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Response of Rice Yield to Nitrogen Application Rate under Variable Soil Conditions

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ABSTRACT: Rice yield and plant growth response to nitrogen (N) fertilizer may vary within a field, probably due to spatially variable soil conditions. An experiment designed for studying the response of rice yield to different rates of N in combination with variable soil conditions was carried out at a field where spatial variation in soil properties, plant growth, and yield across the field was documented from our previous studies for two years. The field with area of 6,600 m^2 was divided into six strips running east-west so that variable soil conditions could be included in each strip. Each strip was subjected to different N application level (six levels from 0 to 165 kg/ha), and schematically divided into 12 grids (10 m × 10 m for each grid) for sampling and measurement of plant growth and rice grain yield. Most of plant growth parameters and rice yield showed high variations even at the same N fertilizer level due to the spatially variable soil condition. However, the maximum plant growth and yield response to N fertilizer rate that was analyzed using boundary line analysis followed the Mitcherlich equation (negative exponential function), approaching a maximum value with increasing N fertilizer rate. Assuming the obtainable maximum rice yield is constrained by a limiting soil property, the following model to predict rice grain yield was obtained:
$Y=10765\{1-0.4704*EXP(-0.0117*FN)\}*MIN(I_{clay}, I_{om}, I_{cec}, I_{TN}, I_{Si})$
where FN is N fertilizer rate (kg/ha), I is index for subscripted soil properties, and MIN is an operator for selecting the minimum value. The observed and predicted yield was well fitted to 1:1 line (Y=X) with determination coefficient of 0.564. As this result was obtained in a very limited condition and did not explain the yield variability so high, this result may not be applied to practical N management. However, this approach has potential for quantifying the grain yield response to N fertilizer rate under variable soil conditions and formulating the site-specific N prescription for the management of spatial yield variability in a field if sufficient data set is acquired for boundary line analysis.

Keywords: rice, soil, nitrogen, yield, response-surface, site-specific crop management

Soil properties and soil nutrients are highly variable within a field and this variation has been found to be major factors causing spatial yield variability of upland crop (Verhagen, 1997; Taylor *et al.*, 2003; Cox *et al.*, 2003) and lowland rice crop (Dobermann, 1994; Nguyen *et al.*, 2004). In such a spatially-variable soil conditions, the uniform fertilizer applications for crop may result in over-fertilizer application in some locations of a field but nutrient deficiency in some others. Excessive fertilizer application, particularly, nitrogen (N) fertilizer has been pointed out as a cause of environmental pollution (Verhagen *et al.*, 1995; Verhagen, 1997; Booltink *et al.*, 2001), whereas N deficiency restricts crop growth and yield (Verhagen *et al.*, 1995; Cahn *et al.*, 1994). In order to deal with this problem, several techniques have been proposed. One of these techniques is to manage the spatial yield variability by applying N fertilizer site-specifically. To prescribe a site-specific N fertilizer amount for rice crop field, it is important to understand grain yield response to rates of nitrogen application under the spatially-variable soil conditions.

Spatial relationships of crop yield to N fertilizer application and soil properties have been studied by many researchers for upland field (Verhagen *et al.*, 1995; Delin *et al.*, 2004, Kahabka *et al.*, 2004; Runge & Hons, 1999) and these studies focused on correlating the spatial difference between field characteristics and crop yield response to nitrogen. Yield response to fertilizer nitrogen for winter wheat and spring barley varied within a field due to variation in plant-available soil nitrogen, local infections of fungal diseases or probable losses of N fertilizer due to excess soil moisture (Delin *et al.*, 2002). Similarly, Gooding *et al.* (1999) stated that crop N fertilizer demand varies across location of the field depending on, for example, plant-available soil nitrogen during crop growth stages and potential yield. However, Kahabka *et al.* (2004) indicated that N fertilizer recommendations for maize based on pre-sideress soil nitrate tests (PSNT) can not be simply applied in site specific management approach. In addition, they found that the greatest source of variability in N requirements was observed with annual effects of weather.

In lowland rice field, spatial variation in soil nutrients was reported to be possibly large even within a small field (Dobermann, 1994; Dobermann *et al.*, 1995, 1996). However, Doberman *et al.* (2002) proposed the field-specific nutrient

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management in rice crop as the potential for managing this spatial variability in a small rice field still is limited at present. And in Korea field-specific N fertilizer application that is prescribed based on organic matter and available Si content in paddy field has been practiced for managing the yield variability among rice fields (Park *et al.*, 2003). The rice field size has been increased by merging the adjacent fields for mechanization and will be increased further in the future for cutting down the rice production cost especially in Korea (Choi, 2001) and Japan (Inamura *et al.*, 2004), increasing the potential need for managing the within-field spatial variability in rice farming as well. Rice yield response to N fertilizer rates in well-designed experiments has been reported by many authors (Li *et al.*, 1991; De Datta *et al.*, 1988; Shen *et al.*, 2004). However, to our understanding, information on yield response to rates of nitrogen fertilizer in relation to within-field spatial soil variability is not available.

In year 2004, a field experiment with six nitrogen levels was conducted in a field where information of spatial variability of rice grain yield and soil properties was well documented from our previous studies in 2002 and 2003. The main objective of this study was to understand how plant growth and yield of rice respond to rates of nitrogen application under variable soil conditions so that prescription rule of N amount can be formulated for site-specific N fertilizer management.

MATERIALS AND METHODS

Experimental layout and sampling procedures

A paddy field located in experimental farm of National Institute of Crop Science, Rural Development Administration (37°16'N), Korea was used for the experiment where rice grain yield response to nitrogen rates under variable soil conditions was investigated in 2004. This field was used as a trial field in 2002 and 2003 with uniform fertilizer rates of 110 N: 70 P: 80 K (kg/ha) under transplanted rice culture. Variation of soil properties in the field ranged from 7.6% to 16.3% for soil CEC, clay content, total N, organic matter and available Si. More information on spatial distribution of soil properties can be found in Nguyen *et al.* (2004) and an example was presented as kriged map (Fig. 1B) for soil organic mater. The field with areas of 6,600 m^2 was divided into six strips running east-west so that variable soil conditions can be included in each strip. Each strip was subjected to different nitrogen application level, and schematically divided into 12 grids (10 m × 10 m for each grid) for sampling and measurement of plant growth and rice grain yield.

Japonica rice (*Oryza sativa L*) variety Daeanbyeo was machine-transplanted at plant spacing of 30 × 15 cm. Six N fertilizer rates of 0, 55, 83, 110, 137, and 165 N (kg/ha) were applied to six strips of the field as designed in Fig. 1A. Nitrogen fertilizer was applied in three splits of 40-30-30% as basal-tillering-panicle fertilizer, potassium fertilizer in two splits of 70-30% as basal-panicle fertilizer, and phosphorus fertilizer in one split (100%) as basal fertilizer. Other field management followed a standard practices typical for Korean farmer's field.

Plant growth parameters such as shoot dry weight (DW), number of tiller (Til), shoot nitrogen concentration (SN), shoot nitrogen uptake (Nup) and SPAD reading (Minolta, SPAD 502), etc. were measured at panicle initiation stage (PIS), heading stage (HD), and harvest stage (HA) of rice. Nitrogen nutrition index (NNI) was calculated with measured SN and DW according to Cui *et al.* (2002). Tiller number was counted for 20 hills at the center of each grid, and the five hills were randomly sampled for plant dry weight and nitrogen concentration measurement. Sampled plant were dried at 70 °C for two days, weighted for DW, and ground through 40-mesh sieve for nitrogen analysis. Nitrogen concentration was analyzed by CNS analyzer

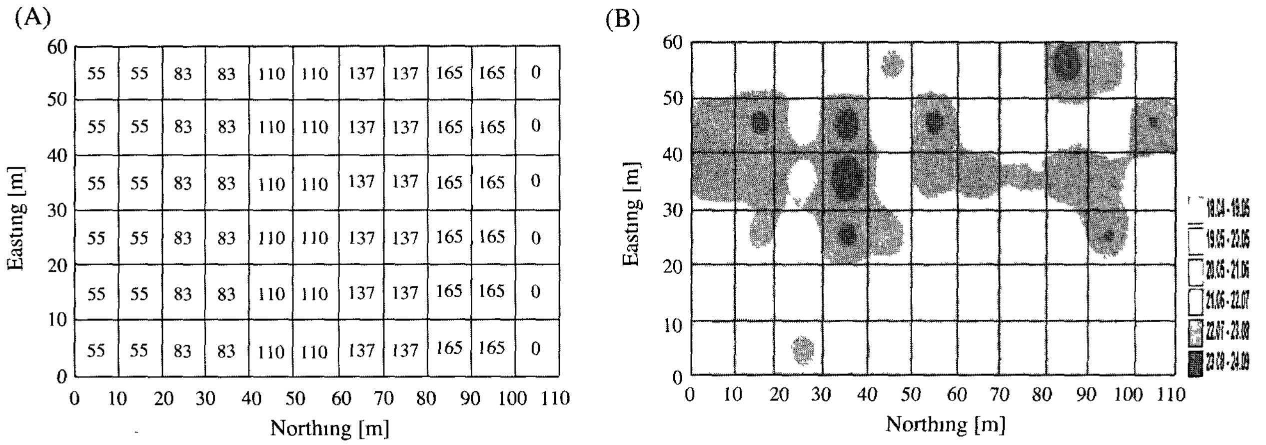

Fig. 1. Experimental field with 66 grids were designed for treat-ments of different nitrogen fertilizer levels (N amount (kg/ha) was shown in each grid) (A). Kriged map of soil spatial variation was presented for organic matter (B).

(Leco, CNS 2000). Grain yields were measured with sample harvested from the area of 6 m^2 for each grid. Final yield of rough rice was adjusted to 14% of water content.

Data analysis

Plant growth and rice yield response to rates of nitrogen under variable soil condition were examined using the following statistical procedures:

(1) Descriptive statistics and simple correlation were used to analyze the spatial variation in plant growth parameters and rice yield and their linear interdependence.

(2) Stepwise multiple linear regression procedure with forward selection was used to identify the soil properties or plant growth parameters, and other factors that have the significant influences on spatial variation of rice yield. Variables were selected for inclusion in the model at $P<0.05$.

(3) Boundary lines were analyzed according to the procedure of Nguyen *et al.*, (2003) for describing the maximum responses of rice yield and plant growth parameters to rates of nitrogen application under variable soil conditions. The boundary line or maximum line was fitted to a negative exponential function of Eq. 1.

$$Y= Ymax \{1-\alpha \exp (\beta X)\} \qquad \text{(Eq. 1)}$$

where Y is dependent variable (growth parameter, yield etc.), X is an independent variable such as N fertilizer rate, Ymax is the maximum growth parameter or yield that rice crop can attain at a given applied N level under the most favorable condition of the other independent variables like soil properties, and α and β are constants. Mitcherlich & Sauerlandt (1934) proposed the same equation to represent the response of plant to the addition of fertilizer.

(4) Several functions can be used to describe crop yield response in relation to variation in other factors (Wood, 1980). In this study, response-surface was selected for describing response of rice yield to the different nitrogen levels in dependence on variable soil properties. The formulated equation for the response-surface is as follow:

$$Y=Ymax\ [(1-a.\exp(bFN)]^{*}\ [(1-\alpha.\exp(\beta X)] \qquad \text{(Eq. 2)}$$

where Y, Ymax, FN and X are grain yield, maximum attainable grain yield, N fertilizer rate and soil properties, respectively.

The response surface graphs were drawn using graphics

Table 1. Descriptive statistics for rice growth and yield under different nitrogen fertilizer levels.

N level (kg/ha)		Panicle initiation stage						Heading stage					Yield (kg/ha)
		DW	Til	SN	Nup	NNI	SPAD	DW	SN	Nup	NNI	SPAD	
0	Mean	1.5	208.3	0.9	14.2	0.2	27.4	6.5	0.9	55.9	0.4	24.2	4685
	Min	1.1	183.3	0.9	11.0	0.2	26.4	6.2	0.8	52.7	0.3	19.2	3791
	Max	2.0	233.3	1.0	19.4	0.3	28.7	6.9	0.9	62.6	0.4	27.5	5623
	CV(%)	22.4	11.0	3.6	22.9	10.5	3.7	4.3	4.1	6.5	5.4	14.2	15.0
55	Mean	2.2	247.2	1.3	28.0	0.3	32.5	7.7	1.5	113.3	0.7	29.1	6537
	Min	1.8	200.0	1.0	19.2	0.3	28.0	6.6	1.3	88.7	0.6	23.6	5135
	Max	3.1	283.3	1.5	36.4	0.4	37.6	8.7	1.7	136.5	0.8	42.8	7986
	CV(%)	17.8	10.3	14.2	19.9	14.4	9.7	8.2	7.5	11.6	8.7	16.8	13.1
83	Mean	2.5	256.9	1.3	31.7	0.4	32.3	7.9	1.4	114.6	0.7	30.1	6628
	Min	2.1	216.7	1.1	22.6	0.3	29.2	7.4	1.3	103.6	0.6	25.2	5887
	Max	3.2	316.7	1.5	40.8	0.4	34.8	8.2	1.6	130.5	0.8	38.4	7473
	CV(%)	12.3	13.4	10.5	17.1	12.6	5.2	2.7	5.6	6.7	6.3	14.3	6.9
110	Mean	2.9	279.2	1.4	40.5	0.4	34.0	8.0	1.5	120.5	0.7	35.3	7001
	Min	2.3	216.7	1.1	32.5	0.4	32.1	6.6	1.4	89.6	0.6	24.8	6106
	Max	3.8	333.3	1.6	54.8	0.5	36.4	9.3	1.7	150.8	0.8	44.8	7704
	CV(%)	13.5	11.4	8.6	15.3	10.1	3.8	8.8	7.3	14.3	10.2	17.4	7.6
137	Mean	3.1	290.3	1.4	42.1	0.4	34.1	8.5	1.6	133.5	0.8	36.1	7444
	Min	2.6	216.7	1.1	29.8	0.3	31.7	7.4	1.5	108.5	0.7	27.2	6321
	Max	3.9	333.3	1.7	50.7	0.5	37.6	9.3	1.9	174.1	0.9	46.0	8197
	CV(%)	11.3	11.1	11.2	15.2	12.2	5.0	7.1	7.6	12.8	9.4	18.8	8.1
165	Mean	3.0	283.3	1.5	45.6	0.5	34.9	8.4	1.6	133.3	0.8	36.9	7772
	Min	2.4	250.0	1.3	31.3	0.4	32.4	7.2	1.3	91.5	0.6	30.4	7335
	Max	3.7	316.7	1.8	62.4	0.6	39.5	9.5	2.1	202.0	1.1	43.6	9887
	CV(%)	14.5	7.5	11.4	24.0	16.2	5.9	8.5	13.9	21.7	17.3	11.3	9.1

DW: dry weight (ton/ha) Til. Tiller number (/m^2) SN: shoot nitrogen concentration (%)
Nup: N uptake (kg/ha) NNI: nitrogen nutrition index SPAD reading
CV. coefficient of variation (%)

software (Sigma plot version 5.0, 1998). kriging map of spatial variation of yield, soil properties, and other related parameters was performed using Acview GIS (ESRI, 1996). The statistical analysis SAS software was used for data analysis of the research.

RESULTS

Plant growth and yield response to different rates of nitrogen

Plant growth at panicle initiation (PIS) and heading stage (HD) and rice yield under variable N rates were summarized in Table 1. Plant growth parameters at PIS and HD were higher in higher nitrogen levels, indicating high effect of applied N on plant growth. Rice yield was significantly increased with increasing rates of nitrogen application. An average difference in grain yield of about 3000 kg/ha was observed between N levels of 0 and 165 kg N/ha (Table 1). The highest spatial variation in rice yield was occurred at no N application treatment and tended to decrease gradually with increase of applied N rates up to 165 kg N/ha.

Response of plant growth and yield to rates of nitrogen application under variable soil conditions was also quantified using boundary line method (Fig. 2 and 3). Most of plant growth parameters and rice yield showed high variations even at the same N fertilizer level due to the spatially variable soil condition. However, the maximum plant growth and yield responses to N fertilizer rate that was analyzed using boundary line analysis was well represented by the Mitcherlich equation (Mitcherlich & Sauerlandt, 1934), approaching a maximum value with increasing N

Table 2. Correlation among plant growth parameters at panicle initiation stage and heading stage and rice yield (n=66).

Growth parameters	Panicle initiation stage							
	Yield	N rate	DW	Tiller	SN	Nup	NNI	SPAD
Yield (kg/ha)	1							
N rate (kg/ha)	0.76**	1						
Dry weight (ton/ha)	0.66**	0.74**	1					
Tiller (m^2)	0.62**	0.62**	0.70**	1				
Shoot nitrogen (%)	0.66**	0.70**	0.59**	0.61**	1			
N uptake (kg/ha)	0.70**	0.80**	0.92**	0.73**	0.84**	1		
NNI	0.71**	0.79**	0.82**	0.071**	0.94**	0.97**	1	
SPAD reading	0.66**	0.66**	0.57**	0.41**	0.57**	0.61**	0.63**	1

Growth parameters	Heading stage						
	Yield	N rate	DW	SN	Nup	NNI	SPAD
N rate (N kg/ha)	0.76**	1					
Dry weight (ton/ha)	0.71**	0.63**	1				
Shoot nitrogen (%)	0.70**	0.69**	0.76**	1			
N uptake (kg/ha)	0.72**	0.69**	0.90**	0.96**	1		
NNI	0.72**	0.70**	0.84**	0.99**	0.99**	1	
SPAD reading	0.53**	0.61**	0.60**	0.50**	0.57**	0.54**	1

*Significant at the 0.05 probability level
**Significant at the 0.01 probability level

Table 3. Parameter estimate of equation for grain yield (Y) response to nitrogen fertilizer application rate (FN) and major soil variables (X)

Soil variables (X)	Y max	a	b	α	β	R^2
OM	10765	0.4297	-0.009	0.2333	-0.0024	0.615
TN	10765	0.4308	-0.009	0.2835	-2.1045	0.617
CEC	10765	0.4234	-0.010	0.3798	-0.0001	0.618
Clay	10765	0.429	-0.0098	0.2507	-0.0042	0.615

Equation: $Y=Ymax[(1-a.exp(bFN)]* [(1-\alpha\ exp(\beta X)]$

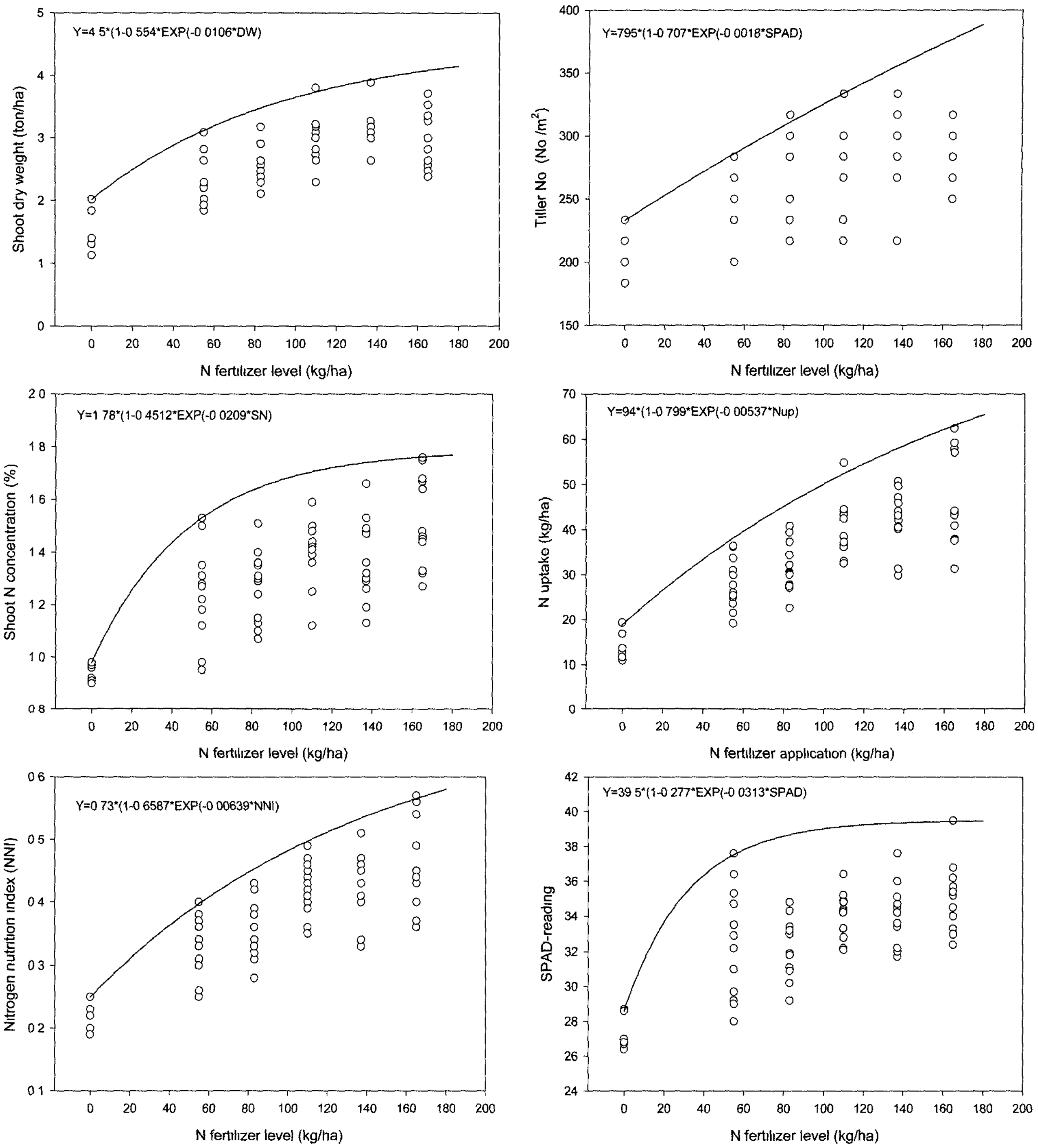

Fig. 2. Boundary line analyses of plant growth (at panicle initiation stage) response to nitrogen fertilizer level (DW: dry weight, SN: shoot nitrogen concentration, NNI: nitrogen nutrition index, Nup: shoot nitrogen content).

fertilizer rate. The shape of the curves in Fig. 2 indicated that applied N had different effect on each plant growth parameter at PIS. Shoot N concentration and SPAD reading approached plateau rapidly at lower N fertilizer level than the other growth parameters such as N uptake, tiller number, nitrogen nutrition index, and shoot dry weight, indicating the clear nitrogen dilution effect due to plant growth.

Factors determining rice yield

Correlations among plant growth parameters at PIS and HD, rice yield, and N fertilizer rate were presented in Table 2.

Most of plant growth parameters at PIS and HD had significant positive correlations ($P<0.01$) with rice grain yield. At both PIS and HD, shoot N uptake and NNI were found to have the highest correlation with rice yield ($r>0.71$). Applied N rate, as expected, showed high correlation with all plant growth parameters measured ($r>0.61$) and rice yield ($r=0.76$). In general, yield had higher correlation coefficient with crop growth parameters at HD than at PIS.

Multiple linear regression model with stepwise procedure was used to investigate yield-determining growth para-meters at HD. Among the growth parameters shoot N content was the only parameter selected by stepwise procedure ($P<0.05$) and this linear regression explained 52% of rice yield variation across field with different N fertilizer level, and also shoot N content at harvest showed a similar regression with determination coefficient of 0.52 (Fig. 4). This result indicates that nitrogen uptake from soil and fertilizer nitrogen is an important factor causing rice yield variation.

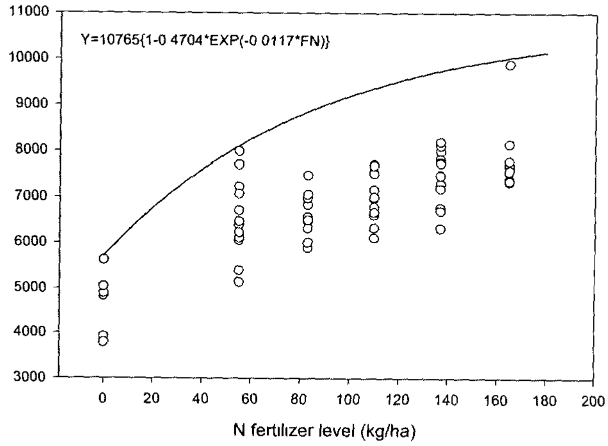

Fig. 3. Boundary line analysis of rice yield response to nitrogen fer-tilizer level (Y: grain yield, kg/ha, and FN. fertilizer level application, kg/ha).

Response-surface of rice yield to major soil properties and nitrogen fertilizer rate

Inter-relationships between rice yield to some major soil properties and nitrogen application level were described through response surface (Eq. 2). This equation was formulated according to the boundary line analysis of rice yield response to N fertilizer rate (Fig. 3) and to soil properties (Nguyen *et al.*, 2004), assuming that the maximum attainable yield response to N fertilizer rate may be constrained by soil conditions and also the maximum attainable yield response to soil conditions may be constrained by N fertilizer rate. The parameter estimates for each soil property were presented in Table 3 and response-surface curves were drawn as in Fig. 5. The yield response-surface model using N fertilizer level and one of major soil properties explained about 62% of rice yield variability.

As the soil limiting factor is different from location to location in the field (Nguyen *et al.*, 2004), we applied the result of boundary line analysis of rice yield to N fertilizer rate (Fig. 3) and to soil properties and the Law of the Minimum to get the following equation (Eq. 3);

$$Y=10765\{1-0.4704*EXP(-0.0117*FN)\} *MIN(I_{clay}, I_{om}, I_{cec}, I_{TN}, I_{Si}) \qquad (Eq. 3)$$

where FN is N fertilizer rate (kg/ha), I is index for sub-scripted soil properties (Nguyen *et al.*, 2004), and MIN( ) is an operator for selecting the minimum value. The observed and predicted value according to Eq. 3 was well fitted to 1:1 line (Y=X) with determination coefficient of 0.564 (Fig. 6).

DISCUSSION

Some research results have demonstrated that soil properties were highly variable within a paddy field (Dobermann,

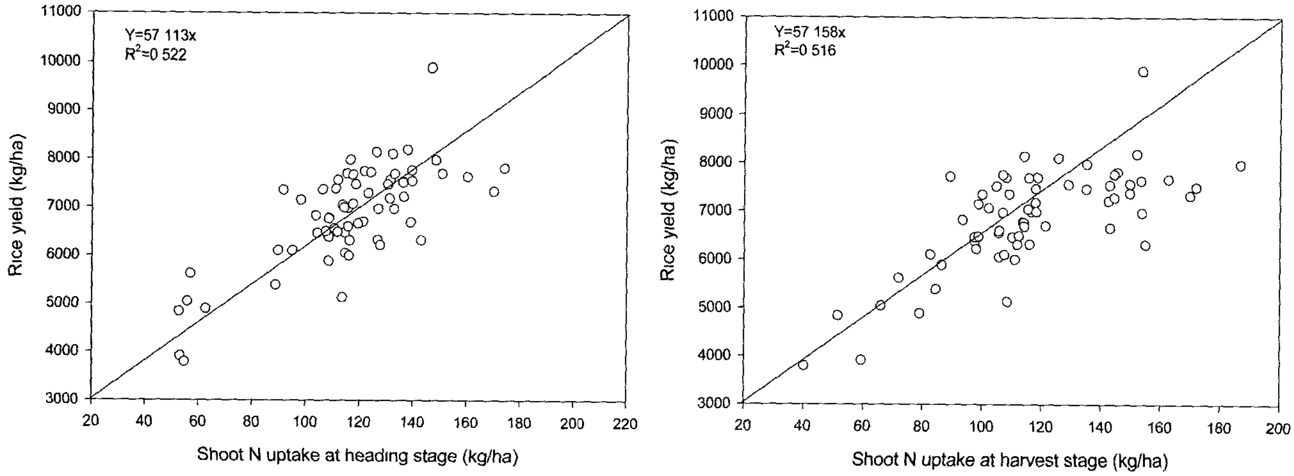

Fig. 4. Relationship between rice yield and shoot nitrogen uptake at heading and harvest stage.

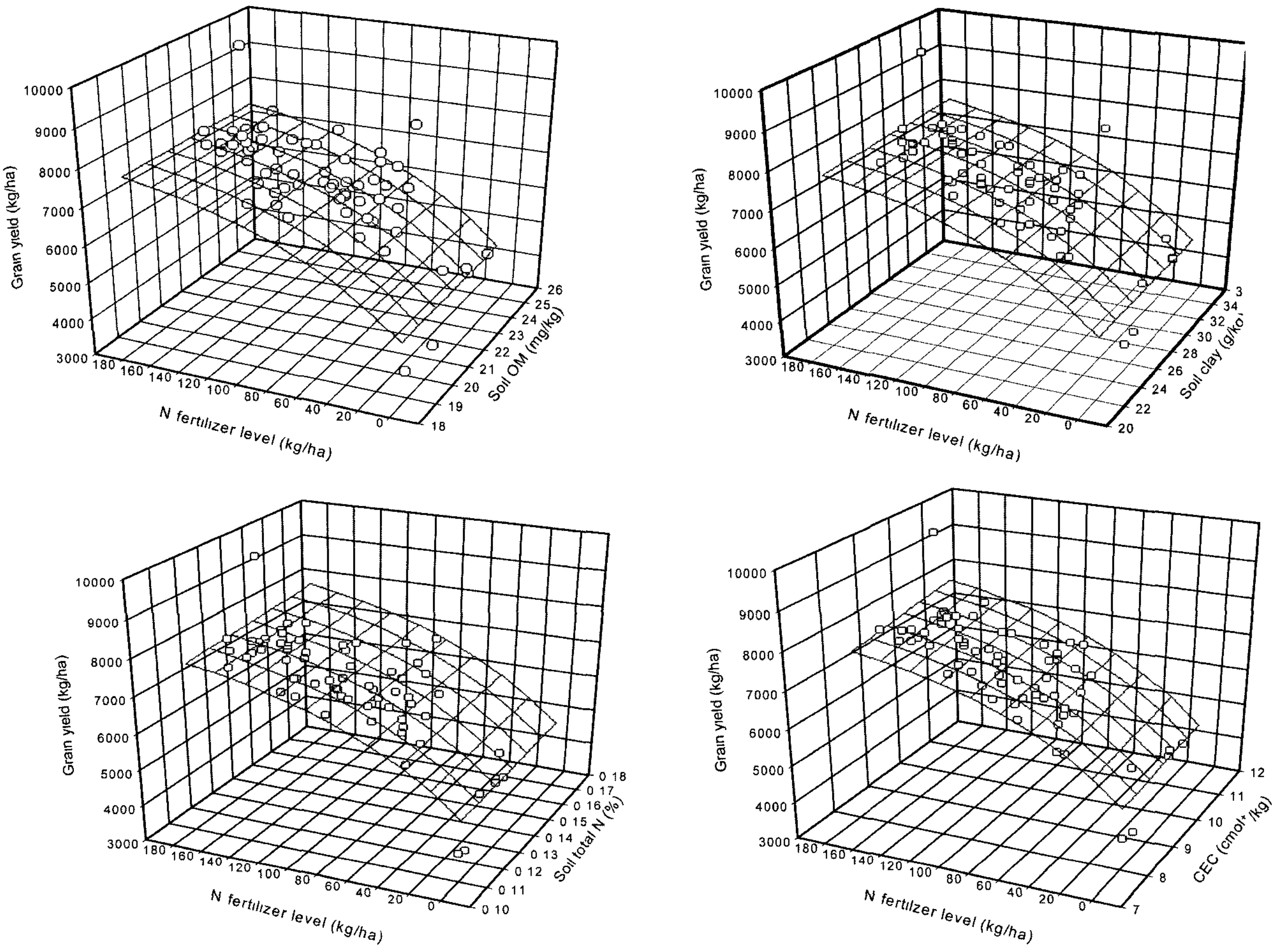

Fig. 5. Response surface of rice yield to N fertilizer level and soil properties Response surfaces were drawn based on the equations as shown in Table 4

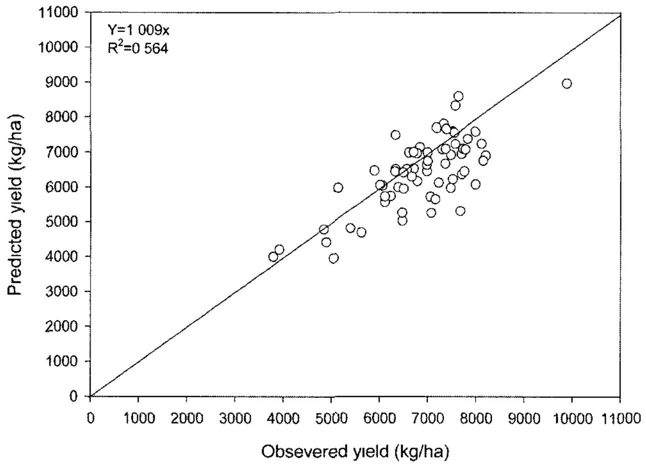

Fig. 6. Relationship between rice yields observed and predicted by applying boundary analysis of rice yield to N fertilizer level and the minimum index of soil properties selected by the Law of Minimum as Eq 3

1996; Nguyen *et al.*, 2003; Yanai, 2000). Field variation of soil properties as a source for differentiated growth of upland crops has been reported in many studies (Englestad *et al.*, 1961; McDaniel & Hajek, 1985). However, without consideration of spatial soil variation in the field, applied N still had profound effect on rice growth and yield even.

Rice yield showed high variations even at the same N fertilizer rate (Table 1 and Fig. 3). The maximum yield responses to N fertilizer rate that was analyzed using boundary line analysis was presented well by the Mitcherlich equation (Mitcherlich & Sauerlandt, 1934), approaching a maximum attainable yield with increasing N fertilizer rate (Fig. 3). This obtainable maximum yield may be constrained by soil conditions, bringing about the spatial variation of growth and yield response to N fertilizer level. Response of crop yield to nitrogen application has been reported to vary across location in a field (Verhangen *et al.*, 1995; Delin *et al.*, 2004; Gooding *et al.*, 1999). In the previous 2-year experiments at the same field as in this study and one other adjacent paddy fields with uniform N application, five soil properties including soil organic mater, total nitrogen, CEC, clay and available Si were found to be the major soil limiting factors causing spatial yield variability of rice (Nguyen *et al.*, 2004). Therefore, we tried to relate the above soil properties to differential yield response to N fertilizer rate. Yield response surface model (Eq. 3) using total amount of applied N fertilizer rate and one of soil properties as independent variable and assuming that the maximum attainable yield response (boundary line) to each independent variable be constrained by each other explained about 62% of the observed yield variation.. Nguyen *et al.* (2004) reported that soil factor limiting rice yield was different from location to location in the same field used for this experiment. Therefore, we tried to relate the boundary yield response to N fertilizer rate (Fig. 4) and soil limiting factor (Nguyen *et al.*, 2004) as in Eq. 3. The observed and predicted value according to Eq. 3 was well fitted to 1:1 line(Y=X) and this approach also explained 56% of the yield variability, a little lower than the above results. This result might have been resulted from the limited data set for boundary line analysis of yield response. However, this approach has potential for quantifying the yield response of grain yield to N fertilizer rate under variable soil conditions and formulating the site-specific N prescription for the management of spatial yield variability in a field if sufficient data set is acquired for boundary line analysis.

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