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Spatial Variability of Nitrous Oxide Emissions and Their Soil-Related Determining Factors in an Agricultural Field

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ABSTRACT

To evaluate spatial variability of nitrous oxide (N_2O) emissions and to elucidate their determining factors on a field-scale basis, N_2O fluxes and various soil properties were evaluated in a 100- × 100-m onion (*Allium cepa* L.) field. Nitrous oxide fluxes were determined by a closed chamber method from the one-hundred 10- × 10-m plots. Physical (e.g., bulk density and water content), chemical (e.g., total N and pH), and biological (e.g., microbial biomass C and N) properties were determined from surface soil samples (0–0.1 m) of each plot. Geostatistical analysis was performed to examine spatial variability of both N_2O fluxes and soil properties. Multivariate analysis was also conducted to elucidate relationships between soil properties and observed fluxes. Nitrous oxide fluxes were highly variable (average 331 μg N m^{-2} h^{-1}, CV 217%) and were log–normally distributed. Log-transformed N_2O fluxes had moderate spatial dependence with a range of >75 m. High N_2O fluxes were observed at sites with relatively low elevation. Multivariate analysis indicated that an organic matter factor and a pH factor of the principal component analysis were the main soil-related determining factors of log-transformed N_2O fluxes. By combining multivariate analysis with geostatistics, a map of predicted N_2O fluxes closely matched the spatial pattern of measured fluxes. The regression equation based on the soil properties explained 56% of the spatially structured variation of the log-transformed N_2O fluxes. Site-specific management to regulate organic matter content and water status of a soil could be a promising means of reducing N_2O emissions from agricultural fields.

NITROUS OXIDE is a trace gas that is involved in both the greenhouse effect (Yung et al., 1976) and destruction of stratospheric ozone (Johnson, 1971). Total annual emissions are estimated to be 17.7 Tg N (6.7–36.6 Tg N), about 60% of which is derived from the soil (Ehhalt et al., 2001). Estimates of N_2O emissions from agricultural soils vary widely, for example, 2.29 to 3.65 Tg N (Bouwman, 1990), 0.2 to 2.1 Tg N (Eichner, 1990), 0.03 to 3 Tg N (Watson et al., 1992), or 2.4 Tg N (Bouwman, 1996). Accurate evaluation of the N_2O emissions from agricultural land on a field scale is urgently required to quantify the amount of total emissions more precisely and to establish practical methods of reducing N_2O emissions.

Evaluation of N_2O emissions in agricultural fields must take account of spatial variability because it is generally accepted that emissions from within even a small area may vary by orders of magnitude (Bouwman, 1996). This heterogeneity makes predictions highly uncertain because in most cases only weak or no spatial dependencies have been demonstrated with considerable variation in the field (Folorunso and Rolston, 1984, 1985; Ball et al., 1997; Clemens et al., 1999; Roever et al., 1999). It is not certain, however, whether this tendency for weak spatial dependency is universal. Elucidation of the determining factors of N_2O emissions is also important because N_2O emissions have been reported to be highly variable depending on soil conditions such as organic matter, water and oxygen status, pH, substrate concentration, carbon supply, and temperature as well as fertilization and land management (Sahrawat and Keeney, 1986). In particular, overall effects of soil properties on N_2O emission rates in the field should be fully evaluated because in many studies only individual factors have been investigated. Furthermore, understanding of spatial relationships is also required to mitigate N_2O emissions in the field through soil management.

The objectives of the present study were to (i) evaluate the spatial variability of N_2O fluxes and soil properties in an agricultural field, (ii) determine the possible cause–effect relationship between soil properties and N_2O fluxes by multivariate analysis, and (iii) interpret the relationships spatially by combining multivariate analysis with geostatistics.

MATERIALS AND METHODS

Experimental Field

The experiment was performed in an agricultural field located in Mikasa City, Hokkaido prefecture, Japan (43°14′ N,

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Abbreviations: MBF, microbial biomass factor; OMF, organic matter factor; PHF, pH factor; SOF, soluble salts factor; SSF, soil structure factor; WFPS, water-filled pore space.

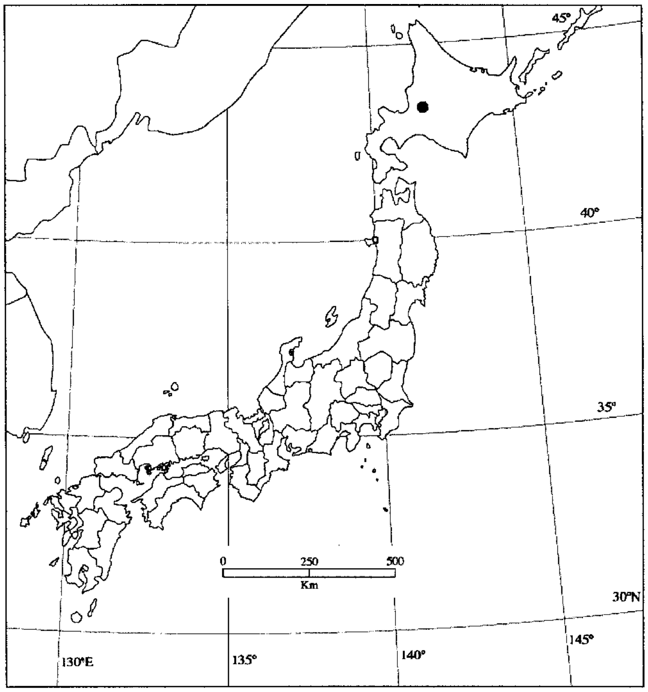

Fig. 1. Location of the study site: Mikasa, Hokkaido, Japan (●).

141°50′ E) with a mean annual temperature and precipitation of 7.2°C and 1204 mm, respectively (Fig. 1). The field examined had an area of 2.1 ha (147 × 146 m) with a slight gradient (0.2%) across the northwest (relatively low) and southeast (relatively high) corners. It has been used to cultivate onion for more than 20 yr after long-term paddy rice (*Oryza sativa* L.) cultivation. The soil is of alluvial origin (clayey aquic) and classified as a fine, mesic, Mollic Fluvaquent (Soil Survey Staff, 1998). The soil in the plow layer has a texture class of silty clay (12% sand, 51% silt, and 37% clay) and a cation exchange capacity (CEC) of 25.5 cmol_c kg^{-1}. Further information on this site can be obtained from Hayashi and Hatano (1999). Fertilization and crop management were conducted homogeneously across the field, and followed standard procedures for this area. On 27 Apr. 1999 chemical fertilizer was applied as ammonium sulfate at rates equivalent to 0.032 kg m^{-2} of N; onion seedlings were transplanted on May 1; onion tops were cut off by agricultural machinery on 23 August to dry out the aboveground material, and onions were harvested on 6 September.

Gas and Soil Sampling and Their Analyses

Gas and soil samples were collected on 17 Aug. 1999. The weather at the time of sampling was partly cloudy, and no rain had been observed since 6 August. The sampling was performed in August because the highest values of the N_2O fluxes of the field were generally observed at this time of the year with relatively high precipitation and temperature according to previous studies (Hatano and Sawamoto, 1997; Sawamoto and Hatano, 2000; Kusa et al., 2002). The central part of the experimental field (100 × 100 m) was divided into one-hundred 10- × 10-m plots. In total, 100 gas samples were collected at the center of the plots, using a closed chamber technique, that is, by covering the soil surface for 15 min with chambers and collecting gas samples at time zero from the open air and after 15 min from the headspace. For the gas sampling, two types of plastic chambers were used with surface areas of 0.0707 and 0.0875 m^2. Preliminary experiments suggested that the type of chamber had a negligible effect on the measurement of N_2O fluxes (data not shown). Soil temperature at a depth of 0.10 m was measured at the time of gas sampling as a physical property of the soil. After collecting gas samples, soil cores 0.14 m in diameter and 0.10 m in depth were taken from the surface layer, again at the center of each plot, using stainless steel core samplers. Sampling and associated measurements, which were performed from north to south, took a total of 5 h to perform (1100–1600 h). Air temperature and relative humidity of the area were relatively constant during this period: 30.2, 30.2, 29.7, 30.5, 28.7, and 27.1°C and 71, 68, 71, 64, 76, and 81%, from 1100 till 1600 h at 1-h intervals, respectively.

The N_2O concentration of each gas sample was measured using gas chromatography (GC-14B; Shimadzu, Kyoto, Japan) with an electron capture detector. Nitrous oxide flux rate from the soil surface was then calculated based on the differences in N_2O concentration between ambient air and the headspace gas sample taken after 15 min.

Each of the soil core samples was subdivided into three subsamples to evaluate physical, chemical, and biological properties of the soil. The first set of subsamples (undisturbed) was used to measure physical properties: bulk density; solid-, liquid-, and gas-phase volumetric percentage; the percentage of water-filled pore space (WFPS) in total pore space; and water content. Three variables, liquid phase percentage, WFPS, and water content, were measured in relation to water status of the soil because water was expected to influence the level of N_2O fluxes to a considerable degree. The second set of subsamples was air-dried, sieved to 2 mm, and analyzed for the following chemical properties: total N content; total C content; C to N ratio; inorganic C content; water-soluble NO_3^-; NH_4^+ and inorganic N (as $NO_3^- + NH_4^+$); available P (Bray 2 method); exchangeable Ca, Mg, K, and Na; pH; and electrical conductivity (EC). Total N content and total C content were determined by the dry combustion method (NC-800 analyzer; Sumika Chemical Analysis Service, Osaka, Japan) with C to N ratio calculated. Inorganic C was determined after extracting the soil with 0.5 M K_2SO_4. The contents of water-soluble NO_3^- and NH_4^+ were determined by the Griess–Ilosvay method (after reduction of NO_3^- to NO_2^-) and indophenol method, respectively, after shaking 1 h at the soil to water ratio of 1:5 (Mulvaney, 1996). All other analytical procedures were as described by Yanai et al. (2000). Total and readily available fractions of N and C were measured because soil N was assumed to supply substrates, and soil C the energy, for the N_2O fluxes. The third set of subsamples (only sieved, not dried) was used to measure biological properties: microbial biomass N and C with the fumigation extraction method (Brookes et al., 1985; Vance et al., 1987). In total, 23 properties (7 physical, 14 chemical, and 2 biological properties) were measured as the soil properties of the field.

Statistical Analysis

Normality and log–normality tests were conducted on the data distributions (chi-square test). In addition to descriptive statistics, to evaluate the determining factors of N_2O fluxes, multivariate analysis was performed. Principal component analysis (PCA) of the soil properties was conducted to summarize data and investigate the relationships among the properties (Kosaki and Juo, 1989). Stepwise multiple regression analysis was subsequently performed, using the scores of the extracted principal components as independent variables and N_2O flux as a dependent variable. The statistical software SYSTAT 8.0 (SPSS, 1998) was used in the analysis.

Geostatistical Analysis

Geostatistical analysis was performed not only on the original data (i.e., measured N_2O fluxes and soil properties), but also on calculated data (i.e., extracted PCA factors and predicted N_2O fluxes). In this analysis, a semivariogram was first used to evaluate the spatial variability of the properties (i.e., to describe the average variances of pairs of points at a given distance apart) (Oliver, 1987; Webster and Oliver, 2001). This mirrors the similarity of pairs separated by equal distance. Often, it is found that the semivariance increases with increasing distance between sampling points to a maximum (the sill) at a moderate distance (the range). Points closer together than the range are autocorrelated whereas points further apart are not related to one another. The variation below the scale of investigation and/or due to experimental errors, the nugget variance, is determined as the ordinate intercept. In the analysis, two indices of spatial dependence were employed. One is the Q value [calculated as (sill − nugget)/sill], which indicates the spatial structure at the sampling scale (Goerres et al., 1997), and the other is the range, which indicates the limit of spatial dependence. In the analysis, the semivariogram model with the smallest residual sum of squares was used for the estimation of the semivariogram parameters. Details of the fitting models are available from Webster and Oliver (2001). Maps were computed subsequently using block kriging to evaluate regional patterns of variation rather than local details. The geostatistical software, GS^+ Version 5.3 for Windows (Gamma Design Software), was used in the analysis (Robertson, 1998).

RESULTS AND DISCUSSION

Descriptive Statistics of Nitrous Oxide Fluxes and Soil Properties

The average value of the N_2O fluxes was 331 $\mu g\ N\ m^{-2}\ h^{-1}$ (Table 1), which was comparable with previously reported values at this site (i.e., 871 $\mu g\ N\ m^{-2}\ h^{-1}$) obtained in the middle of August as the maximum value of the growing period (Hatano and Sawamoto, 1997; Sawamoto and Hatano, 2000; Kusa et al., 2002). This value was relatively high compared with reported values for arable soils, for example, 5.8 to 139 (Goodroad et al., 1984), 41.2 (Ambus and Christensen, 1995), 8.6 (Ball et al., 1997), 0.8 to 11.2 (Roever et al., 1999), and 53.6 $\mu g\ N\ m^{-2}\ h^{-1}$ (Clemens et al., 1999), as reviewed by Mosier (1994) and Bouwman (1996). It was comparable with data after N fertilization (Bremner et al., 1981; Thornton et al., 1996) or after plowing (van der Weerden et al., 2000). This could be due to the high amounts of N fertilizer application (Sahrawat and Keeney, 1986) and relatively moist soil conditions reflecting clayey texture and topography of lowland areas (Sawamoto and Hatano, 2000). Nitrous oxide fluxes displayed high variability with the minimum, maximum, and coefficient of variation (CV) of 6.83 and 5980 $\mu g\ N\ m^{-2}\ h^{-1}$, and 217%, respectively (Table 1). Nitrous oxide data were not normally distributed (i.e., fluxes from several plots appeared to be much higher than the rest). They were, therefore, log-transformed and the descriptive statistics calculated. The log-transformed fluxes had a normal distribution ($P < 0.01$), as has been reported in previous studies (Ambus and Christensen, 1994; Ball et al., 1997; Roever et al., 1999). This result may be because N_2O emissions are related to microbial processes, which are often log–normally distributed (Parkin, 1993).

In contrast to N_2O fluxes, most of the soil properties displayed a normal distribution. The average values represented a typical surface soil of arable land in this area (Table 1). Physical properties indicated that the soil had a bulk density of 1.04 $Mg\ m^{-3}$ with about 60% porosity and WFPS of 47.8%. Chemical properties indicated that the N status of the soil was representative for an alluvial

Table 1. Descriptive statistics of N_2O flux, log-transformed N_2O flux, and physical, chemical, and biological properties of the soil.

	Minimum	Mean	Maximum	CV
				%
N_2O flux				
N_2O flux, $\mu g\ N\ m^{-2}\ h^{-1}$	6.83	331	5980	217
Log-transformed N_2O flux, $\mu g\ N\ m^{-2}\ h^{-1}$	0.83	2.08	3.78	28.8
Physical properties of the soil				
Bulk density, $Mg\ m^{-3}$	0.93	1.04	1.20	5.8
Solid phase percentage, %	35.2	39.2	45.4	5.9
Liquid phase percentage, %	23.9	29.0	37.9	8.2
Gas phase percentage, %	18.7	31.8	40.7	12.3
Water-filled pore space, %	37.0	47.8	66.9	10.5
Water content, %	18.7	21.8	25.1	6.2
Soil temperature, °C	25.4	28.0	30.2	4.3
Chemical properties of the soil				
Total N, $\times 10^{-2}$ kg kg^{-1}	0.134	0.204	0.272	14.2
Total C, $\times 10^{-2}$ kg kg^{-1}	1.99	2.81	3.68	11.7
C to N ratio	11.7	13.9	16.2	5.4
Water-soluble NO_3^-, mg kg^{-1}	7.50	50.1	218	75.6
Water-soluble NH_4^+, mg kg^{-1}	0.50	10.3	39.0	65.5
Inorganic N, mg kg^{-1}	12.6	60.3	233	63.7
Inorganic C, mg kg^{-1}	30.2	84.3	171	43.4
Available P, g kg^{-1}	0.102	0.125	0.153	8.7
Exchangeable Ca, cmol$_c$ kg^{-1}	11.0	16.8	24.7	15.9
Exchangeable Mg, cmol$_c$ kg^{-1}	1.25	1.57	2.56	10.0
Exchangeable K, cmol$_c$ kg^{-1}	0.78	1.16	1.71	14.1
Exchangeable Na, cmol$_c$ kg^{-1}	0.07	0.10	0.15	14.7
pH	4.68	5.60	6.64	6.9
Electrical conductivity, $\times 10^{-3}$ dS m^{-1}	58.0	237	726	60.2
Biological properties of the soil				
Microbial biomass N, mg kg^{-1}	15.0	50.6	140	53.7
Microbial biomass C, mg kg^{-1}	247	571	1057	29.3

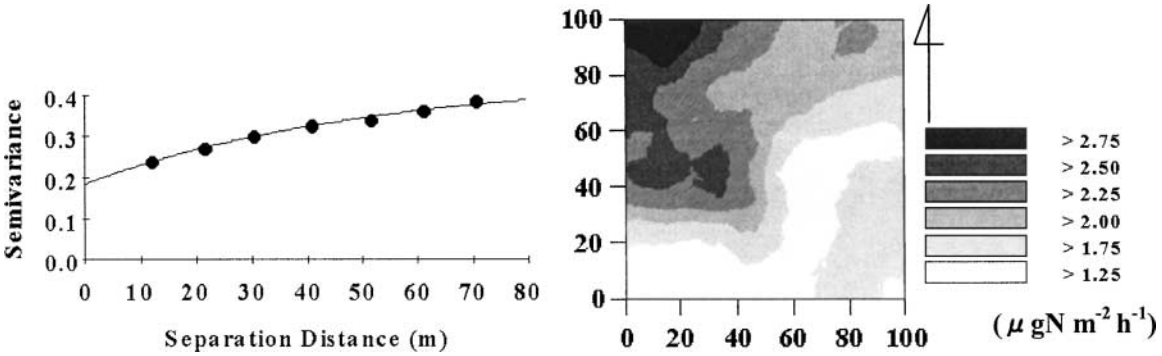

Fig. 2. Semivariogram and isarithmic map of log-transformed N_2O fluxes (measured).

arable soil with a total N content of 2.04 g kg^{-1} and inorganic N (readily available; NO_3^- + NH_4^+) content of 60.3 mg kg^{-1}. The concentrations of NO_3^- and NH_4^+ were sufficient to provide opportunities for both denitrification and nitrification to occur in this soil. The C status (an indicator of energy sources available to microorganisms) and contents of exchangeable cations and available P were also appreciable. Biological properties further showed that the level of microbial biomass N and C and their ratio to total N and C were relatively high, possibly because the biomass community still reflected the original paddy-field condition, for which such ratios are generally high (Shibahara and Inubushi, 1995). The CV values suggested that the soil properties measured had less variability than the N_2O fluxes. In addition, there was a general tendency for the CV values of physical properties (about 10%) to be lower than those of the chemical and biological properties, and CV values of chemical properties representing total and available fractions (10–20%) were lower than those of biological properties (30–50%) and chemical properties representing readily available fractions (>60%). These tendencies would be generally observed in most arable lands (Roever and Kaiser, 1999) and reflect the overall intrinsic characteristics of each soil property, as well as soil type and land management factors.

Spatial Variability of Nitrous Oxide Fluxes and Soil Properties

The variability of N_2O fluxes described in the previous section can be interpreted as the outcome of both spatial and temporal effects, as it took 5 h to perform gas sampling in the 100- × 100-m area. However, measurement of diurnal variation in N_2O emission, which was performed at the northwest corner of the same field on another date (one month earlier), suggested that the temporal fluctuation of N_2O fluxes during daytime was relatively small (less than two times) and even the diurnal difference was within several times (data not shown) as reported by other researchers (e.g., Blackmer et al., 1982; Thomson et al., 1997). Judging from the fact that the variability of N_2O fluxes of this experiment was as much as two orders of magnitude, it was concluded that most of the variation, if not all, was derived from a spatial effect.

Based on this assumption, spatial analysis of N_2O fluxes was performed. Figure 2 shows the semivariogram and isarithmic map of the log-transformed N_2O fluxes. Table 2 shows the geostatistical parameters, which were estimated from the semivariogram. The semivariogam shows that the semivariance increases with increasing distance between sampling points. The degree of spatial dependence was moderate with the Q value of 0.50. The range was estimated to be more than 75 m, suggesting a considerably long range of spatial dependence. This result was in contrast to almost all previously published studies, which indicated no spatial dependence (Folorunso and Rolston, 1984; Ball et al., 1997; Roever et al., 1999) or weak spatial dependence with ranges of several meters only (Folorunso and Rolston, 1985; Clemens et al., 1999), with one exception reporting strong spatial dependence with a range of up to 48 m in a flat grassland field (Ambus and Christensen, 1994). This discrepancy may be due to the fact that the landscape of this field was relatively flat and thus N_2O fluxes were more likely to reflect the gradual and continuous changes of other field conditions, which was rarely the case for ordinary undulating upland fields involved in previous studies. The existence of moderate spatial dependency suggests the possibility for control or regulation of N_2O fluxes with site-specific soil and land management. The map also shows that relatively high N_2O fluxes were observed at sites with a relatively lower elevation (i.e., in the northwest corner of the field).

Figures 3 through 6 show the semivariograms and isarithmic maps of the 23 soil physical, chemical, and biological properties. Their geostatistical parameters are shown in Table 2. The degree of spatial dependence of soil properties varied widely. The Q values were between 0.80 and 1.00 for bulk density, solid phase percentage, water content, soil temperature, total N, total C, and available P, suggesting a highly developed spatial structure. The Q values ranged from 0.50 to 0.80 for liquid phase percentage, gas phase percentage, WFPS, C to N ratio, water-soluble NH_4^+, exchangeable Ca, and pH, indicating moderate spatial structure. However, water-soluble NO_3^-; inorganic N; inorganic C; exchangeable Mg, K, and Na; electrical conductivity; and microbial biomass N and C displayed low spatial dependencies with low Q values. It may be concluded that physical

Table 2. Geostatistical parameters of log-transformed N_2O flux and physical, chemical, and biological properties of the soil.

	Nugget	Sill	Range	Q value	Model†
			m		
Log-transformed N_2O flux, μg N m^{-2} h^{-1}	0.189	0.380	75+	0.50	E
Physical properties of the soil					
Bulk density, Mg m^{-3}	0.001	0.005	75+	0.80	E
Solid phase percentage, %	1.66	8.33	75+	0.80	E
Liquid phase percentage, %	3.57	10.87	75+	0.67	E
Gas phase percentage, %	10.7	21.4	75+	0.50	S
Water-filled pore space, %	17.8	38.2	75+	0.54	E
Water content, %	0.55	3.11	75+	0.82	S
Soil temperature, °C	0.001	2.011	75+	1.00	S
Chemical properties of the soil					
Total N, $\times 10^{-2}$ kg kg^{-1}	0.00004	0.00135	75+	0.97	S
Total C, $\times 10^{-2}$ kg kg^{-1}	0.009	0.164	75+	0.94	S
C to N ratio	0.257	1.024	75+	0.75	S
Water-soluble NO_3^-, mg kg^{-1}	1 439	1 439	–	0.00	L
Water-soluble NH_4^+, mg kg^{-1}	29	89	75+	0.67	E
Inorganic N, mg kg^{-1}	1 484	1 484	–	0.00	L
Inorganic C, mg kg^{-1}	1 370	1 389	–	0.01	L
Available P, g kg^{-1}	0.00001	0.00013	38	0.91	E
Exchangeable Ca, $cmol_c$ kg^{-1}	2.45	8.66	69	0.72	S
Exchangeable Mg, $cmol_c$ kg^{-1}	0.0263	0.0263	–	0.00	L
Exchangeable K, $cmol_c$ kg^{-1}	0.0264	0.0277	–	0.05	L
Exchangeable Na, $cmol_c$ kg^{-1}	0.00018	0.00023	–	0.22	L
pH	0.054	0.176	63	0.70	S
Electrical conductivity, $\times 10^{-3}$ dS m^{-1}	20 338	20 699	–	0.02	L
Biological properties of the soil					
Microbial biomass N, mg kg^{-1}	734	734	–	0.00	L
Microbial biomass C, mg kg^{-1}	26 438	30 184	–	0.12	L

† S, spherical; E, exponential; L, linear.

properties and chemical properties representing the total or available fractions had strong or moderate spatial dependency, whereas chemical properties representing the water-soluble or readily available fractions and biological properties had weak or no spatial dependency. The ranges or the distance of spatial dependency also varied considerably. The ranges were more than 75 m for bulk density; solid-, liquid-, and gas-phase percentages; WFPS; water content; soil temperature; total C; total N; C to N ratio; and water-soluble NH_4^+, whereas no spatial range was observed for water-soluble NO_3^-; inorganic N; inorganic C; exchangeable Mg, K, and Na; electrical conductivity; and microbial biomass N and C. There was a general tendency for the properties with strong spatial dependency to have longer ranges, and vice versa. These results indicate the possibility of regulating N_2O fluxes through site-specific management of those soil properties with strong or moderate spatial dependency. Isarithmic maps of soil properties further showed that spatial variability was variable among soil properties, as shown in Fig. 3 through 6, probably reflecting their intrinsic characteristics such as mobility and reactivity in soil.

Multivariate Analysis of the Relationship between Nitrous Oxide Fluxes and Soil Properties

Principal component analysis identified five principal components (PC1–5) with eigenvalues, or the variances of the components, greater than 1.0. Together these components accounted for 73.3% of the total variance (Table 3). The remaining less-significant components 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, which was accomplished to increase the interpretability of the components, the first component showed high loadings for total N, total C, water content, and soil temperature. Since these properties were related to the organic matter status of the soil, this component was referred to as the organic matter factor (OMF). The second component showed high loadings for bulk density; solid-, liquid-, and gas-phase percentages; and WFPS. Since these properties determined soil physical properties and soil structure, this component was referred to as the soil structure factor (SSF). Similarly, the third component showed high loadings for water-soluble NO_3^-, inorganic N, electrical conductivity, and exchangeable K, and was referred to as the soluble salts factor (SOF). The fourth component, the pH factor (PHF), showed high loadings for the content of exchangeable Ca and pH; and the fifth component, the microbial biomass factor (MBF) showed high loadings for microbial biomass N and C. These factors were considered to correspond to the chemical properties representing total fractions, physical properties, chemical properties representing soluble fractions, chemical properties representing available fractions, and microbiological properties, respectively. Variation of the soil properties was thus summarized into a smaller number of factors, which were independent of each other.

Figure 7 shows the semivariograms and isarithmic maps of the five PCs and Table 4 indicates their geostatistical parameters. The five PCs showed contrasting spatial dependence; strong or moderate spatial dependency was observed for OMF, SSF, and PHF whereas weak dependency was observed for SOF and MBF. These

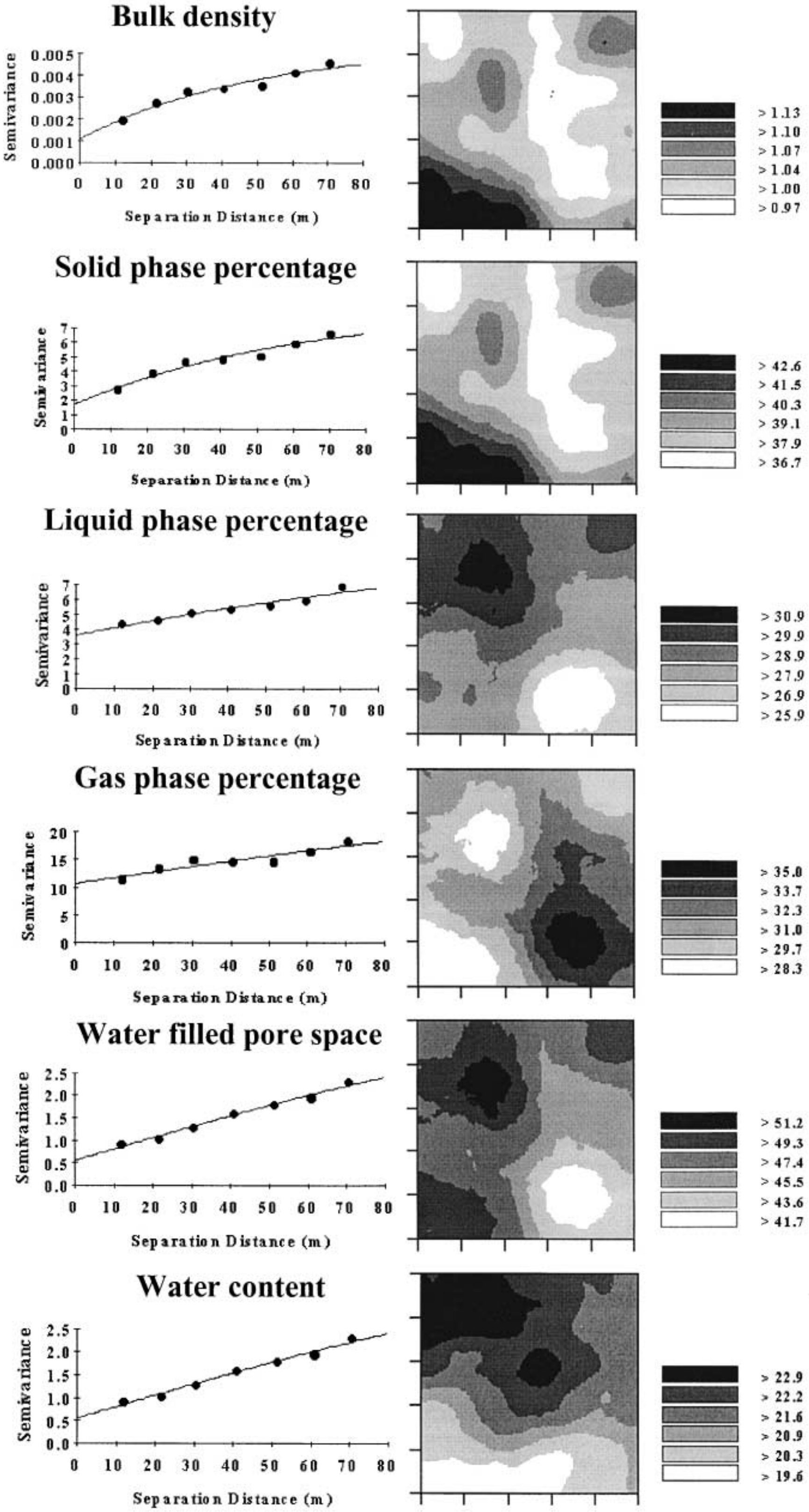

Fig. 3. Semivariograms and isarithmic maps of the soil properties. (Units for the isarithmic maps can be seen in Table 1.)

results reflected the spatial dependency of the original soil properties underlying each PC. Isarithmic maps of the five PCs also showed the similarity of their spatial variability with the original soil properties. This relationship is readily apparent if, for example, total N content, exchangeable Ca, water-soluble NO_3^-, liquid phase

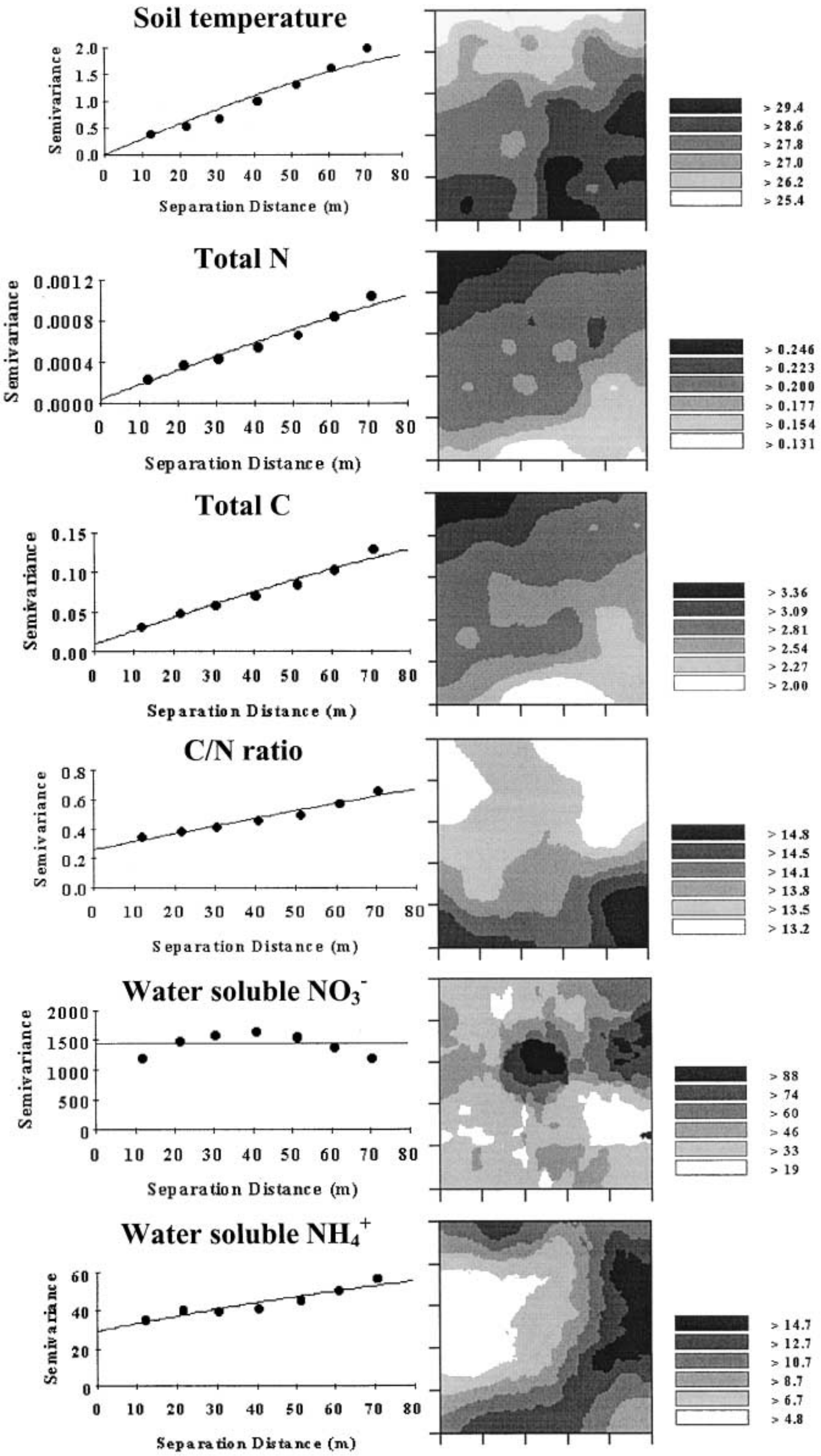

Fig. 4. Semivariograms and isarithmic maps of the soil properties. (Units for the isarithmic maps can be seen in Table 1.)

percentage, and microbial biomass C in Fig. 3 through 6 are compared with OMF, PHF, SOF, SSF, and MBF in Fig. 7, respectively.

Stepwise multiple regression analysis was subsequently performed to obtain a model for predicting N_2O fluxes. In this analysis, log-transformed N_2O flux was used as a dependent variable, and standardized scores of the five principal components described above were used as independent variables. Since no a priori information was available about the regression model, we

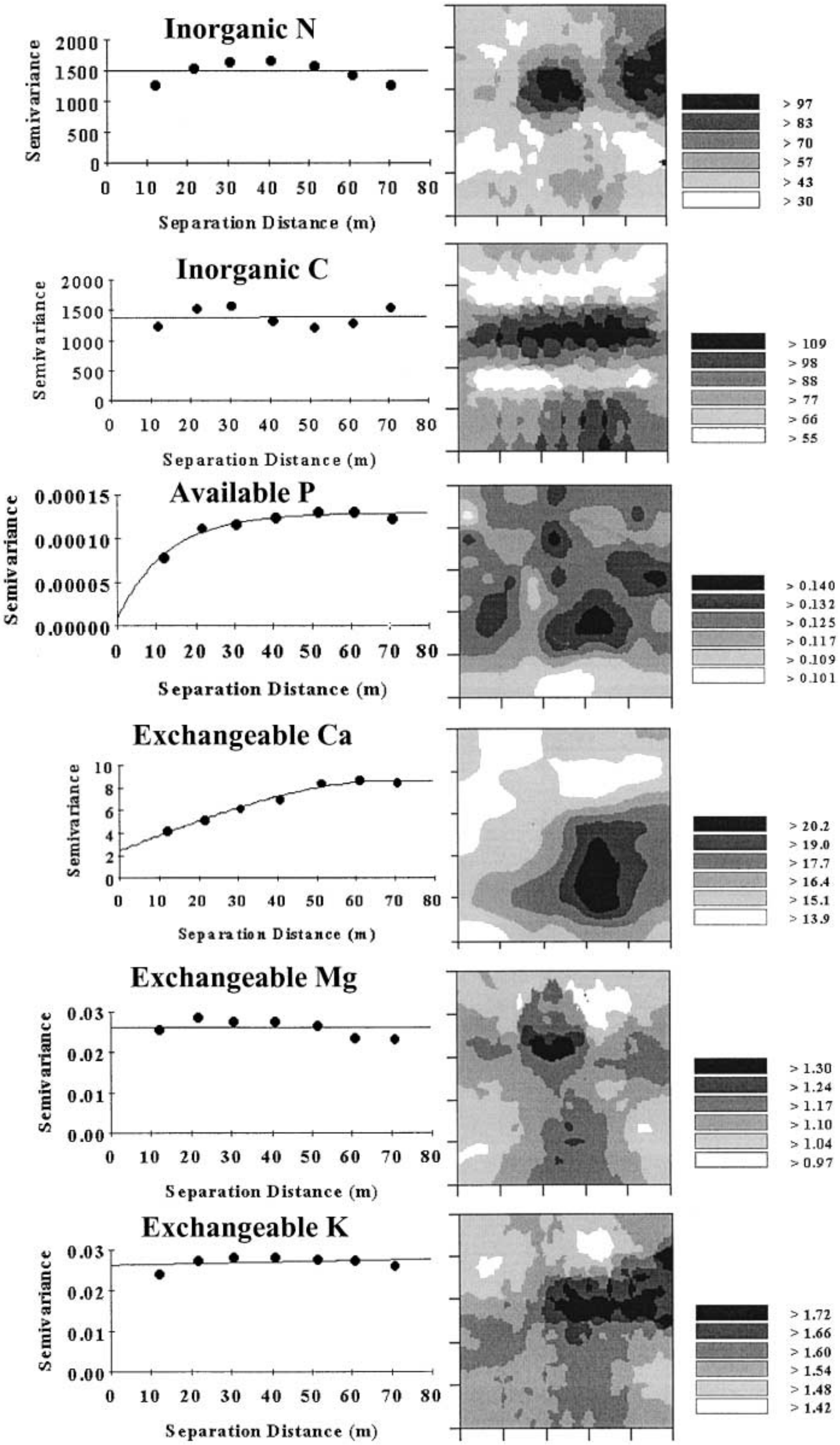

Fig. 5. Semivariograms and isarithmic maps of the soil properties. (Units for the isarithmic maps can be seen in Table 1.)

assumed the presence of a linear combination of first-degree variables. The most appropriate model obtained ($R^2 = 0.28$) with a significance level of $\alpha = 0.15$ was:

$$\text{predicted log-transformed N}_2\text{O flux } (\mu\text{g N m}^{-2}\text{ h}^{-1}) = 0.278 \times \text{OMF} - 0.144 \times \text{PHF} + 2.075 \qquad [1]$$

Spatial analysis of the residual errors showed that the errors were spatially independent, suggesting that the application of this regression model was statistically appropriate.

The fact that R^2 equals 0.28 indicates that the model explains 28% of the total variance of the log-transformed measured N_2O fluxes. It should be noted that

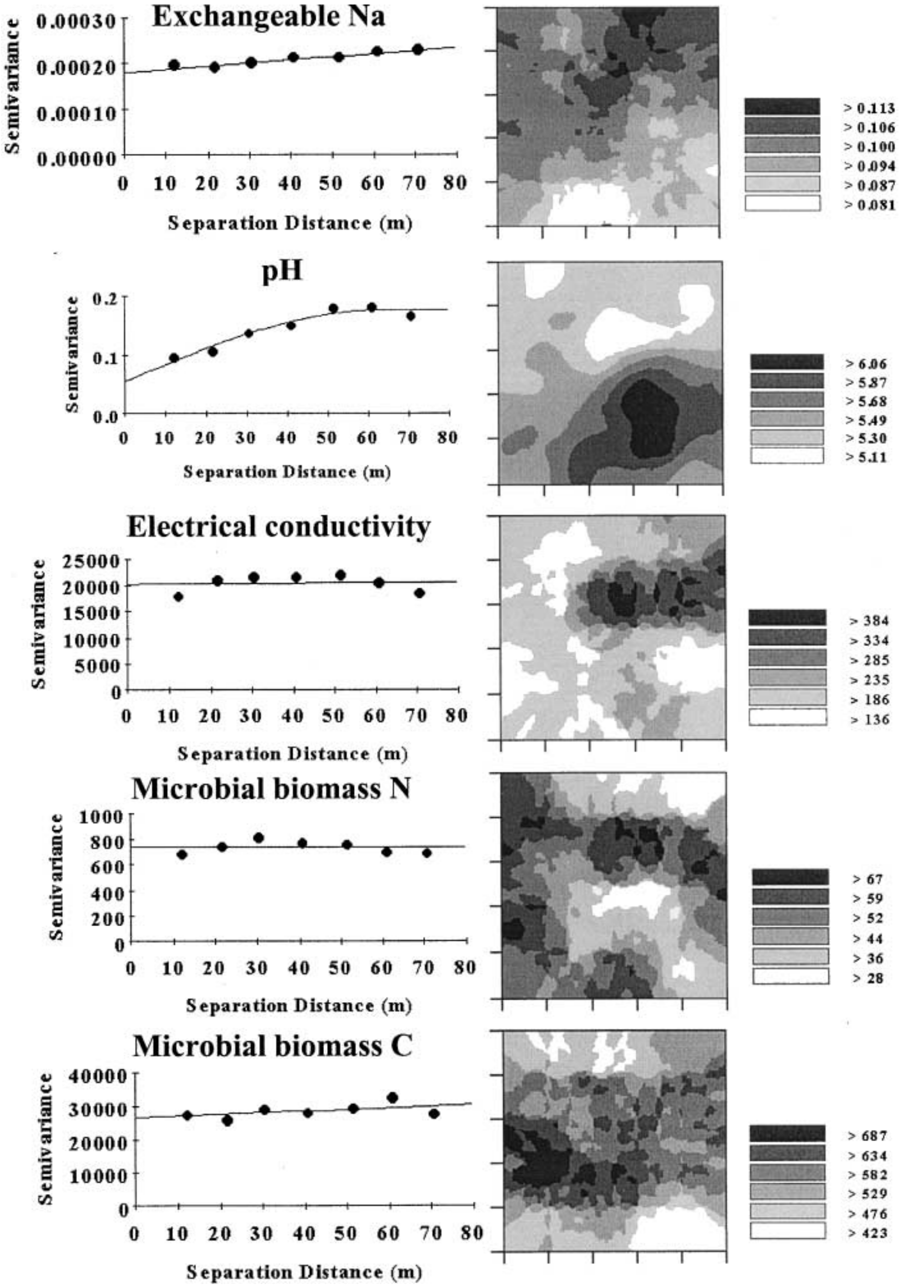

Fig. 6. Semivariograms and isarithmic maps of the soil properties. (Units for the isarithmic maps can be seen in Table 1.)

N_2O fluxes showed a slightly weak but significant relationship with soil properties on a field basis, in spite of the fact that N_2O fluxes were highly variable (as much as two orders of magnitude), as is often the case for those variables derived from biological activities (Parkin, 1993). As the regression coefficients in the equation generally indicate the magnitude of each factor's contribution to the N_2O fluxes, OMF can be identified as the most important factor in this relationship. High N_2O fluxes were thus related to high amounts of organic matter, high water content, and low temperatures. The contribution of PHF was of secondary importance; a low pH encouraged higher N_2O fluxes in this pH range. The components related to soil structure, soluble salts, and microbial biomass (SSF, SOF, and MBF) were not included in the model, although these factors were generally considered to affect the N_2O fluxes. Judging from the fact that N_2O fluxes were positively related to organic matter content and wetness, it was assumed that denitrification was the main mechanism of N_2O emissions. This was consistent with the results of Christensen et al. (1990) where the spatial distribution of denitrification activity in the soil depended on the soil water content and on the amount and distribution of available organic matter. The fact that the ratio of N_2O flux to NO flux was more than 100 also suggested active denitrification (Kusa et al., 2002) although nitrification may have occurred simultaneously based on the data of WFPS (Linn and Doran, 1984). From a spatial perspective, it was reasonable that PCs with relatively strong

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

	Component†				
	PC1: OMF	PC2: SSF	PC3: SOF	PC4: PHF	PC5: MBF
Physical properties					
Bulk density	−0.33	−0.89	−0.05	−0.18	−0.03
Solid phase percentage	−0.34	−0.89	−0.05	−0.18	−0.02
Liquid phase percentage	0.59	−0.76	−0.06	0.10	−0.02
Gas phase percentage	−0.16	0.98	0.07	0.04	0.02
Water-filled pore space	0.34	−0.93	−0.07	0.02	−0.02
Water content	0.86	−0.12	−0.02	0.23	0.00
Soil temperature	−0.80	0.12	0.05	0.31	0.09
Chemical properties					
Total N	0.89	0.05	0.07	−0.14	0.09
Total C	0.84	0.07	−0.04	−0.12	0.05
C to N ratio	−0.56	0.03	−0.27	0.09	−0.13
Water-soluble NO_3^-	0.10	0.04	0.94	−0.13	−0.04
Water-soluble NH_4^+	−0.18	0.05	0.12	0.02	−0.42
Inorganic N	0.07	0.04	0.95	−0.13	−0.11
Inorganic C	−0.05	0.04	0.38	0.37	−0.36
Available P	0.43	0.26	0.25	0.43	0.26
Exchangeable Ca	−0.26	0.16	0.03	0.86	−0.11
Exchangeable Mg	0.02	−0.07	0.62	0.26	0.04
Exchangeable K	−0.07	0.11	0.82	0.19	0.20
Exchangeable Na	0.42	0.04	0.40	−0.20	0.10
pH	−0.45	0.05	−0.49	0.65	−0.08
Electrical conductivity	0.09	0.18	0.92	−0.11	0.06
Biological properties					
Microbial biomass N	−0.14	0.02	0.22	−0.25	0.63
Microbial biomass C	0.05	0.13	0.11	0.13	0.84
Eigenvalue	4.60	4.18	4.45	2.01	1.61
Percentage of total variance‡	20.0	38.2	57.5	66.3	73.3

† OMF, organic matter factor; SSF, soil structure factor; SOF, soluble salts factor; PHF, pH factor; MBF, microbial biomass factor

‡ Calculated as cumulative value.

spatial dependency were extracted to explain the measured N_2O fluxes with moderate spatial dependency. As a practical interpretation, it is concluded that OMF variables can be good indicators of the spatial variation of N_2O fluxes, and site-specific management to regulate organic matter content as well as water status of soil may become an effective means of reducing N_2O fluxes in the field.

Application of Geostatistics to the Interpretation of Determining Factors of Nitrous Oxide Fluxes with Multivariate Analysis

Equation [1] was used to predict N_2O fluxes and to prepare a semivariogram and an isarithmic map (Fig. 8). The isarithmic map of predicted N_2O fluxes was remarkably similar to that of measured N_2O fluxes (Fig. 2), although the variation was somewhat underestimated in the predicted map. Nevertheless, the prediction of N_2O fluxes from soil properties might be an effective way of estimating N_2O fluxes for comparative purposes (e.g., identifying N_2O emission "hot spots" in a field).

From the semivariogram, the Q value was calculated to be 1.00, suggesting that the multiple regression model in fact omitted all random components (i.e., all variation expressed in Eq. [1] was spatially structured). This is supported by the fact that the extracted PCs (i.e., OMF and PHF) had strong or moderate spatial dependency (Fig. 7). On the other hand, the semivariogram of the measured fluxes (Fig. 2) indicates that 50% of the total variation of measured fluxes was spatially structured (Table 2), with the remaining 50% originally random or unable to be controlled at this scale. Since Eq. [1] explains 28% of the total measured flux variance, it can be concluded that this equation is actually accounting for as much as 56% of the spatially structured or nonrandom variation of the N_2O fluxes (28 out of 50%). This is very high compared with other published reports on this matter. In this way, geostatistical analysis in combination with multivariate analysis enables the relationship between dependent and independent variables to be interpreted in a spatial context. This may in turn open up the possibility of site-specific management of the dependent variables, as discussed for the relationship between soil properties and the yield of rice in a paddy field (Yanai et al., 2001).

CONCLUSIONS

Spatial variability of the N_2O fluxes and soil properties was evaluated in an agricultural field, and the important role of soil properties in determining N_2O emissions was demonstrated by combining geostatistics with multivariate analysis. These results suggest that site-specific soil management such as the control of organic matter content or water status could be a promising strategy for reducing N_2O emissions in the field. Based on the fact that more than half of all N_2O emissions for this field were released in August and September (Hatano and Sawamoto, 1997; Sawamoto and Hatano, 2000; Kusa et al., 2002), site and time-specific management could be further established for the efficient reduction of N_2O emissions. In this context, investigations of the spatiotemporal variation of the N_2O fluxes would lead to a better understanding of N_2O emissions. Further

Table 4. Geostatistical parameters of the first five principal components and the predicted and measured values of the log-transformed N_2O fluxes.

	Nugget	Sill	Range	*Q* value	Model†
			m		
Principal components					
Organic matter factor (OMF)	0.00	2.01	75+	1.00	S
Soil structure factor (SSF)	0.12	1.06	36	0.88	E
Soluble salts factor (SOF)	1.02	1.02	–	0.00	L
pH factor (PHF)	0.34	1.15	46	0.71	S
Microbial biomass factor (MBF)	0.86	1.10	–	0.22	L
Log-transformed N_2O flux					
Predicted, $\mu g\ N\ m^{-2}\ h^{-1}$	0.000	0.255	75+	1.00	S
Measured, $\mu g\ N\ m^{-2}\ h^{-1}$	0.189	0.380	75+	0.50	E

† S, spherical; E, exponential; L, linear.

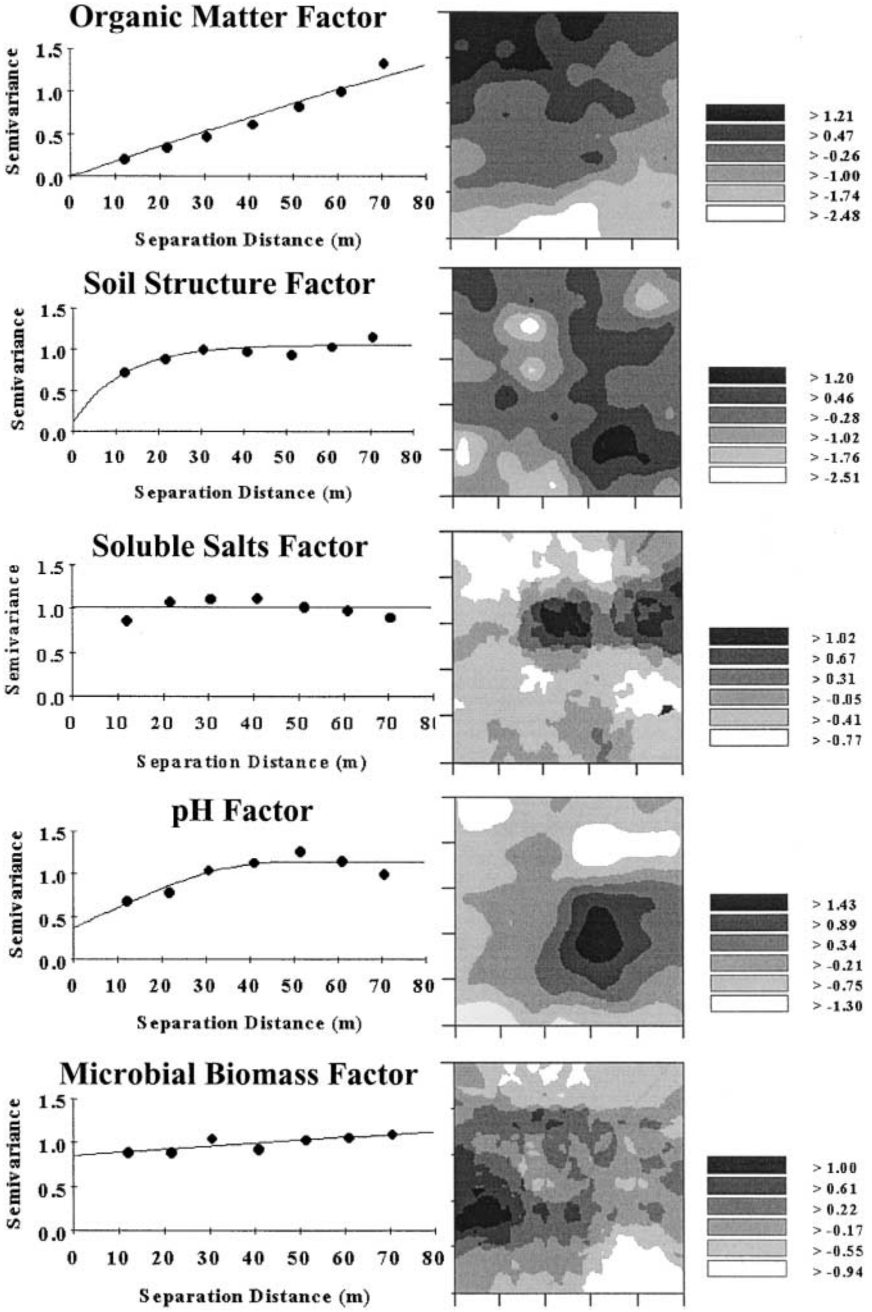

Fig. 7. Semivariograms and isarithmic maps of five principal components of the soil properties.

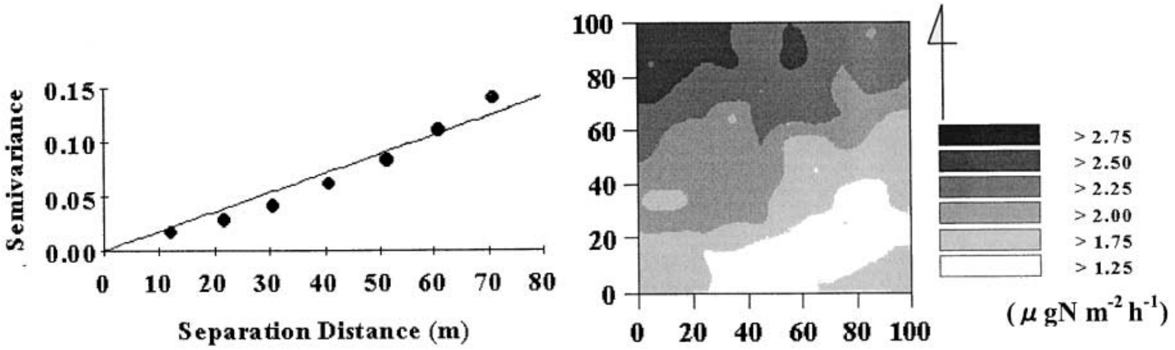

Fig. 8. Semivariograms and isarithmic map of log-transformed N_2O fluxes (predicted).

studies are to be conducted to investigate the effectiveness of site-specific management (such as the control of organic matter content, water status, or inorganic fertilizer application) on the mitigation of N_2O fluxes from agricultural fields.

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