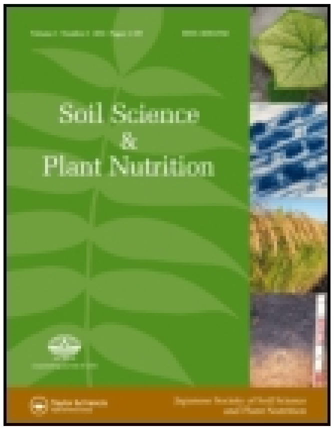

Soil Science and Plant Nutrition
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tssp20

Geostatistical analysis of soil chemical properties and rice yield in a paddy field and application to the analysis of yield-determining factors

Junta Yanai [a] , Choung Keun Lee [a] , Toshikazu Kaho [a] , Michihisa Iida [a] , Tsutomu Matsui [a] , Mikio Umeda [a] & Takashi Kosaki [a]
[a] Graduate School of Agriculture , Kyoto , 606-8502 , Japan
Published online: 04 Jan 2012.

Soil Sci. Plant Nutr., 47 (2), 291-301, 2001

Geostatistical Analysis of Soil Chemical Properties and Rice Yield in a Paddy Field and Application to the Analysis of Yield-Determining Factors

Junta Yanai[1], Choung Keun Lee, Toshikazu Kaho, Michihisa Iida, Tsutomu Matsui, Mikio Umeda, and Takashi Kosaki

Graduate School of Agriculture, Kyoto University, Kyoto, 606-8502 Japan

Received August 25, 2000; accepted in revised form February 2, 2001

To obtain basic information for rational site-specific soil management for rice production, spatial variability of soil chemical properties and grain yield of rice was evaluated in a 50 m×100 m paddy field. One hundred surface soil samples were collected from each of the 5 m×10 m plots before puddling to investigate the spatial variability of their chemical properties: pH, EC, total C content, total N content, C/N ratio, contents of mineralizable N, inorganic N, available P, exchangeable Ca, Mg, K, and Na. Grain yield was also measured at harvest for the corresponding 100 plots. Geostatistical analysis was carried out to examine their within-field spatial variability using semivariograms, and multivariate analysis was also carried out to evaluate yield-determining factors. Geostatistical analysis of the soil properties indicated a high to moderate spatial dependence for all the properties except for the inorganic N content. The ranges of spatial dependence were about 20-30 m for the pH, EC, total C content, total N content, content of exchangeable Na, about 40 m for the contents of available P, mineralizable N, exchangeable Ca and Mg, and about 50-60 m for the C/N ratio and content of exchangeable K. Grain yield showed a moderate spatial dependence with a range of about 50 m. The results of spatial dependence enabled to prepare kriged maps of the soil properties and yield to compare their spatial distribution in the field. Multivariate analysis further showed, in combination with geostatistics, that the soil chemical properties contributed significantly to the yield as yield-determining factors and explained as much as 65% of the spatially structured or non-random variation of the yield. In conclusion, the possible benefit of site-specific soil management or precision agriculture was demonstrated even in an almost flat paddy field.

Key Words: **geostatistics, multivariate analysis, paddy field, rice yield, soil chemical properties.**

Spatial variability of soil properties and crop yield has been one of the major objectives in investigations related to agricultural sciences. Geostatistical analysis (Trangmar et al. 1985; Webster 1985) of such properties provides the basis for describing their spatial variation, for estimating and mapping them, and for planning their rational sampling schemes in the field. Such information can also contribute to site-specific soil/fertilizer

[1] E-mail address: yanai@kais.kyoto-u.ac.jp

management of agricultural systems, i.e. precision agriculture, which enables to increase the yield and to improve the quality of crops with a lower environmental impact of agricultural activities. This will become more important due to the recent tendency to the increase of the average farm size as well as the decrease of the number of farmers.

Against this background, spatial variability of soil properties and crop yield in upland fields has been evaluated, mainly in the USA, European countries, and Australia. For example, yield of wheat (Miller et al. 1988; Bhatti et al. 1999), barley (Finke and Goense 1993), maize (Lengnick 1997; Timlin et al. 1998), upland rice (Trangmar et al. 1987), and pearl millet (Stein et al. 1997) has been examined mainly in hillside fields or irrigated fields, in combination with soil properties. In spite of their historical and economic importance in Japanese agriculture, however, information on spatial variability in paddy fields is still limited only to soil chemical properties (Yanai et al. 2000). No information is available on the spatial relationship between rice yield and soil chemical properties, which are quite often yield-determining factors. The objectives of this study were, therefore, firstly to evaluate the spatial variability of soil properties and grain yield of rice in a paddy field, and secondly to examine the relationship by combining geostatistics with multivariate analysis, both of which may provide basic information for rational site-specific soil management in paddy fields.

MATERIALS AND METHODS

Experimental field. The experiment was carried out at the experimental farm of Kyoto University located in Takatsuki, Osaka prefecture (135°38′E, 34°51′N, 10 m above sea level) with a mean annual temperature and precipitation of 15.8°C and 1,240 mm, respectively. The paddy field examined was almost flat (0.07%) with an area of 0.5 ha (50 m $\times$ 100 m). It had been used as an experimental paddy field since 1928 and an average yield of about 6 Mg ha^{-1} as brown rice had been recorded. The soil of the field was classified as Typic Fluvaquent (Soil Survey Staff 1998) or Gray Lowland soil (Committee for Soil Classification and Nomenclature 1986). The soil in the plow layer showed, on the average, a textural class of clay loam and a CEC value of 14.5 cmol(+) kg^{-1}.

Soil management and fertilization. Field experiments were carried out from May to November, 1999. Basal application of chemical fertilizers at rates equivalent to 3.58, 3.04, and 3.58 g m^{-2} of N, P_2O_5, and K_2O, respectively, was conducted on May 30. Seedlings of rice (*Oryza sativa* L. cv. Minamihikari) were transplanted on June 7, after puddling on June 4. Topdressing of chemical fertilizer was carried out on July 30 at the panicle formation stage, at rates equivalent to 2.86 g m^{-2} of N and 2.86 g m^{-2} of K_2O. All the management and fertilization procedures, which followed conventional practices in this area, were conducted homogeneously in the 50 m $\times$ 100 m field.

Soil sampling and analysis. Soil samples were collected on May 10, 1999, 20 d before the basal application of fertilizers, for the investigation of the spatial variability of soil chemical properties. The field was divided into one-hundred 5 m $\times$ 10 m plots (Fig. 1) and soil sample was collected as a composite of 5 sub-samples from the surface soil (0 to 15 cm deep) within a 2 m circular area centered on each plot.

All the soil samples were air-dried and sieved through a 2 mm mesh sieve before the analyses. The electrical conductivity (EC), pH, total C content, total N content, C/N ratio, contents of mineralizable N, inorganic N, available P, exchangeable Ca, Mg, K, and Na were measured as chemical properties of the soil. Total C content, total N content, and C/N ratio

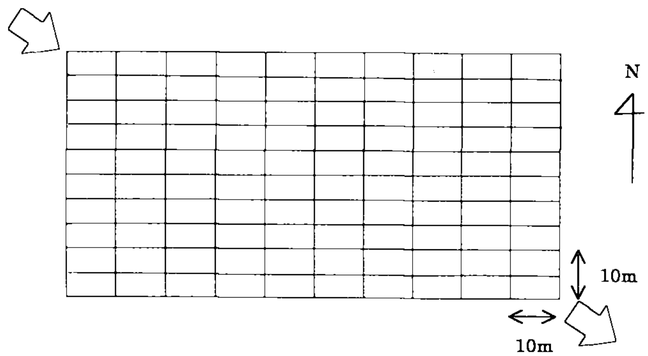

Fig. 1. Schematic diagram of the experimental field and plots for soil and grain samplings. The lattice indicates the 100 sampling areas, and arrows indicate the direction of water flow in the paddy field.

were determined by the dry combustion method (Sumigraph NC analyzer NC-800, Sumika Chem. Anal. Service). Inorganic N content was determined by extracting the sample with a 2 M KCl solution in a 1 : 5 soil : solution ratio. Mineralizable N content was obtained as the difference between the amount of N extractable with 2 M KCl solution before and after incubation at 30°C for 4 weeks under waterlogged conditions. In the analyses, the concentrations of NH_4^+ and NO_3^- (after reduction to NO_2^-) were determined by the indophenol method and Griess-Ilosvay method, respectively (Mulvaney 1996). All the other analytical procedures were previously described by Yanai et al. (2000).

Grain sampling and calculation of grain yield. Grain yield data were collected by Lee et al. (2000), i.e. grain sampling was carried out at harvest, i.e. from October 29 to November 3, 1999. The field was divided into one-hundred 5 m×10 m plots as in the case of soil sampling (Fig. 1). Unhulled rice was harvested in each plot using a head-feeding combine harvester (Yanmar Co. Ee-8) and their fresh weight and moisture content in each plot were measured separately. Grain yield was then calculated based on the dry weight of unhulled rice.

Geostatistical analysis. In the geostatistical analysis, a semivariogram was used to evaluate the spatial variability of the properties, and two indices were used to evaluate the spatial dependence of the soil properties and yield, as described by Yanai et al. (2000). One is the Q value, which indicates the spatial structure on the sampling scale (Goerres et al. 1997). This value is given by the following equation:

$$Q=\frac{S-N}{S}$$

where S and N are the sill and the nugget variance, respectively. The other is the range, which indicates the limit of spatial dependence.

In the analysis, the semivariogram model with the highest r^2 value was used for the estimation of the semivariogram parameters. Maps of each property were computed subsequently using block kriging, by taking account of the data within the range. Block kriging was used instead of punctual kriging because it enables to evaluate the regional patterns of variation rather than local details, due to the construction of smoother maps with smaller estimation variances. A geostatistical software, GS^+ Version 3.1 for Windows (Gamma Design Software), was used in the analysis (Robertson 1998).

Statistical analysis. Descriptive statistics was obtained for each variable in terms of a mean and a coefficient of variation (CV). Multivariate analysis was also carried out to elucidate the yield-determining factors quantitatively, that is, principal component analysis (PCA) of the soil chemical properties was firstly carried out to summarize data and investigate the relationships among the properties, as described in detail by Kosaki and Juo (1989). Secondly, stepwise multiple regression analysis was carried out, using the scores of the extracted principal components and those of positional data as independent variables, and grain yield as a dependent variable, respectively, as described by Kosaki et al. (1989). A statistical software SYSTAT 8.0 was used in the analysis (SPSS Inc. 1998).

RESULTS AND DISCUSSION

Descriptive statistics of soil chemical properties and grain yield in the paddy field

Table 1 gives the descriptive statistics, i.e. the mean, maximum, minimum, and CV for each of the 12 chemical properties of soil and grain yield of rice. The mean of soil properties was representative of a typical paddy soil in Japan with an almost neutral pH range, about 3% carbon, C/N ratio of 11, and adequate contents of exchangeable cations and available phosphorus, as described by Yanai et al. (2000) for the soil samples collected in the spring of 1998. The mean of unhulled rice yield was 7.34 Mg ha^{-1} on a dry weight basis, which corresponds to about 6.75 Mg ha^{-1} as hulled or brown rice with a water content of 15%, i.e. within the average level for Minamihikari in this region (Lee et al. 2000). The CV values for EC, total C content, total N content, contents of mineralizable N, inorganic N, available P, exchangeable Mg, K, and Na exceeded 10%, indicating a considerable variability of the soil properties even in the paddy field, whereas, the value for grain yield was 5.89%, suggesting a lower within-field variability.

Spatial dependence of soil chemical properties and grain yield in the paddy field

Figures 2 and 3 (left) show the semivariograms for the 12 soil chemical properties and grain yield, respectively. The nugget variance, sill, range, and Q value of each were estimated from each of the semivariograms by using the fitting model with the highest r^2 value (Table 2). The degree of spatial dependence of the soil properties varied among the properties examined. The Q values ranged from 0.72 to 1.00 for the pH, EC, total C content, total N content, C/N ratio, contents of available P, exchangeable Ca, Mg, K, and Na, suggesting a highly developed spatial structure. The value for the mineralizable N content was 0.50;

Table 1. Descriptive statistics of chemical properties of the soil and grain yield.

	pH	EC ($\times 10^{-4}$ S m^{-1})	Total-C ($\times 10^{-2}$ kg kg^{-1})	Total-N ($\times 10^{-2}$ kg kg^{-1})	C/N	Min. N[a] (mg kg^{-1})	Inorg. N[b] (mg kg^{-1})
Mean	6.40	108	3.17	0.29	11.0	88.9	13.6
Maximum	6.66	175	4.56	0.39	13.2	148	34.5
Minimum	6.14	82.7	2.15	0.23	9.09	59.3	7.74
CV[c]	1.63	14.7	16.0	12.7	8.16	18.6	34.7

	Available P[d] (g kg^{-1})	exCa[e] (cmol(+) kg^{-1})	exMg[e] (cmol(+) kg^{-1})	exK[e] (cmol(+) kg^{-1})	exNa[e] (cmol(+) kg^{-1})	Grain yield[f] (Mg ha^{-1})
Mean	2.33	12.5	1.40	0.64	0.17	7.34
Maximum	3.02	15.4	1.92	0.85	0.25	8.02
Minimum	1.70	10.1	0.88	0.43	0.12	6.01
CV[c]	13.6	9.34	13.2	12.0	14.9	5.89

[a]Mineralizable N. [b]Inorganic N. [c]Coefficient of variation (%). [d]Bray No. 2 method. [e]Exchangeable Ca, Mg, K, and Na. [f]Unhulled rice.

indicating the presence of a moderate development of the spatial structure, whereas, the inorganic N content was considered to show a low spatial dependence based on visual judgement rather than using the fitting model with low r^2. For the properties except for the inorganic N content, therefore, the ranges could be interpreted as the distance of spatial dependence. The ranges were about 20–30 m for the pH, EC, total C content, total N content, and content of exchangeable Na. The ranges for the contents of available P, mineralizable N, exchangeable Ca and Mg were about 40 m, whereas, those for the C/N ratio and content of exchangeable K were about 50–60 m.

For the grain yield, on the contrary, the Q value was 0.66, indicating a relatively well developed spatial structure (Lee et al. 2000). The range was estimated to be 52.9 m, suggesting a relatively long range of spatial dependence. These results indicate the possible benefit of site-specific soil management for these properties, and accordingly, for the grain yield.

Spatial variability of soil chemical properties and grain yield

Figures 2 and 3 (right) show the kriged maps for the soil chemical properties and grain yield, respectively, which were drawn by block kriging based on the data within the ranges. Considerable spatial variability was clearly observed for all the soil properties except for the inorganic N content, and also for the grain yield, in accordance with the results of the semivariograms. That is, total C content, total N content, contents of mineralizable N, available P, and exchangeable Ca were relatively high in the area about 10–30 m from the southern border of the field with some gradation from west to east. Spatial variability of these properties presumably reflected the microrelief as the area had a relatively low elevation, as shown in Fig. 4 (Lee et al. 2000) and the water flow from northwest to southeast, in addition to the uneven organic matter application from 1978 to 1980, when the areas 12.5–25 m and 25–37.5 m from the southern border of the field received 40 and 20 Mg ha^{-1} more cow manure annually than the other areas (0–12.5 m and 37.5–50 m) (Yabuki et al. 1980). The pH and content of exchangeable K, on the contrary, showed a slight gradation from northwest to southeast, probably reflecting the water flow in that direction.

On the other hand, grain yield was slightly higher in the southern area compared with the northern one, as reported by Lee et al. (2000). This pattern was also observed for the total C content, total N content, and contents of mineralizable N and available P of soil, suggesting that grain yield may be affected by these soil properties.

Multivariate analysis of the relationship between soil chemical properties and grain yield of rice

As a result of PCA, the first three principal components (PC1 to PC3) were derived as components with eigenvalues higher than 1.0, and they accounted for more than 70% of the total variance (Table 3). The remaining components became less significant and were considered as errors, which included the random components of soil variation and various types of errors in soil sampling and analysis. Based on the component loadings after varimax rotation, the first component showed high to moderate loadings with the total C content, total N content, contents of available P and mineralizable N. Since these properties were related to the organic matter status, the first component was referred to as "organic matter factor (OMF)." The second component showed high to moderate loadings with the contents of exchangeable Ca, Mg, K in addition to the content of inorganic N and C/N ratio. Since these properties correspond to base status of soil, this component was referred to as "exchangeable base factor (EBF)." Since the third component showed high loadings with

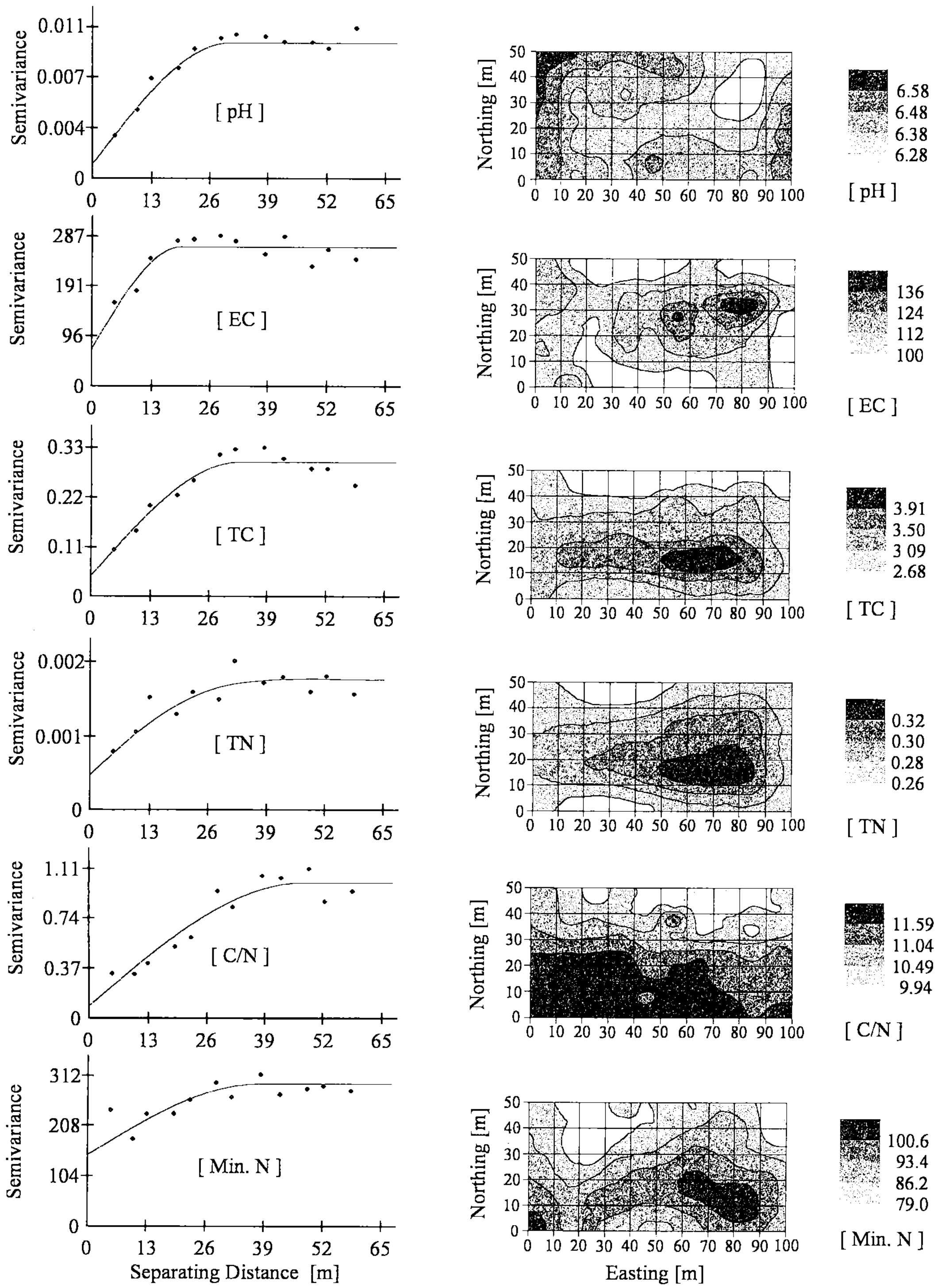

Fig. 2. Semivariograms and kriged maps of chemical properties of the soil in the paddy field. pH: EC ($\times 10^{-4}$ S m^{-1}); TC, TN: total C and N ($\times 10^{-2}$ kg kg^{-1}); C/N: C/N ratio; Min. N: mineralizable N (mg kg^{-1}).

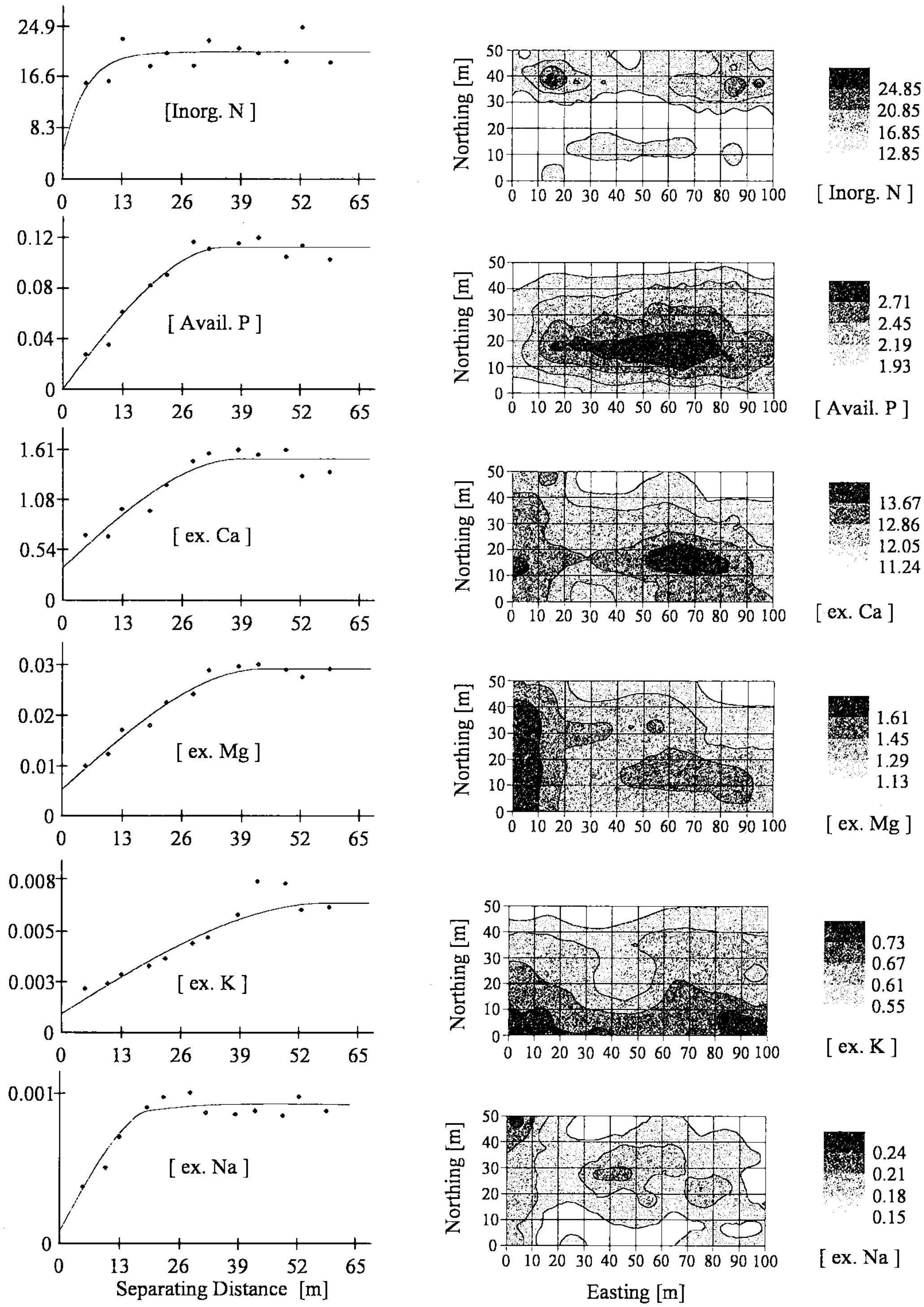

Fig. 2. Continued. Inorg. N: inorganic N (mg kg^{-1}); Avail. P: available P (g kg^{-1}); ex. Ca, ex. Mg, ex. K, and ex. Na: exchangeable Ca, Mg, K, and Na (cmol(+) kg^{-1}).

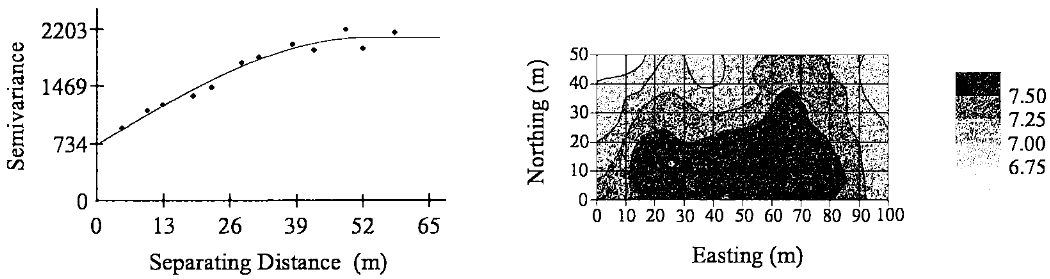

Fig. 3. Semivariogram and kriged map of measured rice yield in the paddy field (Mg ha^{-1}) (cited from Lee et al. 2000).

Table 2. Geostatistical parameters of chemical properties of the soil and grain yield.

	pH	EC ($\times 10^{-4}$ S m^{-1})	Total-C ($\times 10^{-2}$ kg kg^{-1})	Total-N ($\times 10^{-2}$ kg kg^{-1})	C/N	Min. N[a] (mg kg^{-1})	Inorg. N[b] (mg kg^{-1})
Nugget (N)	0.001	69.4	0.045	0.0005	0.085	146	4.24
Sill (S)	0.010	266	0.296	0.0018	1.001	292	20.8
Range (R)	30.7	19.9	32.8	32.8	47.7	38.2	14.7
Q value[c]	0.90	0.74	0.85	0.72	0.92	0.50	0.78
Model	Spher.[d]	Spher.	Spher.	Spher.	Spher.	Spher.	Expo.[d]
r^2	0.97	0.77	0.89	0.86	0.90	0.64	0.35

	Available P[e] (g kg^{-1})	exCa[f]	exMg[f]	exK[f]	exNa[f]	Grain yield (Mg ha^{-1})
		(cmol(+) kg^{-1})				
Nugget (N)	0	0.344	0.006	0.001	0.0001	723
Sill (S)	0.115	1.51	0.033	0.007	0.0009	2,095
Range (R)	35.4	38.9	43.8	58.2	24.2	52.9
Q value[c]	1.00	0.77	0.82	0.86	0.89	0.66
Model	Spher.	Spher.	Spher.	Spher.	Spher.	Spher.
r^2	0.96	0.88	0.97	0.89	0.92	0.96

[a]Mineralizable N. [b]Inorganic N. [c]Calculated as $(S-N)/S$. [d]Spher., spherical; Expo., exponential. [e]Bray No. 2 method. [f]Exchangeable Ca, Mg, K, and Na.

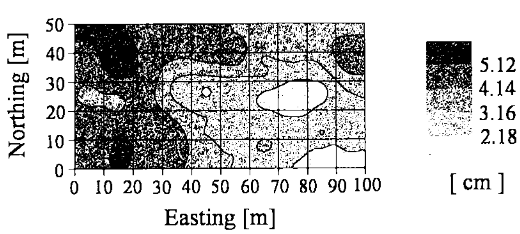

Fig. 4. Relative elevation of the paddy field (cited from Lee et al. 2000).

the content of exchangeable Na and EC, this component was designated as "soluble salts factor (SSF)." In this way, variation of the soil properties was summarized into a small number of factors, which were independent of each other.

Stepwise multiple regression analysis was subsequently performed to obtain the optimum model for predicting the rice yield performance. In the analysis, grain yield was used as a dependent variable, and standardized scores of the three principal components described above were used as independent variables. Since no *a priori* information was available about

Table 3. Component loadings, eigenvalues, percentage of total variance explained for the first three principal components.

Variable	PC1	PC2	PC3
pH	−0.63	0.56	0.24
EC	0.37	−0.35	0.67
Total-C	0.85	0.36	0.26
Total-N	0.85	−0.04	0.37
C/N	0.33	0.79	−0.04
Mineralizable N	0.54	0.35	−0.04
Inorganic N	0.08	−0.67	0.11
Available P	0.86	0.18	0.09
Exchangeable Ca	0.45	0.57	0.50
Exchangeable Mg	0.19	0.61	0.67
Exchangeable K	0.31	0.56	0.03
Exchangeable Na	−0.03	−0.02	0.86
Eigenvalue	3.43	2.79	2.18
Percentage of total variance[a] (%)	28.6	51.9	70.1

[a] Calculated as cumulative value.

the regression model, we assumed the presence of a linear combination of the first and second degree terms of the variables and excluded the term for the crossing effect. The reason for the inclusion of the second degree terms is that the optimum value to produce the highest yield may lie within the range of the data employed.

The most appropriate model obtained with significance levels of $\alpha = 0.15$ was:

$$\text{Predicted yield} = 739 + 21.6\ (\text{OMF}) + 10.3\ (\text{EBF}) - 7.05\ (\text{SSF})^2$$

with R^2 equal to 0.43. The fact that R^2 equals 0.43 in this model indicates that the model using only soil chemical factors explains 43% of the total variance of the measured yield. The regression coefficients in the equation generally indicate the magnitude of each factor in its contribution to the rice yield performance. Since OMF contributed to rice yield with the largest magnitude, organic matter application increased yield to a large extent. The contribution of EBF was next to that of OMF among the soil factors, suggesting the importance of the base status of soil for yield, whereas, SSF showed a negative contribution to the yield as the second degree term.

To obtain a better model for predicting yield performance, another stepwise multiple regression analysis was further carried out, using grain yield as a dependent variable, and the three soil factors and standardized scores of the coordinate data, i.e. X: west-east, and Y: north-south direction, as independent variables. For the coordinate data, the origin of the coordinates was set at the center of the field. The following equation was obtained with significance levels of $\alpha = 0.15$:

$$\begin{aligned}\text{Predicted yield} &= 744 + 26.7\ (\text{OMF}) - 15.6\ (\text{X})^2 + 10.9\ (\text{EBF}) + 10.5\ (\text{Y})^2 - 6.71\ (\text{OMF})^2 \\ &= 770 - 6.71\ (\text{OMF} - 1.99)^2 - 15.6\ (\text{X})^2 + 10.9\ (\text{EBF}) + 10.5\ (\text{Y})^2\end{aligned}$$

with R^2 being equal to 0.52. It is suggested that the inclusion of the coordinate data improved the model considerably. Since OMF contributed to rice yield with the largest magnitude, organic matter application increased yield to a large extent. As the first and the second degree terms were involved in this model, the optimum was included in the range of the data, which was actually near the maximum value of OMF. The contribution of EBF was

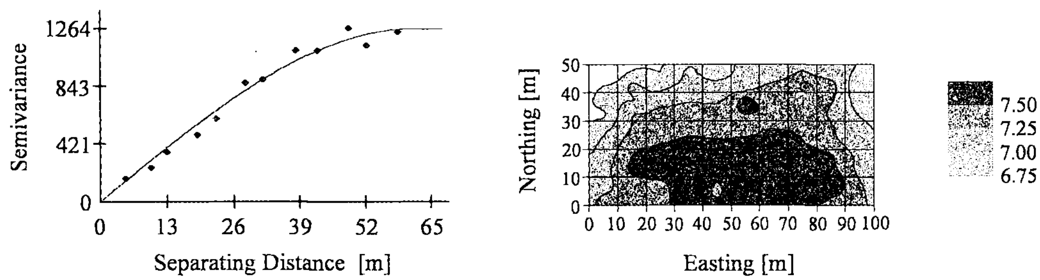

Fig. 5. Semivariogram and kriged map of estimated rice yield in the paddy field (Mg ha^{-1}).

next to that of OMF among the soil factors, suggesting the importance of the base status of soil for yield, whereas, SSF was eliminated from the prediction function at this significance level. Both positional data X and Y affected yield in the second degree terms, but the contribution was negative for X and positive for Y. The positive contribution of Y in the second degree term implies that the yield increased near the northern and southern borders, presumably due to the border effect associated with the favourable conditions for sunlight and CO_2 acquisition. On the other hand, the negative contribution of X in the second degree term implies that the yield decreased near the western and eastern borders, presumably due to the deterioration of the soil physical conditions and possible direct damage to plants caused by repeated traffic of agricultural machines, which outweighed the positive border effect.

Application of geostatistics to the interpretation of yield-determining factors with multivariate analysis

Figure 5 shows the semivariogram and kriged map of the estimated yield, which was calculated by the second model described above. From the semivariogram, the Q value was calculated to be 1.00, suggesting that the multiple regression model, which explained 52% of the total variance of the yield, in fact omitted all the random components of the yield. This suggested that all the variation expressed in the estimate was spatially structured. On the other hand, the semivariogram of the measured yield (Fig. 3) indicated that 66% of the total variation of the measured yield was spatially structured (Table 2), and 34% of the variation was originally random or unable to be controlled on this scale. These results, therefore, indicated that the equation based on the soil chemical properties and coordinate data explained about 79% (i.e. 52% out of 66%) of the spatially structured or non-random variation of the yield. This value would still be 65% (i.e. 43% out of 66%) even if only the soil chemical properties were taken into account.

Conclusion

Spatial variability of the soil chemical properties and yield of rice was evaluated in a paddy field and a high contribution of soil chemical properties as yield-determining factors was well demonstrated by combining geostatistics with multivariate analysis. These results suggest the possible benefit of rational site-specific soil management or precision agriculture in the paddy field and may provide basic information for such kind of management in paddy fields in general, although only one case study was conducted. Investigations of a similar relationship in various fields and during different cultivation years may enable to define the general concept of spatial variability of paddy fields in Japan. Also, further studies will be conducted to investigate the effectiveness of site-specific soil management such as fertilizer application to increase grain yield with reduced application rate through minimizing yield variation in paddy fields.

Acknowledgments. The authors are grateful to Mr. H. Kagata and Mr. R. Wada, Experimental Farm of Kyoto University, for the agricultural management during the experiment, and Drs. T. Inamura and T. Amano, Kyoto University, for their valuable discussions on the spatial variability of the paddy field. This research was partly supported by Bio-oriented Technology Research Advancement Institution (BRAIN).

REFERENCES

Bhatti, A.U., Bakhsh, A., Afzal, M., and Gurmani, A.H. 1999: Spatial variability of soil properties and wheat yields in an irrigated field. *Commun. Soil Sci. Plant Anal.*, **30**, 1279–1290

Committee for Soil Classification and Nomenclature 1986: Unified soil classification system in Japan (1st approximation). *Pedologist*, **30**, 123–139 (in Japanese)

Finke, P.A. and Goense, D. 1993: Differences in barley grain yields as a result of soil variability. *J. Agric. Sci.*, **120**, 171–180

Goerres, J.H., Dichiaro, M.J., Lyons, J.B., and Amador, J.A. 1997: Spatial and temporal patterns of soil biological activity in a forest and an old field. *Soil Biol. Biochem.*, **30**, 219–230

Kosaki, T. and Juo, A.S.R. 1989: Multivariate approach to grouping soils in small fields. I. Extraction of factors causing soil variation by principal component analysis. *Soil Sci. Plant Nutr.*, **35**, 469–477

Kosaki, T., Wasano, K., and Juo, A.S.R. 1989: Multivariate statistical analysis of yield-determining factors. *Soil Sci. Plant Nutr.*, **35**, 597–607

Lee, C.K., Yanai, J., Kaho, T., Iida, M., Umeda, M., Kosaki, T., and Matsui, T. 2001: Mapping of field information in a paddy field. *J. Jpn. Soc. Agric. Mach.*, **63** (in Japanese) (in press)

Lengnick, L.L. 1997: Spatial variability of early season nitrogen availability indicators in corn. *Commun. Soil Sci. Plant Anal.*, **28**, 1721–1736

Miller, M.P., Singer, M.J., and Nielsen, D.R. 1988: Spatial variability of wheat yield and soil properties on complex hills. *Soil Sci. Soc. Am. J.*, **52**, 1133–1141

Mulvaney, R.L. 1996: Nitrogen—Inorganic forms. *In* Methods of Soil Analysis, Part 3, Chemical Methods, SSSA Book Series No. 5, p. 1123–1184, Soil Science Society of America and American Society of Agronomy, Madison

Robertson, G.P. 1998: GS+: Geostatistics for the Environmental Sciences, Gamma Design Software, Plainwell, MI

Soil Survey Staff 1998: Keys to Soil Taxonomy (8th edition), 326 pp., USDA Natural Resources Conservation Service, Washington, D.C.

SPSS Inc. 1998: SYSTAT 8.0, Statistics, 1086 pp., SPSS Inc., Chicago

Stein, A., Brouwer, J., and Bouma, J. 1997: Methods for comparing spatial variability patterns of millet yield and soil data. *Soil Sci. Soc. Am. J.*, **61**, 861–870

Timlin, D.J., Pachepsky, Y., Snyder, V.A., and Bryant, R.B. 1998: Spatial and temporal variability of corn grain yield on a hillslope. *Soil Sci. Soc. Am. J.*, **62**, 764–773

Trangmar, B.B., Yost, R.S., and Uehara, G. 1985: Application of geostatistics to spatial studies of soil properties. *Adv. Agron.*, **38**, 45–94

Trangmar, B.B., Yost, R.S., Wade, M.K., Uehara, G., and Sudjadi, M. 1987: Spatial variation of soil properties and rice yield on recently cleared land. *Soil Sci. Soc. Am. J.*, **51**, 668–674

Webster, R. 1985: Quantitative spatial analysis of soil in the field. *In* Advances in Soil Science, Vol. 3, Ed. B.A. Stewart, p. 1–70, Springer-Verlag New York Inc., New York

Yabuki, H., Natori, K., Ichihashi, H., and Sekiyama, F. 1980: Effect of consecutive manure application on the direct seeding cultivation of paddy rice. *Annu. Rep. Kyoto Univ. Exp. Farm, Kyoto Univ.*, p. 8–9 (in Japanese)

Yanai, J., Lee, C.K., Umeda, M., and Kosaki, T. 2000: Spatial variability of soil chemical properties in a paddy field. *Soil Sci. Plant Nutr.*, **46**, 473–482