002 and suggested that there was a considerable difference in the natural soil N supply from PIS to harvest and recovery efficiency of applied N at PIS between two years of the experiment and among N rate treatments within a year. As a result, the assumption of constant natural soil N supply and N recovery efficiency in Eq. 3 for N prescription in our study apparently resulted in an error source in the calibration equation for the calculation of SND accumulation from PIS to harvest because natural soil N supply and recovery efficiency of N applied at PIS might vary from one location to the other (spatial variation) and from year to year (temporal variation). This should be considered for improving SND accumulation from PIS to harvest estimation and N topdressing rate prescription for rice at PIS.

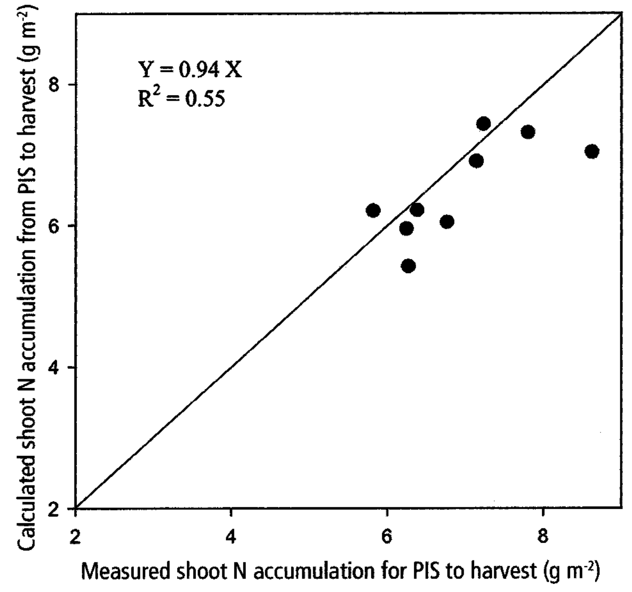

Fig. 4. Measured versus calculated shoot N accumulation from PIS to harvest in nine plots of the prescribed N treatment of Hwaseongbyeo rice cultivar (using Eq. 3). Solid line is 1:1 line.

The variation in response of GY and PC to SND at PIS and from PIS to harvest

The overestimation of grain yield in year 2005 (Fig. 2 and 5) indicated that response of GY to SND at PIS and from PIS to harvest was possibly higher in 2005 than that in the 2003 and 2004 experiments. The different response of grain yield and milled-rice protein content to SND at PIS and from PIS to harvest was also observed by Kim (2004). Kim (2004) showed that under favorable weather (higher sunshine duration) condition from PIS to harvest, rice grain yield had higher response to SND at PIS and from PIS to harvest in comparison to that of years with unfavorable weather conditions.

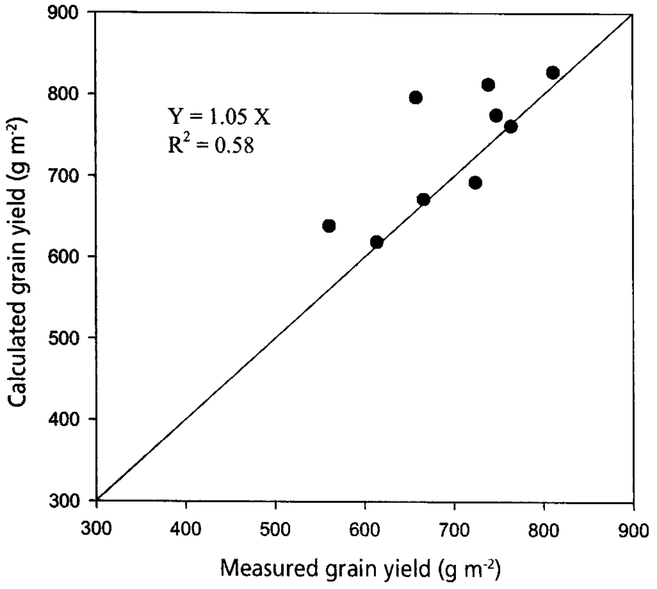

Fig. 5. Measured versus calculated grain yield of nine plots of the prescribed N rate treatment of Hwaseongbyeo rice cultivar (using Eq. 3 to Eq. 5). Solid line is 1:1 line.

Conclusion

Stepwise multiple regression models using SND and applied N rates at PIS explained 82% variation in shoot N accumulated from PIS to harvest in 2003-2004 while stepwise multiple linear regression using SND at PIS in combination with SND accumulated from PIS to harvest quantified 87 and 73% variation in rice GY and PC in two-year data (2003-2004), respectively. Shoot N accumulation from PIS to harvest was curve-linearly correlated with GY but linearly correlated with milled-rice protein content. Therefore, it was difficult to obtain high grain yield and low milled-rice protein content by only adjusting N rate at PIS in rice production. Optimum SND at PIS for minimum protein content was 5.99 g/m^2 and N uptake from PIS to harvest was as small as possible. Application of the models for prescribing N rate at PIS for the target PC of 6.8% obtained an average PC of 6.78% and reduced variation in PC from 4.6% in the FRT of 3.6 g N m^{-2} to 2.6% in the PRT. In addition, the PRT increased GY by 42.1 g m^{-2}, resulting in high agronomic N-use efficiency of 68.8 kg grain per additional kg applied N in comparison to the FRT. The higher response of GY to the applied N in the PRT might have resulted from the better match between the applied N amount and crop N demand.

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