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Analysis of Within-Field Spatial Variation of Rice Growth and Yield in Relation to Soil Properties

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ABSTRACT: For developing the site-specific fertilizer management strategies of crop, it is essential to know the spatial variability of soil factors and to assess their influence on the variability of crop growth and yield. In 2002 and 2003 cropping seasons within-field spatial variability of rice growth and yield was examined in relation to spatial variation of soil properties in the two paddy fields having each area of ca. 6,600 m^2 in Suwon, Korea. The fields were managed without fertilizer or with uniform application of N, P, and K fertilizer under direct-seeded and transplanted rice. Stable soil properties such as content of clay (Clay), total nitrogen (TN), organic mater (OM), silica (Si), cation exchange capacity (CEC), and rice growth and yield were measured in each grid of 10 x 10m. The two fields showed quite similar spatial variation in soil properties, showing the smallest coefficient of variation (CV) in Clay (7.6%) and the largest in Si (21.4%). The CV of plant growth parameters measured at panicle initiation (PIS) and heading stage (HD) ranged from 6 to 38%, and that of rice yield ranged from 11 to 21%. CEC, OM, TN, and available Si showed significant correlations with rice growth and yield. Multiple linear regression model with stepwise procedure selected independent variables of N fertilizer level, climate condition and soil properties, explaining as much as 76% of yield variability, of which 21.6% is ascribed to soil properties. Among the soil properties, the most important soil factors causing yield spatial variability was OM, followed by Si, TN, and CEC. Boundary line response of rice yield to soil properties was represented well by Mitcherich equation (negative exponential equation) that was used to quantify the influence of soil properties on rice yield, and then the Law of the Minimum was used to identify the soil limiting factor for each grid. This boundary line approach using five stable soil properties as limiting factor explained an average of about 50% of the spatial yield variability. Although the determination coefficient was not very high, an advantage of the method was that it identified clearly which soil parameter was yield limiting factor and where it was distributed in the field.

***Keywords*:** spatial variation, yield, soil property, rice, precision farming

The challenge for agricultural scientists in the new millennium is how to ensure food security to the ever-increasing world population while reducing the environmental pollution due to agricultural production. One of the several alternative farming techniques that have been invented in an effort to solve the problems is precision agriculture. In precision agriculture, the questions by both researchers and farmers are what causes the spatial variability of crop yield within a field and how to effectively manage this spatial variation so as to maximize the crop yield while minimizing the pollution problem. Precision agriculture has been developed and practiced mainly in developed western countries where crop is produced in large-scale upland field, thus being spatially heterogeneous in soil properties and crop yield.

In most of rice growing countries, paddy field size is so small that spatial variability of crop yield in a paddy field has not drawn any attention in rice crop management but managing variability among fields has been the main concern. However, spatial variability of soil nutrients and rice yield is reported to be large even within a small rice field (Doberman, 1994; Doberman *et al.*, 1995, 1996). And 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). These situations will increase the potential need for managing the within-field spatial variability in rice farming as well.

Spatial variation management, for example, through variable rate application of fertilizer is possible only if experts can give correct site-specific recommendations (Geypens, 1999; James & Godwin, 2003). Spatial yield variability of crop may be caused by a non-uniform distribution of soil properties, pest pressure, rooting depth, and other factors (Sawyer, 1994). Therefore, for the management of crop spatial variability not only the precise information on spatial variation of both biotic and abiotic factors need to be documented but also crop growth and yield response to those factors need to be clarified (Geypens, 1999; Cambardella & Karlen, 1999; Machado *et al.*, 2002). Spatial variation of crop yield and related factors has been reported

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extensively for both upland crops and lowland paddy rice (De Datta *et al.*, 1987; Dobermann *et al.*, 1995; Sawyer, 1994; Cambardella *et al.*, 1996; Timlin *et al.*, 1998; Sadler *et al.*, 2000), and for various soil properties such as soil texture, pH (Ovalles & Collins, 1986), and organic matter (Miller *et al.*, 1995). Cox *et al.* (2003) studied variability of selected soil properties such as soil clay content and exchangeable cation in 8.4 ha in USA and reported that most of exchangeable cations had high spatial variation (CV>30%) while pH had consistently low variation (CV<12%). Similarly, Pierce *et al.* (1994) indicated that CV of pH was 6% while CV for exchangeable Mg was up to 81%. In a direct-seeded flooded rice field, Dobermann (1994) reported that fairly stable soil properties such as pH, soil texture, and soil organic matter had lower CV of 10 to16% but more dynamic properties such as EC, exchangeable NH_4-N, NO_3-N etc. had CV exceeding 29% and as large as 122%. These coefficients of variation found by Dobermann (1994) were in agreement with those reported by Trangmar *et al.* (1985).

Among factors affecting crop growth and yield, spatial variation of soil properties have been considered as one of important factors and received a great deal of attention. Effects of spatial soil variability on crop growth and yield have been reported for corn (Cambardella *et al.*, 1996; Timlin *et al.*, 1998), soybean (Sudduth *et al.*, 1996) in USA, and rice in Russia and at IRRI (Dobermann, 1994; De Datta *et al.*, 1987). Cox *et al.* (2003) found that soybean yield was consistently higher in high clay content areas compared to the other location, suggesting that clay content would be an important yield determining factor and should be used as a basis for site-specific soil management. However, Pierce *et al.* (1994) reported that corn yield was found to be highly spatially-variable but little correlation was found between corn yield and soil fertility due to the influence of other limiting factors. Machado *et al.* (2002) found that grain yield was influenced by interrelationship among many factors and recommended that information on seasonally-stable factors like elevation and soil texture is useful in identifying management zones for water and fertilizer application while water and fertilizer management should be complemented by in-season management of seasonally-unstable factors like soil NO_3-N, rainfall, pest and disease effects on grain yield. Using factor analysis, Dobermann (1994) found that factors reflecting soil fertility status have significantly influenced the plant population density, grain yield and straw yield of rice. He also indicated that the model using five factors (soil fertility status, land preparation, nitrogen fertilizer application, seeding rate, and phosphorus-availability) explained 75% of the plant population density and 56% of the rice yield variation. Similarly, Casanova *et al.* (1999) reported that 54% of rice yield variation in Spain could be explained with soil variables such as CEC, pH, total nitrogen, and clay/sand ratio through the stepwise multiple regression analysis, and they identified the size of yield gap due to soil properties by applying boundary line analysis and the Law of the Minimum.

In conclusion, spatial variation of soil, plant growth and yield have been studied and reported somewhere. However, the information on spatial variation in soil and crop under flooded paddy rice in Korea is still very limited for management of spatial yield variation. Therefore, the objectives of our study were (1) to characterize within-field spatial variation in yield response to soil and plant growth variability under flooded paddy field condition, and (2) to test if boundary line analysis of rice yield response to soil factors and the Law of the Minimum could be applied for identifying and quantifying the soil factors that are closely related with the spatial variability of rice crop performance.

MATERIALS AND METHODS

Experimental fields and fertilizer application

The two adjacent paddy fields, assigned as Field A and Field B were used for this research. Each field has an area of 60 m x 110 m and is almost flat (0.07%). The fields have been used as the experimental field of National Institute of Crop Science, Rural Development Administration (37^{0}16'N), Korea since 1906. On average the fields have soil textures of silt clay and chemical properties of most commonly found in Korean paddy field (Table 1). On the two trial fields, designed experiments for evaluating the effects of season, cultural method, and fertilizer application on the spatial variability of rice growth and yield and assessing the soil factors causing the spatial variability of crop growth and yield were carried out under direct-seeded and transplanted rice culture with and without fertilizer application in 2002 and 2003 (Table 2). The fields were schemati-

Table 1. General of soil properties of the experimental fields.

Field	Sand (%)	Clay (%)	TN (g/kg)	OM (g/kg)	Avail P (mg/kg)	Avail. Si (mg/kg)	Exchangeable cation ($cmol_c$/kg)				CEC
							K^+	Ca^+	Mg^+	Na^+	($cmol_c$/kg)
Field A	24.5	27.6	1.1	21.4	129	96.4	1.03	3.64	0.81	0.73	9.46
Field B	26.7	28.6	1.2	21.2	96.4	129	1.00	3.86	0.83	0.70	9.68

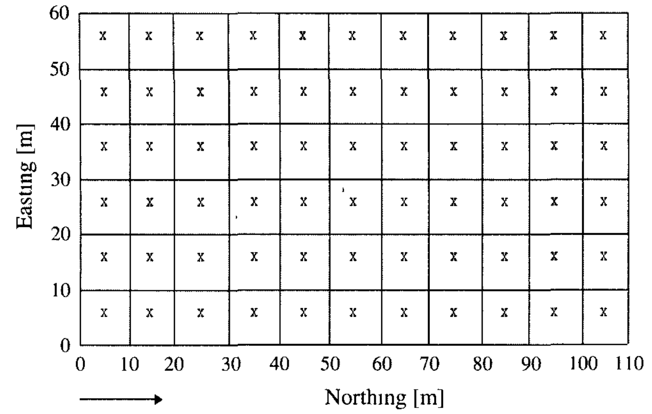


Fig. 1. Schematic grids of the experimental field (Field A and B) for measuring soil properties, plant growth and grain yield (doted × is measurement point of each grid).

cally divided as grids of 10 m x 10 m for measuring soil properties, plant growth and yield of rice (Fig. 1).

Rice cultivation and field management

Japonica rice varieties, Surabyeo and Daeanbyeo were used for the experiments in 2002 and 2003, respectively. Rice was machine-transplanted at 15 by 30 cm hill space at Field A (2002, 2003) and Field B (2003), and direct-seeded with broadcasting on flooded soil at Field B in 2002 for over-viewing the variation of rice yield and plant growth under different methods of rice culture. The fertilizer of 110 N: 70 P: 80 K (kg/ha) were applied uniformly for Field A in 2002 and 2003 and Field B in 2002. Field B in 2003 was not applied with fertilizer for assessing the fertilization effects (Table 2).

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 is one split (100%) as basal fertilizer. Other field management followed a standard practices typical for Korean farmer's field.

Soil sampling and analysis

Soil samplings were collected one week after basal fertilizer application at the center of 10 by 10 m grids (66 grids each for Field A and Field B) in 2002 and 2003. Each soil sample was collected as a composite of 5 sub-samples taken from topsoil layer (0-15 cm deep) and within a 50 cm circular area from the center of each grid. The samples were air-dried and passed through 2 mm sieve before analyses. The soil chemical properties were measured following analytical method described by Kim (1996): soil texture (hydrometer method), electrical conductivity (EC meter, CM 30S, TOA Electronic), pH (soil/water extract 1:5 suspension), organic matter content (Walkey-Black method), total nitrogen (Kjeldahl method), available phosphorus (Bray No. 2 extraction and analyzed by Foss-FIA Star 2002), available silica (extraction with 1N NaOAc and analyzed by colorimetric method), cation exchange capacity (Ammonium Acetate-NH_4OAc method) and content of exchangeable K, Mg, Ca and Na (extracted by ammonium acetate solution and measured by inductively-coupled plasma emission spectrometer, ICP-GBC-Intergra XL, France).

Measurement of plant growth and rice yield

Plant growth parameters such as shoot dry weight (DW), number of tiller (Til), shoot nitrogen concentration (SN), shoot nitrogen content (Nup) and SPAD reading, etc. were measured at panicle initiation (PIS), heading (HD) and harvest (HS) stages 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 central part of each grid, and the five hills were sampled for plant dry weight and nitrogen concentration measurement. Sampled plant were dried at 70 °C for two days, weighed for DW, and ground through 40-mesh sieve for nitrogen analysis. Nitrogen concentration was analyzed by CNS analyzer (Leco, CNS 2000). Grain yields were measured with sample harvested from the area of 6 m^2 near soil sampling position for each grid. Final yield of rough rice was adjusted to 14% of water content.

Data analysis

Four main mathematical methods were used to describe the spatial variation of soil properties, plant growth, and

Table 2. Summary of the experimental treatments.

Field	Year	Varieties	Cultivation	Fertilizer application
Field A	2002	Surabyeo	Transplanted	Uniform Fertilizer application (UFA)
	2003	Daeanbyeo	Transplanted	Uniform Fertilizer application (UFA)
Field B	2002	Surabyeo	Direct-seeding	Uniform Fertilizer application (UFA)
	2003	Daeanbyeo	Transplanted	No fertilizer application (NFA)

UFA: uniform fertilizer application (110 N: 70 P: 80 K (kg/ha)) NFA. No fertilizer application grain yield of rice and to quantify the spatial variation of rice yield response to plant growth parameters and soil properties:

(1) Descriptive statistics and simple correlation were used to analyze the spatial variation of soil properties, 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 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 line analysis was used to describe the maximum response of rice yield to a given level of a soil factor under non-limiting condition of the other factors, and quantify the degree of influence of soil factors on rice yield. Since boundary line analysis was firstly applied to the analysis of biological data by Webb (1972), many researchers (Walworth *et al.*, 1986; Schnug *et al.*, 1995; Casanova *et al.*, 1999, 2002; Cui & Lee, 2002) have used the boundary line analysis for identifying process-limiting factor in agriculture. In the present research, rice yield was scatter-plotted against soil properties, and data points, so called boundary points, that lie on the uppermost edge were selected by eye. The set of boundary points form a boundary line describing the maximum attainable yield over the range of independent variable measured (Fig. 6). The boundary lines of rice yield response to the soil properties and plant growth parameters were fitted to the following negative exponential function:

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

In Eq. 1, Y is dependent variable (yield), X is a independent variable such as soil properties or plant growth parameters, Ymax is the maximum yield that a crop can attain under the most favorable condition of the independent variables, and α and β are constants. If we exclude Ymax from the Eq.1, the value of "$1-\alpha \exp(\beta X)$" ranges from 0 to 1 and can be used as soil index (I_{soil}) expressing the relative availability of a given soil property to crop performance. Though the Law of the Minimum advocated by Liebig in 1855 is criticized that it ignores the plant flexibility to acclimate physiologically and morphologically to changing environmental conditions (Sinclair & Park, 1993), the Law was employed for identifying a limiting soil factor to rice yield as it is simple and has been successfully used in many other studies (Waggoner & Norwell, 1979; Casanova *et al.*, 1999, 2002). The limitting soil factor is a soil parameter that has the lowest soil index (minimum index) among the soil indices calculated by the above boundary line method. The minimum index values selected for all plots were then used for regression to predict rice grain yield. The appliation of the law of the minimum for yield prediction may be expressed as the following equation:

$$Y = Ymax\ Min(I_{OM}, I_{Clay}, I_{TN}, \ldots I_{CEC}) \qquad \text{(Eq. 2)}$$

In Eq. 2, Y is grain yield, I_{OM}, I_{Clay}, I_{TN},...I_{CEC} is soil index determined by boundary line method, Min ( ) is the mathmatical operator that select the lowest index among the soil indices enumerated in the parentheses, and Ymax is the maximum attanable yield.

The analytical software SAS (SAS institute Inc. 8.12) was mainly used for statistical analysis and kriging map of spatial variation of yield, soil properties content and other related parameters was performed using Acview GIS (ESRI, 1996).

RESULTS

Spatial variability of soil properties, plant growth, and rice yield

Soil properties

Several soil chemical properties including soil clay and sand content, cation exchange capacity (CEC), total nitrogen (TN), organic mater (OM), exchangeable P, K, Ca and Mg etc as in Table 1 were collected for understanding their spatial variation distribution. However, some soil properties such as exchangeable P, K, Ca and Mg had high coefficient of variation are excluded in the analysis as they were applied as fertilizer and high temporal variation. We presented only fairly stable soil properties such as CEC, OM, TN, clay content and available Si that may have significant influence on spatial variability of plant growth and yield. Spatial variation distribution of the selected soil properties in year 2003 from Field A and B were presented as kriged maps in Fig. 2. Considerable spatial variation in soil properties was observed in both Field A and B. Most of soil parameters showed higher values in the east and lower in the west sites in Field A, while higher in the south and lower in the north in Field B.

The descriptive statistics of the selected soil properties pooled over two years (2002 and 2003) were presented in Table 3 (a). The mean and spatial variability of soil properties in Field A were somewhat lower than those in Field B, but the order of variability was consistent, being the lowest in clay content and the highest in available Si content. Coefficient of variation (CV) of the soil properties ranged from 7.6% for clay content to 21.4% for available Si. Correlation coefficient (r) values among soil properties were calculated for the data pooled over fields and two years in Table 3 (a). Most of the soil properties showed significant correlation with each other ($P<0.05$), as the close relationship among soil clay content, CEC, OM and TN has been frequently reported (Table 3 (b)).

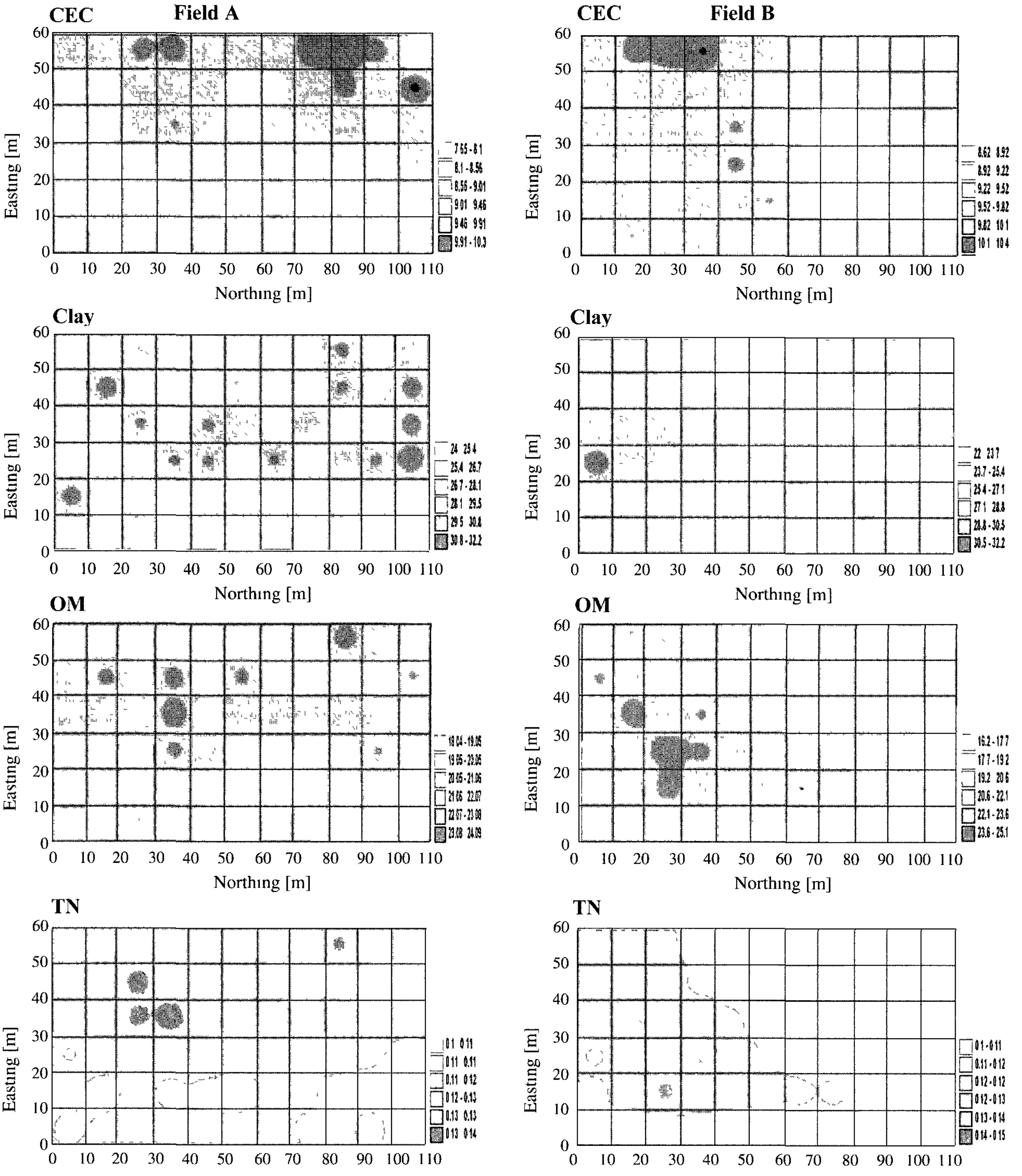


Fig. 2. Kriged map of spatial variation of soil properties at Field A (uniform fertilizer application with transplanted method) and Field B (no fertilizer application with transplanted method) in year 2003.

Plant growth and rice yield

Descriptive statistics for spatial variation in plant growth parameters measured at PIS and HD and grain yield without fertilization under transplanted rice culture was shown in Table 4, while the data with conventional fertilizer application under transplanting culture and direct-seeding were presented in Table 5 and 6, respectively. Generally, the variation in shoot N uptake among the plant growth and N nutrition parameters at

Table 3. (a) Descriptive statistics for major soil properties of the experimental fields (Field A and Field B).

Soil properties	Field A (n=132)				Field B (n=132)			
	Mean	Min.	Max.	CV(%)	Mean	Min.	Max	CV(%)
CEC (cmolc/kg)	9.46	8.53	10.3	11.6	9.68	8.02	9.62	11.7
Clay (%)	27.6	22.5	32.2	7.59	28.6	26.6	32.2	9.1
Total N (%)	0.11	0.09	0.15	8.83	0.12	0.12	0.10	10.2
Organic matter (g/kg))	21.4	18.3	25.1	10.9	21.2	17.1	24.3	11.0
Available Si (mg/kg)	96.4	65.0	165	16.3	129	87.5	111	21.4

Soil properties: mean value of soil properties in 2002 and 2003
Field A: uniform and normal rate of N application with transplanted method in 2002 and 2003.
Field B: uniform and normal rate of N application with directed-seeding method in 2002 and no fertilizer application with transplanted method in 2003

Table 3. (b) Correlation coefficients between soil properties.

Variable	CEC	Clay	Total N	OM
CEC	1			
Clay	0.42**	1		
Total N	0.45**	0.38**	1	
Organic matter (OM)	0.36*	0.65**	0.72**	1

*Significant at the 0.05 probability level
**Significant at the 0.01 probability level
Data was pooled over Field A and B in 2002 and 2004

Table 4. Descriptive statistics for plant growth and yield at Field B with no fertilizer application in 2003. (n=66)

Stages	Variables	Mean	Minimum	Maximum	CV (%)
Panicle initiation stage	Dry weight (ton/ha)	1.2	0.68	1.44	18.0
	Tiller number (/m^2)	186.4	133	266	17.2
	Shoot nitrogen (%)	1.4	1.06	1.80	13.8
	N uptake (kg/ha)	13.7	8.00	18.8	20.4
	Nitrogen nutrition index	0.3	0.18	0.32	14.2
	SPAD reading	27.7	21.7	34.9	9.5
Heading stage	Dry weight (ton/ha)	3.9	2.1	5.80	22.1
	Shoot nitrogen (%)	1.3	1.16	1.65	9.3
	N uptake (kg/ha)	51.7	26.9	91.9	27.1
	Nitrogen nutrition index	0.5	0.33	0.65	14.7
	SPAD reading	29.2	24.7	34.0	6.2
Harvest	Yield (kg/ha)	4334	3204	6179	18.9

PIS and HD was the highest (in N uptake) and the lowest in SPAD reading regardless of fertilizer treatment and rice cultural method. It should be noted that the low variation in SPAD reading may be resulted from the relative small standard deviation of SPAD reading that was measured only for the uppermost fully-expanded leaf instead of the whole canopy.

The much lower values in most of the plant growth parameters were observed in the treatment without N application (Table 4) in comparison to those of the treatments with N application regardless of transplanted or direct-seeded culture (Tables 5 and 6). This indicated that the application of N fertilizer had a crucial effect on plant growth parameters at both PIS and HD. Among plant growth parameters, shoot dry weight was a parameter that was most affected by N application, resulting in quite smaller variation of shoot N concentration due to the dilution effect (Cui *et al.*, 2002). However, the overall trend of higher CV values for both plant growth and grain yield in Field B without N application (Table 4) than those in Field A with N application under the same transplanted rice

Table 5. Descriptive statistics for plant growth and yield of transplanted rice at the Field A with normal fertilizer application in 2002 and 2003.

Stages	Variables	2002				2003			
		Mean	Min.	Max.	CV(%)	Mean	Min	Max	CV(%)
Panicle initiation stage	Dry weight (ton/ha)	2.3	1.71	3.04	15.8	2.4	1.55	3.22	16.6
	Tiller number (/m^2)	227.8	150	316	17.5	259.6	183	350	14.2
	Shoot nitrogen (%)	1.4	1.08	2.06	15.5	1.5	1.20	1.90	10.7
	N uptake (kg/ha)	32.6	19.6	62.7	27.7	36.5	21.5	53.3	21.9
	Nitrogen nutrition index	0.4	0.27	0.64	19.7	0.4	0.30	0.54	14.4
	SPAD reading	32.3	28.2	39.2	7.7	30.2	24.1	36.8	7.5
Heading stage	Dry weight (ton/ha)	5.3	1.80	8.70	29.1	7.9	5.40	9.6	12.0
	Shoot nitrogen (%)	1.5	0.99	2.05	15.3	1.5	1.27	1.87	9.3
	N uptake (kg/ha)	79.9	20.0	155	38.2	119.9	16.9	174	16.8
	Nitrogen nutrition index	0.6	0.28	0.91	23.9	0.7	0.53	0.93	11.7
	SPAD reading	36.6	30.4	42.1	7.6	33.6	25.9	40.3	9.1
Harvest	Yield (kg/ha)	5691	4026	7273	11.5	6373	4673	7676	11.0

Table 6. Descriptive statistics for plant growth and yield of direct-seeded rice with normal rate of fertilizer application (Field B: 2002).

Stages	Variables	Mean	Minimum	Maximum	CV (%)
Panicle initiation stage	Dry weight (ton/ha)	2.4	1.69	3.0	13.7
	Tiller number (/m^2)	208.2	116	300	20.6
	Shoot nitrogen (%)	1.4	1.14	1.80	10.8
	N uptake (kg/ha)	33.8	21.0	51.0	19.7
	Nitrogen nutrition index	0.4	0.29	0.54	13.0
	SPAD reading	29	24.7	34.7	8.1
Heading stage	Dry weight (ton/ha)	6.5	5.0	8.0	8.0
	Shoot nitrogen (%)	1.4	1.07	1.79	11.3
	N uptake (kg/ha)	93.9	63.0	123	16.8
	Nitrogen nutrition index	0.6	0.44	0.77	13.1
	SPAD reading	31.9	27.2	38.0	7.0
Harvest	Yield (kg/ha)	5021	1509	6563	21.5

culture (Table 5) suggested that even uniform application of N fertilizer potentially reduced variation in rice growth and grain yield. The spatial distribution pattern of rice yield in Field B without N fertilization was presented with kriged maps as in Fig. 3. It also reveals variable yield distribution across field. The pattern of spatial yield distribution across the field was very similar to the spatial distribution patterns of stable soil properties in Field B as presented in Fig. 2, suggesting that the spatial yield variability might have been caused by the spatial distribution of the soil properties

Results of variation in plant growth at Field A with conventional fertilizer application and transplanted rice in year 2002 and 2003 were presented in Table 5. Plant growth parameters varied highly across the field in both experiment years of 2002 and 2003.

However, the spatial variability of them showed no big difference between the experiment years. Coefficient of variation for plant growth and N nutrition parameters ranged from 7.6% for SPAD reading to 38% for shoot nitrogen uptake. Variation of shoot nitrogen uptake was highest compared with the other plant properties. Rice yield ranged from 4000 to 7000 (kg/ha), coefficient of variation of about 11% was recorded both in 2002 and 2003. The spatial distribution patterns of rice yield were compared with kriged maps as in Fig. 4. The major patterns of spatial yield distribution across the field were maintained similar with minor difference over the two experimental years. And the pattern of spatial yield distribution showed some similarity to the spatial distribution pattern of some stable soil properties like CEC in Field A as presented in Fig. 2.

To understand the spatial variation of plant growth and rice yield under direct-seeded rice cultivation, an experiment

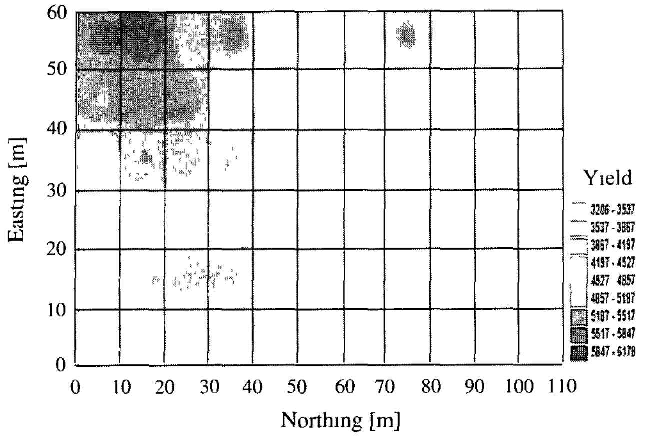


Fig. 3. Kriged map of spatial variation of rice yield at the Field B with transplanted rice and no fertilizer application in 2003.

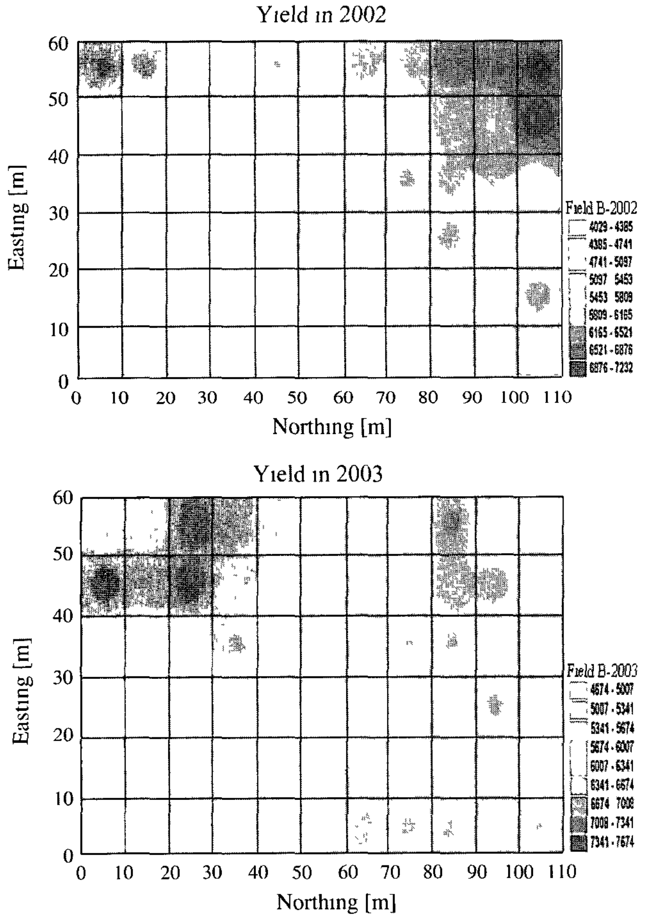


Fig. 4. Kriged map of spatial variation of rice yield at the Field A with conventional fertilizer application and transplanted rice in 2002 and 2003.

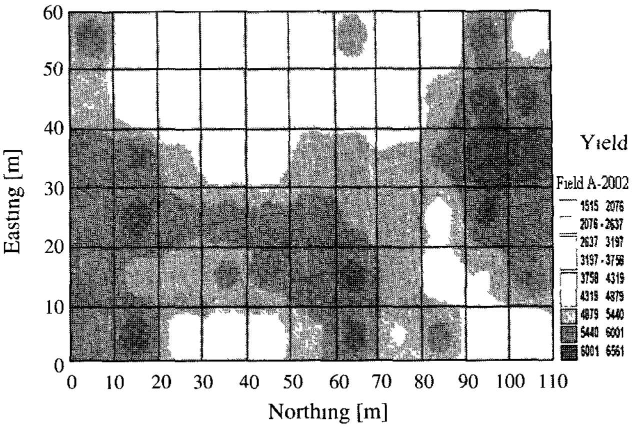


Fig. 5. Kriged map spatial variation at Field B with direct-seeded rice and conventional fertilizer application in 2002.

was carried out at Field B with conventional fertilizer application and direct-seeded rice in 2002. The variation of plant growth parameters at PIS and HD under direct-seeded rice cultivation (Table 6) was generally less variable compared to the experimental field with transplanted rice cultivation in the same year 2002 (Table 5). However, spatial yield variability of the field with direct-seeded culture was very high (21.5%) and much higher than the variation in rice yield of the field under transplanted culture in the same year 2002 (11.5%). The higher CV of grain yield in direct-seeded culture might have been caused by the high variation of plant population density and field lodging at some part of the field during grain filling period in direct-seeded field. The spatial distribution pattern of rice yield (Fig. 5) was quite different from that of the same field (Field B) without N fertilization in 2003 and from that of the spatial distribution pattern of soil properties in Field B (Fig. 2). Rice yield was rather lower at the high fertility in the southeast site because of lodging damage during ripening stage.

Relationship among soil properties, plant growth, and rice yield

Plant growth and soil properties

Plant growth at panicle initiation stage was related with soil properties (Table 7). Several soil properties such as CEC, OM and TN have positive significant correlations with all the plant growth parameters measured at Field A where conventional fertilizer application and transplanted rice cultivation were used. However, soil properties have lower correlation with plant growth parameters at Field B with fertilization under direct-seeded rice culture in year 2002 and with no fertilization under transplanted rice culture in 2003. This result might be due to the spatial heterogeneity of plant population in direct-seeded rice cultivation and to the spatial prevalence of nutrients limitation such as N, P, K, etc in the trial with no fertilizer application in 2003.

Table 7. Correlation coefficients between soil properties and plant growth parameters at panicle initiation stage.

Year	Parameter	Field A				Field B			
		CEC	Clay	TN	OM	CEC	Clay	TN	OM
		Uniform fertilizer with transplanted method				Uniform fertilizer with direct-seeded method			
2002	Shoot N	0.43**	-0.01	0.36*	0.32*	0.18	0.21	0.19	0.15
	Dry weight	0.37*	0.16	0.25*	0.31*	0.16	0.15	0.12	0.07
	N uptake	0.46**	0.10	0.36*	0.36*	0.21	0.22	0.20	0.13
	NNI	0.46**	0.05	0.37*	0.36*	0.20	0.22	0.21	0.15
	SPAD reading	0.58**	0.10	0.35*	0.38*	0.33*	0.06	0.01	0.04
	Tiller	0.45**	0.21	0.49*	0.40*	0.23*	0.14	0.19	0.11
		Uniform fertilizer with transplanted method				No fertilizer application with transplanted method			
2003	Shoot N	0.37*	0.27*	0.37*	0.31*	0.19	0.23*	0.29*	0.24*
	Dry weight	0.32*	0.14	0.14	0.36*	0.11	0.06	0.05	0.03
	N uptake	0.41*	0.24*	0.28*	0.42**	0.02	0.20	0.15	0.17
	NNI	0.43**	0.27*	0.34*	0.41*	0.13	0.26*	0.24*	0.22
	SPAD reading	0.49**	0.22	0.36*	0.30*	0.18	0.29*	0.17	0.15
	Tiller	0.24*	0.13	-0.02*	0.08	0.11	0.18	0.33*	0.31*

Table 8. Correlation coefficients between soil properties and grain yield

Variables	Rice yield at Field A		Rice yield at Field B	
	UFA-T (2002)	UFA-T (2003)	UFA-D (2002)	NFA-T (2003)
CEC	0.60**	0.63**	0.62**	0.64**
Clay	0.30*	0.48**	0.55**	0.49**
Total N	0.50**	0.52**	0.54**	0.57**
Organic matter	0.56**	0.55**	0.58**	0.62**
Available Si	0.53**	0.51**	0.48**	0.49**

UFA-D: Uniform fertilizer application (normal rate) with direct-seeded method
NFA-T: No fertilizer application with transplanting method
UFA-T: Uniform fertilizer application with transplanting method
*Significant at the 0.05 probability level
**Significant at the 0.01 probability level

Rice yields and soil properties

Relationship between soil properties and rice yield was determined using correlation coefficients (Table 8). Several soil properties in both Field A and B had positive correlations with grain yield through experiments in 2002 and 2003, regardless of difference in cultivation method and fertilizer treatment. Rice yield had the highest correlations with CEC (r ranging from 0.60 to 0.64 over two years). OM and N also showed close correlations with grain yields.

Multiple linear regression with stepwise procedure was used to select factors determining rice yield among several measured soil properties. A model based on selected variables (N fertilizer level, sunshine hours from PIS to harvest, CEC, OM, TN and available Si) explained as much as 76% of yield variability (Table 9). Nitrogen fertilizer level and sunshine hours were included to separate the effect of fertilizer application and from the spatial yield variation due to soil properties. Among the soil variables, OM, TN, Si, and CEC except clay content were included in the model. OM was evaluated as the most important soil factor explaining the spatial yield variability, followed by available Si, TN, and CEC.

Plant growth and rice yield

Pooled data at Field A and B over two experiment years were used for the analysis of relationship between plant parameters at PIS and HD and rice yield. In general, plant growth parameters at HD had higher correlation with grain yield than those at PIS except for SPAD value (Table 10). Multiple linear regression procedure was also used to identify factors that have significant influence on the spatial variation of rice yield. Model based on the selected variables of tiller number, SPAD reading and NNI at panicle initiation stage explained an average of 66% of spatial yield variability, while the model on the selected variables of DW, Nup and SPAD reading at heading stage explained about 66% of spatial yield variability (Table 11). The most important variable was tiller number at PIS and shoot DW at HD, explaining more than 50% of the spatial yield variability.

Spatial yield variability analysis in relation to soil properties and plant growth with boundary line analysis

Boundary line was formulated using Eq. 1 and well described the maximum rice yield attainable at the different levels of each soil factor under non-limiting conditions of the other factors. Boundary line analysis were applied for some selected soil properties including CEC, OM, TN, clay content, and available Si (Fig. 6) and boundary line equations and soil indices for each soil parameter were finally obtained (Table 12).

The limiting soil factor was defined as the factor that has the lowest soil index value according to Liebig's law. The index value of a soil property that has the minimun index for each plot was plotted against the yield of each grid and obtained simple linear regression between them (Fig. 7). The coefficient of determination ranged from 0.45 to 0.53 depending on fertilizer treatment, cultural method and experimental year. The different regression coefficients resulted from the different maximum yields (Ymax) according to cultural method and climate conditions. Relationship between observed and predicted yield of rice using boundary line approach was shown in Fig. 8. The coefficient of determination was 0.51, indicating that variation in minimum soil index selected from five major stable soil properties could explain 51% of the spatial variability of rice yield over two years and several different cultivation techniques. Kriged maps of spatial variation of minimum index of soil properties and of grain yield (Fig. 9 (a) and Fig. 9 (b)) clearly reveal the similarity of spatial variation patterns of the minimum soil index and rice yield. Although the coefficient of determination of this approach was not so high, an advantage of the boundary line method was that it clearly indicated the limiting soil factor in each plot as in Fig. 10 and then it is beneficial information for managing spatial variation of plant growth and yield.

DISCUSSION

Spatial variability of soil properties, plant growth, and rice yield

The measured variables including soil and plant properties

Table 9. Multiple linear stepwise regression of grain yield to rate of nitrogen fertilizer, sunshine hours, and soil properties. Data (n=197) were pooled across years and fields with transplanted rice.

Variables	Fer N	SunH	CEC	OM	TN	Si	Model R-square
Parameter estimate	19.5	21.5	470.0	90.7	11013	10.97	0 760
Partial R-square	0.507	0.037	0 007	0.134	0.0073	0.068	

SunH: sunshine hour from panicle initiation stage to harvest
FerN. N fertilizer application rate (kg/ha)
TN: soil total nitrogen (%)
Si. soil available silica

Table 10. Correlation of rice yield with plant growth parameters at panicle initiation stage. (*n*=256)

Variable	Panicle initiation stage	Heading stage
Shoot dry weight (ton/ha)	0.65**	0.74**
Tiller (No./m^2)	0 58**	ND
Shoot N concentration (%)	0.28*	0.51**
N uptake (kg/ha)	0.65**	0.76**
Nitrogen nutrition index	0.61**	0.72**
SPAD	0.70**	0.61**

Data used for this analysis obtained at Field A and B in 2002 and 2003 (*n*=256)
ND: no data
*Significant at the 0.05 probability level
**Significant at the 0.01 probability level

Table 11. Multiple linear stepwise regression of grain yield to plant growth and nutrition status at panicle initiation and heading stage.

	Panicle initiation stage			Model R-square	Heading stage			Model R-square
	Tiller N.	SPAD	NNI		DW	Nup	SPAD	
Parameter estimate	10.0	90 0	3827	0.662	325	7 49	102.0	0.661
Partial R-square	0.53	0.09	0 03		0.58	0.02	0.06	

Nup: shoot nitrogen content, Tiller N: tiller number, DW: shoot dry weight and SPAD: SPAD reading and rice yield in the two experimental fields in years of 2002 and 2003 had significant spatial variation within a single field regardless of years, fertilizer treatment and rice cultural method (Tables 3 (a), 4, 5 and 6). We may see from Table 3 (a) that CV of most of the soil properties was around 10% except of 16.3 and 21.4% for available Si in the Field A and B, respectively. The soil variation found in this study was lower than that reported by Cox *et al.* (2003). However, the research of Cox *et al.* (2003) was conducted in much large area (8.4 ha) of upland corn crop in comparison to the rice

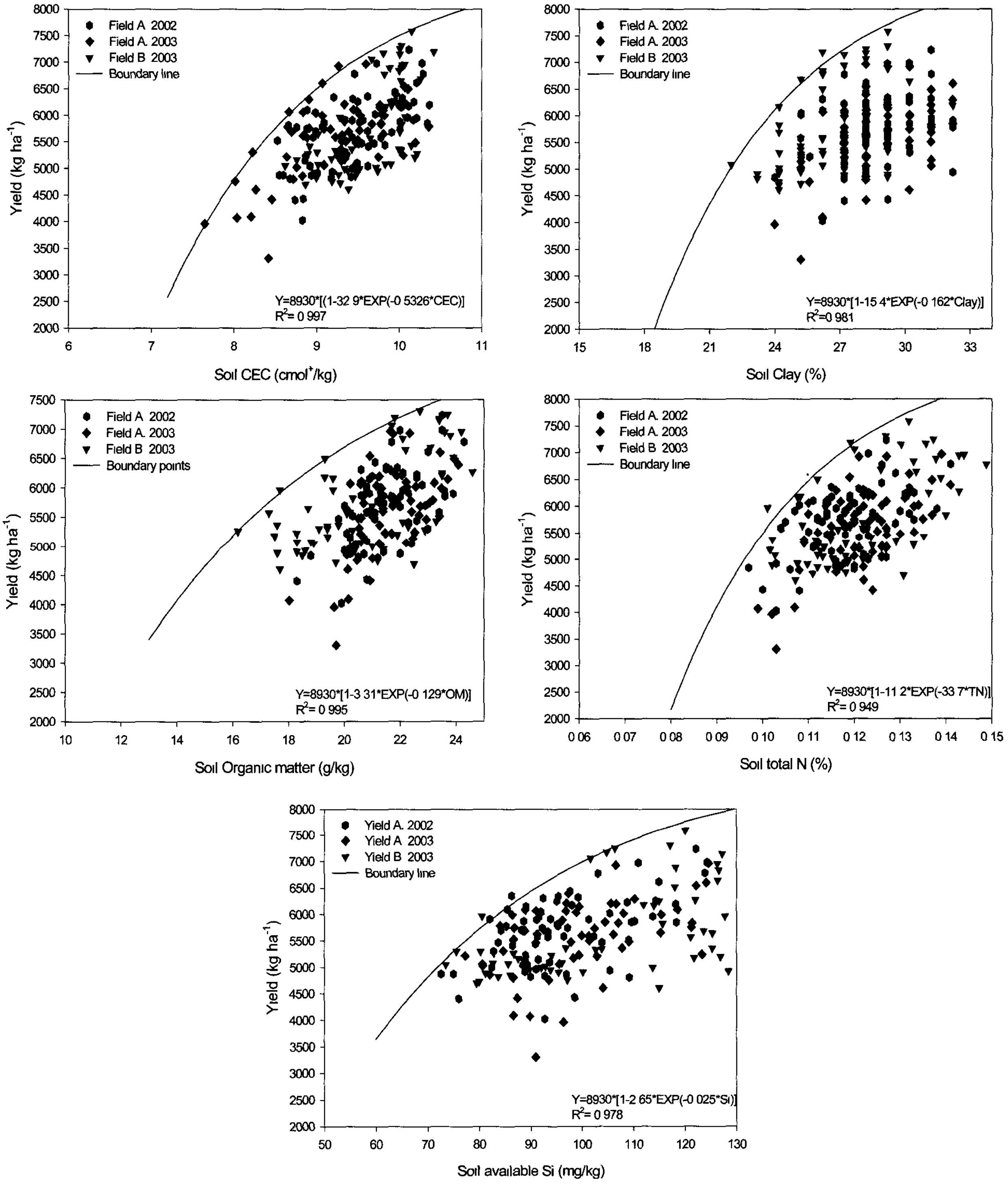


Fig. 6. Boundary line analysis of grain yield response to soil properties (Data used for this analysis obtained from experimental Field A and B in 2002 and 2003)

field (1.2 ha) in this experiment. The variation in soil properties of our research was in agreement with the results reported by Dobermann (1994) whose research was also conducted in the flooded paddy area of 3.6 ha. Based on degree of soil spatial variation, In comparison of the report by Casanova *et al.* (1999) that the variation in soil properties was as high as 36.9% for OM and 33.3% for N, our results (<10%) were much lower. The reason for the difference may result from that Casanova *et al.* (1999) conducted their experiment on very large scale and this was the variation among 50 fields compared to the within-field variation in our study.

At a field scale, plant growth parameters at PIS and HD were highly variable during experiments in 2002 and 2003. The higher variation of plant parameters such as plant dry matter, tiller number, and shoot nitrogen uptake was observed in comparison to the other parameters related to

Table 12. Boundary line equation for rice yield response to soil properties.

Boundary line equation	Index equation
ƒ(CEC)=8930*[(1-32 9*EXP(-0.5326*CEC)]	I_{CEC}=1-32.9*EXP(-0.5326*CEC)
ƒ(Clay)=8930*[1-15.4*EXP(-0.162*Clay)]	I_{Clay}=1-15.4*EXP(-0.162*Clay)
ƒ(TN)=8930*[1-11.2*EXP(-33.7*TN)]	I_{TN}=1-11.2*EXP(-33.7*TN)
ƒ(OM)=8930*[1-3.31*EXP(-0.129*OM)]	I_{OM}=1-3 31*EXP(-0.129*OM)
ƒ(Si)=8930*[1-2.65*EXP(-0.025*Si)]	I_{Si}=1-2.65*EXP(-0.025*Si)

Data from experimental Field A and B were used for this analysis with transplanted method
CEC: cation exchange capacity ($cmol^+/kg$) Clay. Soil clay (%) TN: soil total nitrogen (%)
OM: organic matter (g/kg) Si: available silica (mg/kg)

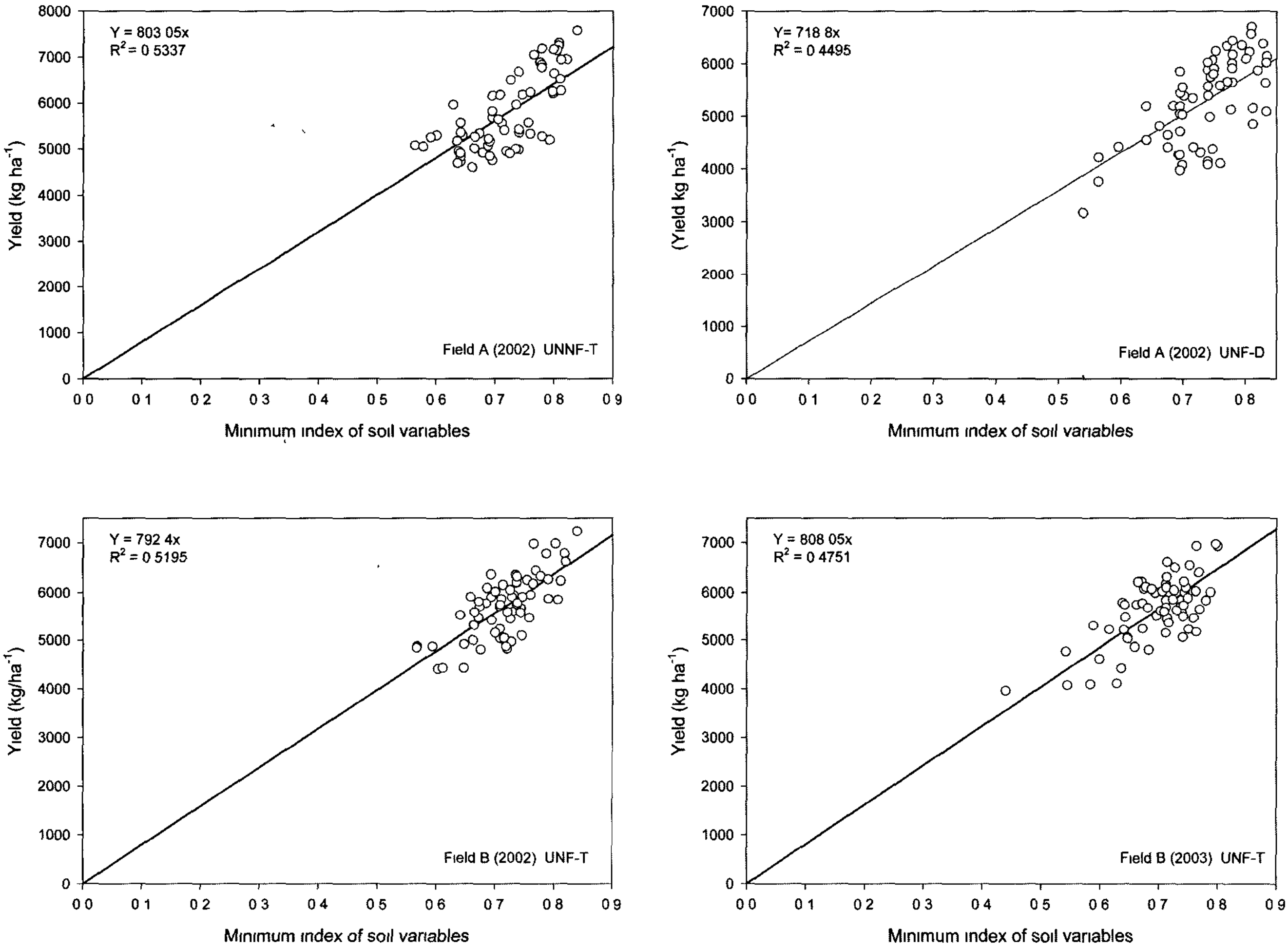


Fig. 7. Relationship between the minimum soil index identified from the boundary line analysis of rice yield response to soil properties (Table 12) and rice grain yield in Field A (2002 and 2003) and Field B (2002 and 2003).

plant nitrogen concentration such as shoot N concentration and SPAD values. This may result from the dilution effect (Cui *et al.*, 2002). Similar result of high variation of plant growth and yield of Field B in year 2003 (without fertilizer application) compared to the Field A in year 2003 (with N application) was reported by Dobermann (1994) and Dobermann & Pampolino (1995). The adverse growth condition under no N application may be the cause of the difference. The high spatial yield variation under direct-seeded field (21.5%) in Field B year 2002 compared to 11.5% in Field A under transplanting in the same year was as expected due to higher spatial variation of plant density and field lodging under direct-seeded culture. The higher spatial yield variation (39.0%) under direct-seeded rice field was also reported by Dobermann (1994) while lower spatial yield variation (14.4-17.6%) under transplanted rice culture was found by Dobermann *et al.* (1996).

The lower spatial variation in plant growth parameters at PIS and HD than that of rice yield under direct-seeding rice culture (Table 6) was in contrast to the results under transplanting rice culture and those reported by Salder *et al.* (2000). This might have resulted from the lodging damage during grain filling period at high fertility site in the field. Direct-seeding rice culture is reported to be more susceptible to lodging, compared to transplanted rice culture (Doberman, 1995).

Relationship among spatial variation in soil properties, plant growth and yield of rice

The significant correlation was observed among the measured soil properties (Table 3 (b)) and similar results were reported by Casanova *et al.* (1999), Basso *et al.* (2001), and Kravchcenko & Bullock (2000). The significantly high correlation of organic matter and clay content with CEC reflected the fact that total charge of CEC is originated mainly from surface charge of clay and organic matter in the soil. The high correlation between total N and organic matter (r=0.72) was clear because N was one of the consistently proportional component of soil organic matter.

The spatial variation of rice yield and plant growth in response to soil properties was examined to understand complex interactions between these factors within a field (Table 7). Plant growth at panicle initiation stage of the fields with transplanted rice had significant correlations with soil properties. The highest correlation for soil CEC and then for organic matter and soil total nitrogen was obtained in Field A with transplanted rice and ordinary uniform fertilization, while lower correlation was obtained in Field B with direct-seeded culture (year 2002) or no fertilization (year 2003). Similar high correlations of crop growth parameters with CEC were also reported by other researchers (Huang & Broadbent, 1998; Dobermann *et al.*, 1996; Casanova *et al.*, 1999). The lower correlation between soil and plant parameters at PIS and HD in Field B than in Field A suggests that other factors limit plant growth greater than the stable soil factors in without-fertilization or direct-seeded culture. Pierce *et al.* (1994) indicated that corn yield was loosely correlated with soil fertility parameters under unfavorable drought condition.

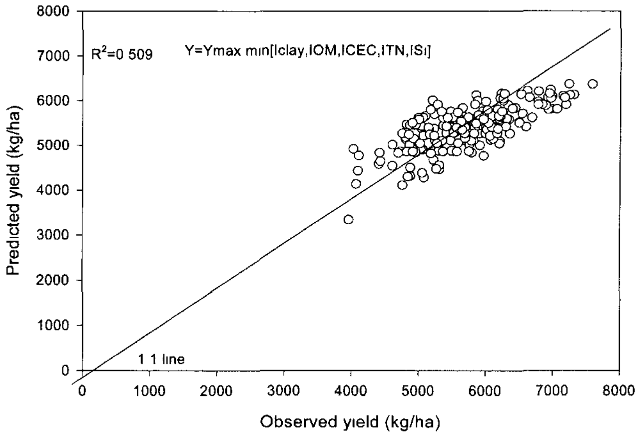


Fig. 8. Relationship between observed and predicted rice yield by boundary analysis and the Law of the minimum.

The significant correlation between soil properties and rice yield regardless of rice variety, cultural method, crop season, and fertilizer application (Table 8) promises the potential use of variation in soil properties within field for managing rice yield spatial variability. Shortage of very high correlation of crop growth and yield with soil properties in this study reflects that plant growth and grain yield are influenced by interrelationship among many factors (Machado *et al.*, 2002). To improve this limitation, they recommended that information on seasonally stable factors like elevation and soil texture is useful in identifying management zones while the management should be complemented by in-season management of seasonally unstable factors like rainfall, pest, and disease etc. Multiple linear regression using various soil, weather and management parameters for predicting rice grain yield over two years of two fields (R^2=0.76) showed the success of the multiple linear regression when interrelated influence among many factors were taken into account. This result was in line with Dobermann (1994) who used factor analysis for rice yield prediction or with Casanova *et al.* (1999) that explained spatial variability of rice yield using multiple regression analysis. Plant growth parameters measured at PIS or HD showed high correlation with rice grain yield (Table 10). Success of model to predict crop yield and yield components using crop parameters at critical

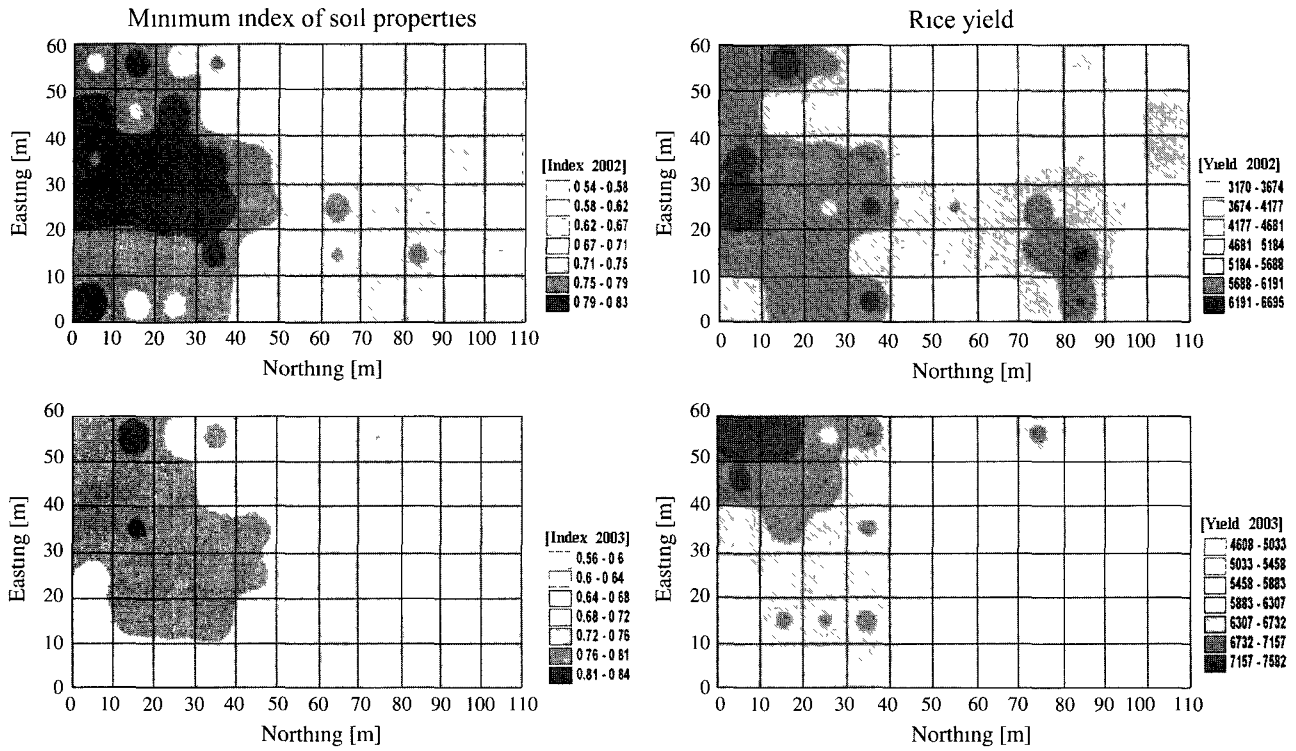


Fig. 9. (a) Kriged map of spatial variation of minimum index identified from the boundary line analysis of rice yield response to soil properties (Table 12) at the Field A in 2002 and 2003 (uniform fertilizer application with transplanted cultivation method).

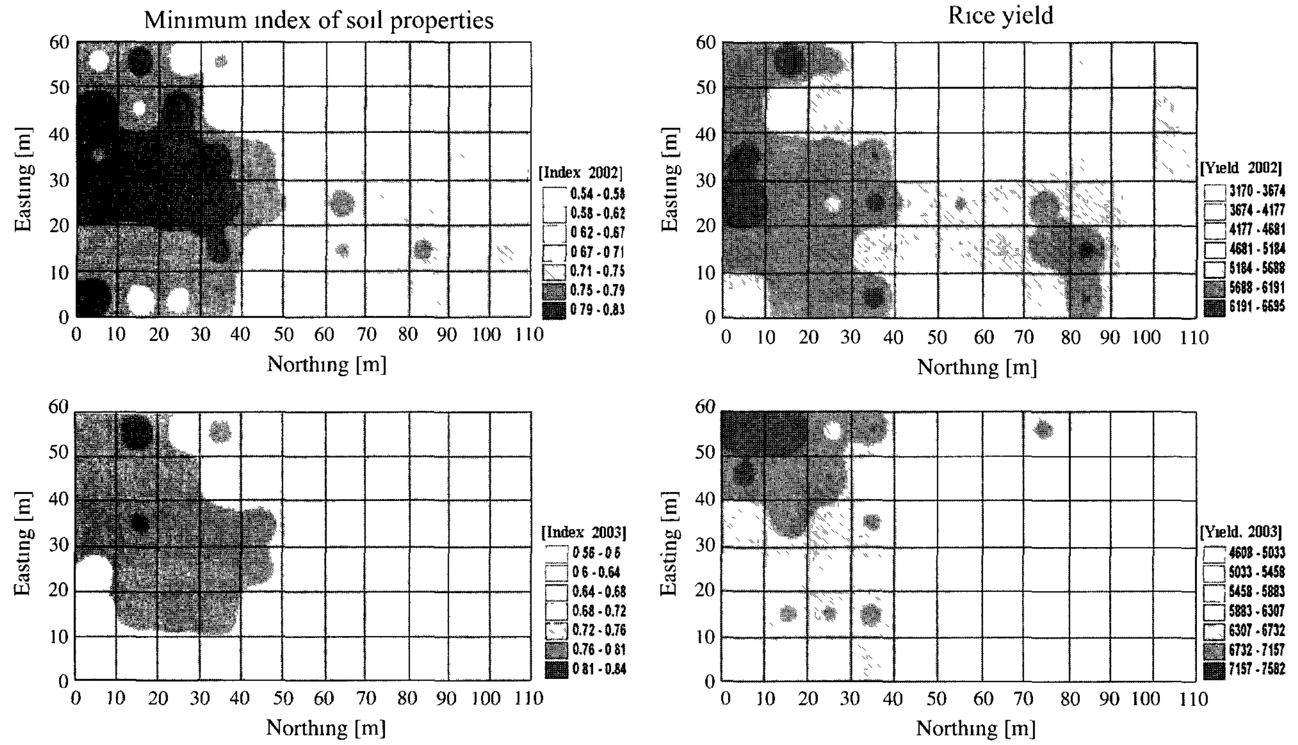
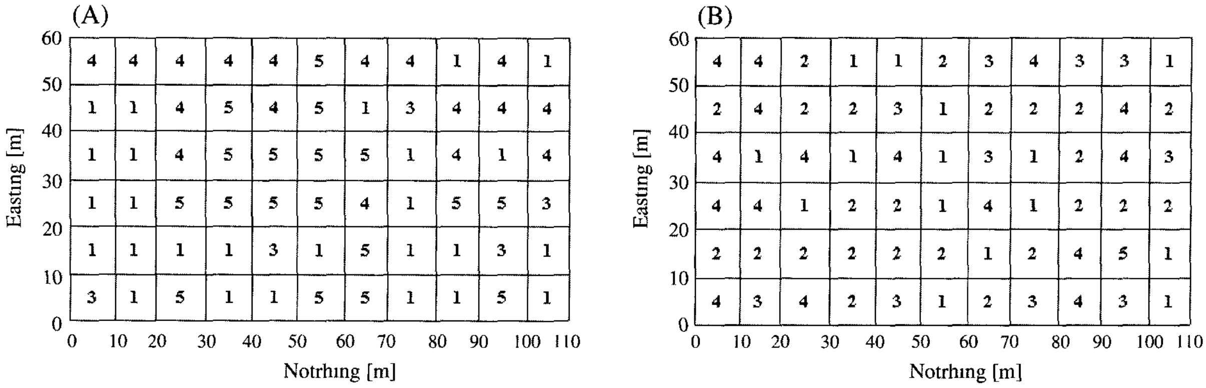


Fig. 9. (b) Kriged map of spatial variation of minimum index identified from the boundary line analysis of rice yield response to soil properties (Table 12) at the Field B in 2002 (uniform fertilizer application and direct-seeded) and 2003 (no fertilizer application and transplanted)



(A)

4	4	4	4	4	5	4	4	1	4	1
1	1	4	5	4	5	1	3	4	4	4
1	1	4	5	5	5	5	1	4	1	4
1	1	5	5	5	5	4	1	5	5	3
1	1	1	1	3	1	5	1	1	3	1
3	1	5	1	1	5	5	1	1	5	1

(B)

4	4	2	1	1	2	3	4	3	3	1
2	4	2	2	3	1	2	2	2	4	2
4	1	4	1	4	1	3	1	2	4	3
4	4	1	2	2	1	4	1	2	2	2
2	2	2	2	2	2	1	2	4	5	1
4	3	4	2	3	1	2	3	4	3	1

Fig. 10. Spatial distribution of soil limiting factors {CEC (1), Clay (2), TN (3), OM (4) and Si (5)} at Field A (A) and at Field B (B) in 2003.

growth periods have been proved (Cui & Lee, 2002; Casanova *et al.*, 2002). The multiple regression models to predict rice grain yield in this study explained 66% when plant parameters at PIS or at HD were used.

Even though multiple linear techniques had advantage in identifying influencing factors of crop yield or in predicting the value of a dependent variable from known or assumed values of other variables (Webster, 1997), collinearities among the independent variables is a major problem in regression techniques (Webster, 1997). Collinearity problems have been reported in most of earth science research (Mann, 1987; Bruce *et al.*, 1988; Hair *et al.*, 1992) as so did they in our study.. It is the fact that soil clay had relatively high correlations with rice yield (Table 8.). It was, however, excluded from the multiple linear regression model. This is firmly due to collinearities (soil clay content had very close correlation with soil CEC or OM). The same problem happened to the model to predict grain yield using plant properties (Table 11). For examples, shoot nitrogen uptake at PIS or HD were excluded from the model because it was highly correlated with other crop growth parameters.

Spatial yield variability with boundary line analysis and application of the Law of the Minimum

Boundary line or maximum line describes the response of dependent variable (yield) to variation in the test paramater (soil variables) where all other factor as close as possible to non-limiting factors in terms of rice yield (Casanova *et al.*, 1999). In this paper we independently developed our own procedures (Nguyen *et al.*, 2003). Spatial variation distributions of rice yields showed a similarity with surface maps of soil minimum index (Fig. 9.a. and b.) representing that the higher the index is the greater the rice yield is. Dobermann (1994) reported that multiple linear regression model based on soil properties explained 56% of spatial yield variability in Russia, and Casanova *et al.* (1999) found that 54% of yield variation was due to soil properties in Spain. These results are very similar to the result obtained from boundary line.analysis in this research (Fig.7 and Fig. 8). Even though multiple linear regression is a simple and convenient technique to quantify variation of rice yield in relation to soil properties, collinearity problems that violate the accuracy of model prediction can be occurred. Waggoner & Norvell (1979) first applied a mathematical technique to the Law of the Minimum, but it was shown adequate only within a given yield range where crops can adjust and maintain a condition of limiting factor (Sinclair & Park, 1993). Boundary line method allows all influencing or yield-determining factors to be quantified, and there is no violence of collinearity problem. In this paper, some soil properties such as clay content were eliminated out of the multiple linear regression models, but they were all retained and quantified with boundary line analysis (Fig. 6, Fig. 10, and Table 12). Boundary line analysis of yield response of rice to soil properties is highly recommended, particularly for identifying and quantifying the limiting factors for rice growth, and addressing the spatial variability of rice yield.

CONCLUSION

Within-field spatial variation of rice yields and plant growth response to soil properties were investigated in two paddy fields in Korea through 2002 and 2003. The result can be summarized as follow: Many measured variables including soil properties, plant growth and grain yield were found to be highly variable under different climate condition, cultivation and fertilizer application. Variation in plant growth and rice yield were strongly affected by different cultivation method. Rice yield and plant growth under direct-seeded rice appeared to be more variable than that of the field under transplanted rice. Measured soil properties were highly variable across the field or location. Plant growth of rice at PIS and heading stage were highly correlated with fairly stable soil properties such as CEC, TN, OM, soil texture, etc. This enabled us to interpret that variation of plant growth can be mainly caused by variation in soil properties within a single field. Many soil properties had significant correlations with rice yield such as soil CEC, OM, clay content, TN and available Si. They were found to be the major soil factors causing spatial yield variability in this research. Multiple linear regression model based on plant growth at PIS and heading stage explained an average of about 66% of spatial yield variability of rice crop, while model based on soil properties explained about 55% of spatial yield variability. Overall analysis of fertilizer application, climate condition and soil properties were carried using regression model accounting up to 76% of spatial yield variability. Boundary line analysis and an application of the Law of the minimum were well applied for an analysis of spatial variation of rice yield response to soil properties as explaining an average of 50% of yield spatial variability. Results of spatial variation of plant growth, soil properties and yield obtained from this research are consistent and agreed with other reported results (Dobermann, 1994; Casanova *et al.*, 1999).

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