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Nitrous Oxide (N_2O) Emissions from a Japanese Lowland Soil Cropped to Onion: III. Relationship with Soil Physical Properties

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Abstract: We studied the spatial variability of soil physical properties and related these properties to N_2O emissions. The study was conducted in a Japanese lowland soil cropped to onion in Mikassa, Hokkaido (Japan). N_2O emissions measurements and soil sampling were conducted along a 100×100 m (1999) and 60×60 m (2000) grids with samples taken at 10 m spacing. Air samples for N_2O determination were collected using the closed-chamber technique. Air samples were stored in vial bottles for analysis with a gas chromatograph with electron capture detector within 24 h after sampling. Soil samples were collected with a 5 cm diameter and a 5 cm height cylinder. Soil physical properties measured were soil temperature (T), bulk density (ρb), volumetric water content (θ_v), gravimetric water content (θ_g), air-filled porosity (fa), total pore space (TPS), relative gas diffusivity coefficient (D_s/D_o) and the pore tortuosity factor (τ). Results showed that N_2O emissions were highest in 1999 as compared to 2000. They were fitted to a linear variogram in 1999 while they responded to a spherical variogram model in 2000. Positive first degree surface trends were also found in N_2O emissions data in both years and the removal of these trends did not change variogram models, but significantly improved them by increasing the R^2 and Q values. Soil physical properties responded to a range of variograms, from linear to spherical models. Detrending soil physical properties either increased (T) or decreased (θ_v) the range and R^2 values. Soil T, τ, D_s/D_o, WFPS were significantly correlated with N_2O emissions. N_2O emissions and soil properties varied considerably in space and time. More studies are needed to identify other soil physical properties which might better correlate with N_2O emissions, besides the traditional T and WFPS.

Key words: Nitrous oxide emissions, spatial variability, soil physical properties

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INTRODUCTION

Soils can function both as sources and sinks for the three main greenhouse gases: carbon dioxide (CO_2), nitrous oxide (N_2O) and methane. Globally, CO_2, CH_4 and N_2O, contribute 60, 15 and 5%, respectively, to the anthropogenic greenhouse effect. Atmospheric CO_2, CH_4 and N_2O are currently increasing by 0.5, 1.1 and 0.3% per year, respectively (Guo and Zhou, 2007) and If greenhouse gases emissions continue to increase at the present rate, it is predicted that the average global temperature will increase by about 1°C by the year 2025 and by 3°C by the end of the century (IPCC, 2001). Soil

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properties are key factors in determining greenhouse gas soil emissions and static and dynamic soil properties both affect the water, gases and solutes that pass through and over soils (Hillel, 2004; Wall and Hytönen, 2005). Roughly a third of CH_4 and two-thirds of N_2O emissions to the atmosphere come from soils (Prather *et al*., 1995). Studies have showed that soil properties such as soil texture, temperature, available moisture, pH, available C (labile and non labile components of soil organic matter) and N content of the soil influence greenhouse gases production and emissions from soil (Van-den Paul van Dusselaer *et al*., 1998; Velthof *et al*., 1996; Davidson *et al*., 2000). Soil chemical properties such as labile C and N content influence greenhouse gases at production level while the escape of these gases from soil to the atmosphere is mainly controlled by soil physical properties (Nkongolo *et al*., 2008). The relationship between N_2O emissions and soil physical properties has been investigated by several researchers (Jones *et al*., 2007; Nkongolo *et al*., 2008). However, despite these investigations, the spatial and temporal variability of N_2O emissions and soil controlling factors still present a major challenge (Ball *et al*., 1997; Yanai *et al*., 2003). In fact, consistent correlations between these soil controlling factors and N_2O emissions (or other greenhouse gases) have mainly been observed in controlled environments (Hatano and Lipiec, 2004; Pilegaard *et al*., 2006; Schindlbacher *et al*., 2004) with conflicting results in field environments (Janssens *et al*., 2001). In a study assessing the spatial variability of soil properties and gases emissions in southern Ohio (USA), Jacinthe and Lal (2006) found stronger and statistically significant relationships between gas emissions and soil properties in July 2003. However, in May 2004, this trend changed and they observed only few statistically significant relationships. Paro *et al*. (2007) studied the spatial variability of soil thermal properties and CO_2, CH_4 and N_2O emissions in a forest soil of central Missouri. They reported a significant correlation between soil temperature and CO_2 and N_2O emissions, but no correlation with CH_4. However, Johnson *et al*. (2007) conducted a similar study in a pasture in central missouri, but could not relate CO_2 and N_2O to soil temperature. In opposite, only CH_4 was related to soil temperature. Jones *et al*. (2007) studied the influence of organic and mineral N fertilizer on N_2O emissions from a temperate grassland in Scotland. They investigated the influence of environmental conditions on N_2O emissions by a series of single and multiple regression analysis but could not find a relationship between soil moisture and N_2O. Studies in various ecosystems and conditions are therefore still needed to increase our understanding of greenhouse gas emissions and their potential soil-controlling factors. The objective of this study were (a) to assess the spatial variability of soil physical properties and (b) study the relationship between N_2O emissions and soil physical properties in a lowland soil cropped to onion.

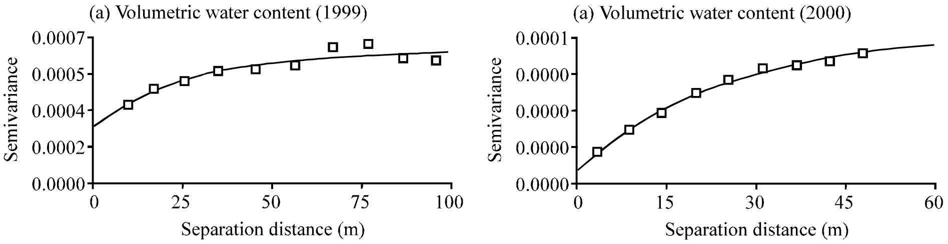
MATERIALS AND METHODS

Study Area

Air and soil samples for determination of N_2O emissions and soil properties, respectively, were collected in Mikassa, Hokkaido province (Fig. 1, part I), but all analyses were done in the Laboratory of Soil Science at Hokkaido University in Sapporo. Sapporo is Japan's third largest city in area and is located on the western plains of Hokkaido, the northernmost island of Japan. Its geographical locations are 43°11' N, 141°30' E. Sapporo enjoys a mild climate with a year-round average temperature of 9.1°C. The average temperature in January was -3.7°C and in July, 20.3°C in 2000. More than sixty percent of surface area of Sapporo (primarily in the southwest) is mountainous, creating a concentration of urban activity focused around the Toyohira River, which runs through the city.

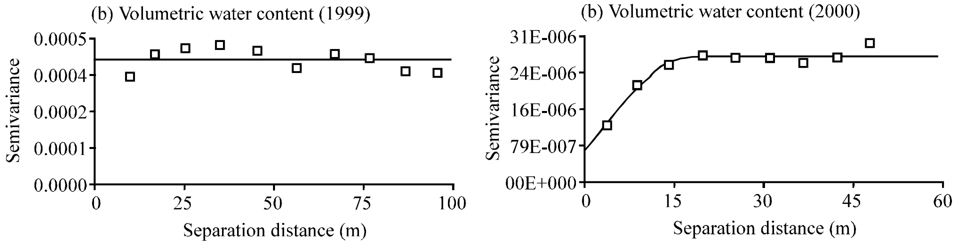
Field Study

The field study itself was conducted in a 140×140 m upland field yearly cropped to onion (*Allium cepa* L.) in Mikassa, Hokkaido, Japan (43°14' N, 141°50' E). The experimental field is showed in Fig. 2 (part I). The annual average temperature in Mikassa is 7.2°C and the average annual rainfall



Exponential model (C_o = 0.0003, C_o+C = 0.0007, A_o = 27.20, r^2 = 0.877, RSS = 1.023E-08)

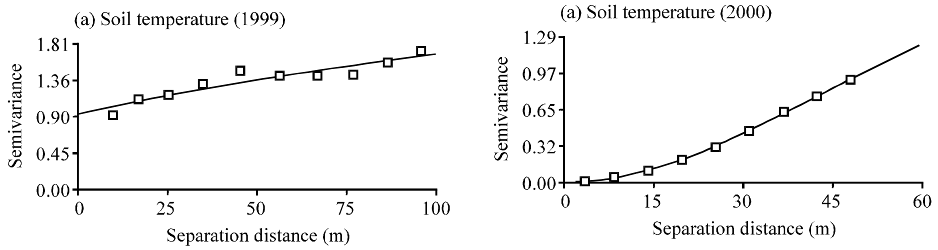
Exponential model (C_o = 0.0000, C_o+C = 0.0001, A_o = 25.00, r^2 = 0.993, RSS = 8.785E-12)



Linear model (C_o = 0.0004, C_o+C = 0.0004, A_o = 95.28, r^2 = 0.099, RSS = 1.370E-08)

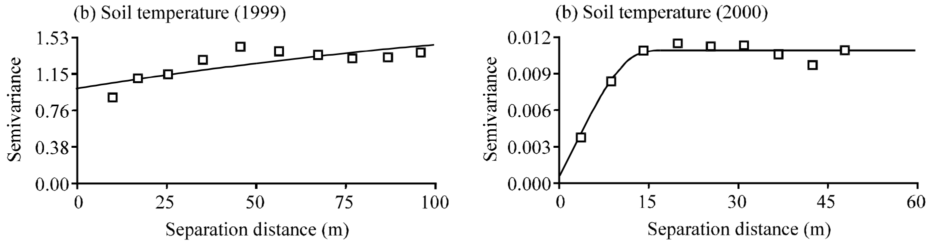
Spherical model (C_o = 0.0000, C_o+C = 0.0000, A_o = 18.50, r^2 = 0.939, RSS = 1.476E-11)

Fig. 1: Variograms of soil Volumetric Water Content (VWC) in an onion field in Mikassa in 1999 and 2000, (a) original data and (b) de-trended residuals



Exponential model (C_o = 0.9750, C_o+C = 2.9720, A_o = 201.00, r^2 = 0.861, RSS = 0.0754)

Gaussian model (C_o = 0.0010, C_o+C = 2.0070, A_o = 59.00, r^2 = 1.000, RSS = 3.807E-04)



Exponential model (C_o = 1.0480, C_o+C = 2.0979, A_o = 163.10, r^2 = 0.592, RSS = 0.108)

Spherical model (C_o = 1.0000, C_o+C = 2.0114, A_o = 15.30, r^2 = 0.553, RSS = 2.619E-06)

Fig. 2: Variograms of soil Temperature (T) at 5 cm depth in an onion field in Mikassa in 1999 and 2000, (a) original data and (b) de-trended residuals

is 1204 mm. The soil of the experimental site is classified as fine, mesic, mollic Fluvaquent. The physical and chemical properties of different horizons were reported elsewhere. Soil texture consists of a silty or heavy clay from the Ap layer (0-28 cm) down to the C horizon (48-100 cm). The groundwater table lays at 70-80 cm depth throughout the growing season. Surface drains are installed at 80-100 cm depth at 12 m intervals and are connected to the same effluent exit, draining about 0.95 ha (125×76 m) for monitoring nitrate leaching. Fertilizer nitrogen (322 kg N ha^{-1}) is yearly applied once at the end of April, shortly before transplanting. Onion is harvested during the second or third week of September. In June 1999, the field was sampled for N_2O emissions and soil physical and chemical properties, using a 100 by 100 m grid at 10 m spacing for a total of 100 sampling locations (through a cooperative study between Hokkaido University, Kyushu University and Nagoya University). A year later in September, 2000, the same field was again sampled for N_2O and soil chemical and physical properties, using a 60×60 m grid at 10 m spacing for a total of 36 locations. Data collected in 1999 and 2000 are analyzed in this study.

Measurements of Soil Physical Properties

Immediately after N_2O emissions measurements, two soil samples were taken at a point close to where emissions were measured (inside a 20 cm diameter area). Soil samples were taken with a 5 cm diameter by 5 cm height cylinder and brought to the laboratory for analysis. Each sample fresh weight was measured and then transferred into a three phase meter for soil and air volume determination. Soil samples were put into an oven to be dried at 105°C for 24 h at constant weight and later transferred again into a three phase meter to determine the volume of dry soil. Soil bulk density (ρ_b), Total Pore Space (TPS), volumetric (θ_v) and gravimetric water contents (θ_g), air-filled porosity (f_a), relative gas diffusion coefficient (D_s/D_O) and the pore tortuosity factor (τ) were later calculated as described in Nkongolo *et al.* (2007).

Variograms Fitting

Isotropic (direction independent) semivariance of data was calculated using GS^+ geostatistical software (Gamma Design Software, 2007). Semivariance is defined in the following equation:

$$\gamma(h) = \frac{1}{\left[2m(h)\right]} \sum_{i=1}^{m(h)} \left[Z_{(xi)} - Z_{(xi+h)} \right]^2$$

where, γ is the semivariance for m data pairs separated by a distance of h, known as a lag and Z is the value at positions xi and xi+h.

RESULTS AND DISCUSSION

Analysis of the Spatial Variability of Soil Physical Properties

Summary of Simple Statistics for Soil Physical Properties

Summary of simple statistics for soil physical properties measured in Mikassa, Hokkaido (Japan) in 1999 and 2000 are shown in Table 1. Contrary to soil chemical properties, all properties measured in 1999 were also the ones assessed in 2000. Coefficients of variation ranged between 3.87 to 24.46% in 1999 and 2.37 to 51.64% in 2000. These values were in the range of normally reported data, except for the relative gas diffusion coefficient (D_s/D_o), which had extreme values for both years. The mean values were the same or closer to their medians and standard deviations were very low, implying that the data approached normality. Soil temperature, air-filled porosity and relative gas diffusion coefficient were highest in 1999, while soil water content and tortuosity increased in 2000. As

Table 1: Summary of simple statistics for soil physical properties measured in an onion field in Mikassa

Properties	Mean	SD	CV (%)	Median	Skew
1999					
f_a($m^3\ m^{-3}$)	0.31	0.04	12.26	0.32	-0.63
ρ_b (kg m^{-3})	1.04	0.06	5.85	1.03	0.63
θ_v ($m^3\ m^{-3}$)	0.29	0.04	13.63	0.29	5.05
θ_g ($m^3\ m^{-3}$)					
WFPS (%)	47.83	5.01	10.47	47.45	0.77
TPS ($m^3\ m^{-3}$)	0.60	0.06	9.44	0.61	-7.43
D_s/D_o ($m^2\ sec^{-1}\ m^{-2}$ sec)	0.14	0.33	24.46	0.10	9.76
τ ($m^3\ m^{-3}$)	3.19	0.46	14.47	3.13	1.67
T_5(°C)	30.99	1.20	3.87	31.05	-0.12
T_{10}(°C)	28.04	1.20	4.27	28.20	-0.23
2000					
f_a ($m^3\ m^{-3}$)	0.11	0.03	24.34	0.11	0.92
ρ_b (kg m^{-3})	1.12	0.04	3.28	1.12	-0.13
θ_v ($m^3\ m^{-3}$)	0.47	0.02	3.90	0.47	-1.09
θ_g ($m^3\ m^{-3}$)	0.42	0.02	3.82	0.43	0.15
TPS ($m^3\ m^{-3}$)	0.58	0.01	2.37	0.58	0.11
D_s/D_o ($m^2\ sec^{-1}\ m^{-2}$ sec)	0.01	0.01	51.64	0.01	1.75
τ ($m^3\ m^{-3}$)	9.38	2.20	23.47	9.17	0.55
T_5(°C)	17.53	1.00	5.71	17.56	-0.07
T_{10} (°C)	15.91	0.83	5.22	15.97	-0.39

f_a: Air-filled porosity, ρ_b: Bulk density, θ_v: Volumetric water content, θ_g: Gravimetric water content, TPS: Total Pore Space, D_s/D_o: Relative gas diffusion coefficient, τ: Pore tortuosity, T_5: Soil temperature at 5 cm from the surface, T_{10}: Soil temperature at 10 cm from the surface

Table 2: Linear trend surface analysis for soil physical properties measured in onion field in Mikassa

	1999		2000	
Properties	r	F	r	F
f_a ($m^3\ m^{-3}$)	0.31	4.96	0.31	1.70
ρ_b (kg m^{-3})	0.42	10.23	0.17	0.48
θ_v ($m^3\ m^{-3}$)	0.47	13.61	0.37	2.66
WFPS (%)	0.34	6.37	0.32	1.94
TPS ($m^3\ m^{-3}$)	0.39	9.41	0.17	0.48
D_s/D_o ($m^2\ sec^{-1}\ m^{-2}$ sec)	0.31	5.05	0.25	1.08
τ ($m^3\ m^{-3}$)	0.27	3.88	-	-
T_5 (°C)	0.23	2.77	0.95	162.25
T_{10} (°C)	0.84	116.38	-	-

expected, soil bulk density and total pore space did not vary for both years. Difference in soil air and water contents and temperature can be explained by the difference in climatic conditions. There was more rainfall in September 2000 as compared to June 1999.

Surface Trends Analysis for Soil Physical Properties

Results for linear trend analysis are shown in Table 2 for both 1999 and 2000, respectively. All soil physical properties measured in 1999 showed positive linear trend. However, only soil volumetric water content (F = 2.66, r = 0.37) and temperature at 5 cm depth (F = 162.25, r = 0.95) showed positive linear trends.

Variogram Models Fitting for Soil Physical Properties

Isotropic variogram parameters for soil physical properties and their de-trended residuals are shown in Table 3 and 4 for 1999 and 2000, respectively. Figure 1-5 show variogram models fitted to data in both years (Fig. 1, 2) and in 1999 only (Fig. 3-5). As for nitrous oxide emissions, the criterion for model selection was highest R^2 (wellness of fit), except when visual examination suggested otherwise. In 1999, all field measured soil physical properties were fitted to exponential variogram models, except for bulk density (ρ_b) and Total Pore Space (TPS) which responded to spherical models.

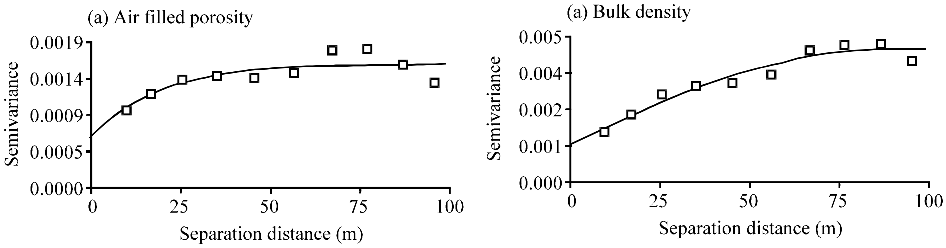
Table 3: Isotropic variogram parameters and their detrended residuals for soil physical properties measured in onion field in Mikassa (Japan) in 1999

Properties	Model	Nugget	Sill	Range	$C/(C_0+C)$	R^2
Field measured properties						
f_a (m^3 m^{-3})	EXP	0.00	0.00	20.00	0.59	0.71
ρ_b (kg m^{-3})	SPH	0.00	0.01	85.00	0.72	0.94
θ_v (m^3 m^{-3})	EXP	0.00	0.00	27.20	0.57	0.88
WFPS (%)	EXP	18.63	37.27	124.70	0.50	0.55
TPS (m^3 m^{-3})	SPH	0.00	0.00	82.30	0.71	0.94
D_s/D_o (m^2 sec^{-1} m^{-2} sec)	EXP	0.00	0.00	16.90	0.67	0.74
τ (m^3 m^{-3})	EXP	0.18	0.35	300.20	0.50	0.23
T_5 (°C)	EXP	0.98	2.97	201.00	0.67	0.86
Detrended residuals						
f_a (m^3 m^{-3})	EXP	0.00	0.00	310.90	0.50	0.26
ρ_b (kg m^{-3})	EXP	0.00	0.00	14.30	0.90	0.68
θ_v (m^3 m^{-3})	LIN	0.00	0.00	95.28	0.00	0.10
WFPS (%)	LIN	20.81	22.05	95.25	0.05	0.04
TPS (m^3 m^{-3})	EXP	0.00	0.00	15.90	0.80	0.71
D_s/D_o (m^2 sec^{-1} m^{-2} sec)	EXP	0.00	0.00	310.90	0.44	0.16
τ (m^3 m^{-3})	LIN	0.18	0.19	95.28	0.06	0.03
T_5 (°C)	EXP	1.05	2.09	163.10	0.50	0.59

Table 4: Isotropic variogram parameters and their detrended residuals for soil physical properties measured in onion field in Mikassa (Japan) in 2000

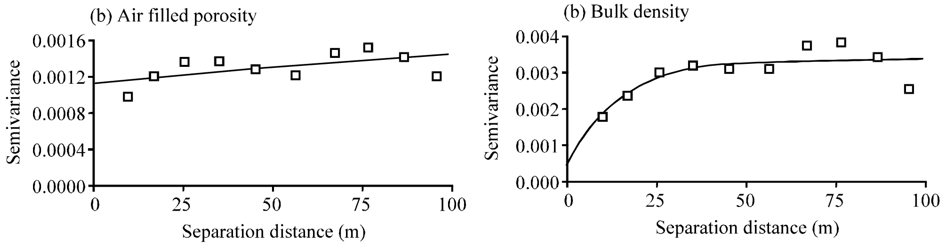
Properties	Model	Nugget	Sill	Range	$C/(C_0+C)$	R^2
Field measured properties						
f_a (m^3 m^{-3})	EXP	0.18	1.60	73.89	0.88	0.91
ρ_b (kg m^{-3})	SPH	0.00	1.29	14.97	0.99	0.46
θ_v (m^3 m^{-3})	EXP	0.00	0.00	25.00	1.00	0.99
θ_g (m^3 m^{-3})	SPH	0.00	0.00	18.88	-	0.68
WFPS (%)	LIN	0.19	2.30	34.06	0.92	0.91
TPS (m^3 m^{-3})	SPH	0.00	0.00	13.97	-	0.51
D_s/D_o (m^2 sec^{-1} m^{-2} sec)	LIN	0.00	0.00	34.02	0.93	0.96
τ (m^3 m^{-3})	SPH	0.01	0.42	13.89	0.97	0.79
T_5(°C)	GAU	0.00	2.01	59.00	1.00	1.00
T_{10}(°C)	SPH	0.00	1.05	14.53	0.99	0.57
Detrended residuals						
θ_v (m^3 m^{-3})	SPH	0.00	0.00	18.50	1.00	0.94
T_5 (°C)	SPH	0.00	0.01	15.30	1.00	0.95
T_{10} (°C)	SPH	0.00	0.02	24.10	1.00	0.88

The ranges of spatial variability were far above the maximum sampling distance for Water Filled Pore Space (WFPS), pore tortuosity (τ) and soil temperature (T) at 5 cm depth. However, ranges were less than the sampling distance of 100 m for air-filled pore space (f_a), volumetric water content (θ_v) and Total Pore Space (TPS), implying that this sampling distance was acceptable. Sill values were close to zero, except for water-filled pore space which had a sill value of 37.27 m and soil temperature (2.97 m). The R^2 values ranged from 0.23 for pore tortuosity to 0.94 for bulk density and total pore space. The spatial structure ($C/(C_o+C)$ values ranged from 0.50 (weakest) to 0.72 (highest) for this sampling period. Detrended residuals from 1999 data were fitted to the same variogram models as for field collected data for soil air-filled porosity, gas diffusion coefficient (D_s/D_o) and soil temperature only. Detrended residuals for all other soil physical properties responded to different variogram models. In addition, all R^2 values all were decreased by detrending. The sill still followed the same trend and the spatial structure improved for bulk density and total pore space. In 2000 (Table 4), soil bulk density, gravimetric water content, pore tortuosity and soil temperature (at 10 cm depth) responded to spherical variogram models. Air-filled porosity and volumetric water content responded to exponential models, water filled pore space and the gas diffusion coefficient to linear and finally soil temperature at 5 cm depth to Gaussian models. The range of spatial variability was below the sampling distance of 60 m for all soil physical properties studied, except for air-filled porosity which had a range



Exponential model (C_o = 0.0007, C_o+C = 0.0017, A_o = 20.00, r^2 = 0.711, RSS = 1.662E-07)

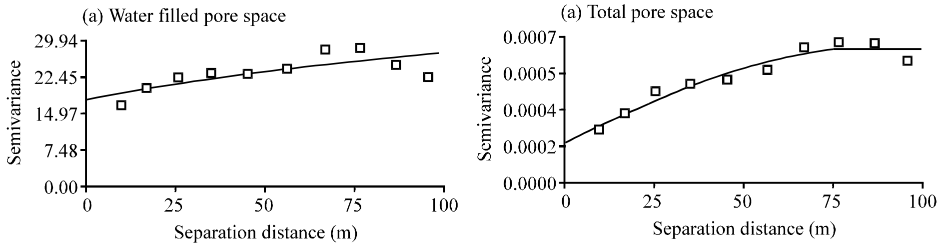
Spherical model (C_o = 0.0013, C_o+C = 0.0046, A_o = 85.00, r^2 = 0.940, RSS = 5.760E-07)



Exponential model (C_o = 0.0012, C_o+C = 0.0024, A_o = 310.90, r^2 = 0.257, RSS = 1.911E-07)

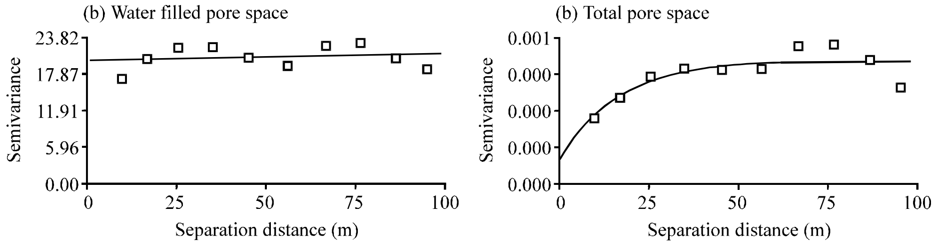
Exponential model (C_o = 0.0003, C_o+C = 0.0033, A_o = 14.30, r^2 = 0.683, RSS = 1.101E-06)

Fig. 3: Variograms of soil air filled porosity (Afp) and bulk density (Bdy) in an onion field in Mikassa in 1999, (a) original data and (b) de-trended residuals



Exponential model (C_o = 18.6300, C_o+C = 37.2700, A_o = 124.70, r^2 = 0.551, RSS = 54.8)

Spherical model (C_o = 0.0002, C_o+C = 0.0007, A_o = 82.30, r^2 = 0.938, RSS = 1.268E-08)

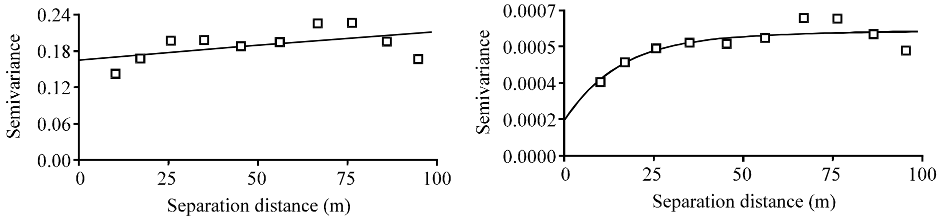


Linear model (C_o = 20.8128, C_o+C = 22.0478, A_o = 95.25, r^2 = 0.038, RSS = 35.9)

Exponential model (C_o = 0.0001, C_o+C = 0.0005, A_o = 15.90, r^2 = 0.713, RSS = 1.968E-08)

Fig. 4: Variograms of soil Water Filled Pore Space (WFPS) and Total Pore Space (TPS) in an onion field in Mikassa in 1999, (a) original data and (b) de-trended residuals

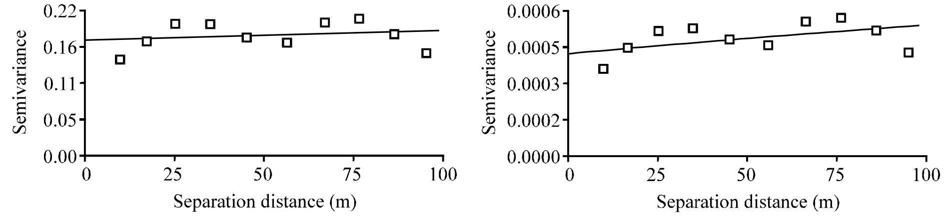
(a) Pore tortuosity (a) Gas difussion coeff.



Exponential model (C_o = 0.1749, C_o+C = 0.3508, A_o = 300.20, r^2 = 0.231, RSS = 5.370E-03)

Exponential model (C_o = 0.0002, C_o+C = 0.0006, A_o = 16.90, r^2 = 0.743, RSS = 2.349E-08)

(b) Pore tortuosity (b) Gas diffusion coeff.



Linear model (C_o = 0.1814, C_o+C = 0.1943, A_o = 95.28, r^2 = 0.034, RSS = 4.724E-03)

Exponential model (C_o = 0.0005, C_o+C = 0.0009, A_o = 310.90, r^2 = 0.162, RSS = 3.613E-08)

Fig. 5: Variograms of soil pore tortuosity (Tort) and relative gas diffusivity in an onion field in Mikassa in 1999, (a) original data and (b) de-trended residuals

of 73.89 m. The C/(C_0+C) values were all close to unity suggesting a highly developed spatial structure that existed in field measured data. However, the R^2 ranged from 0.46 for soil bulk density to 1.0 with soil temperature measured at 5 cm depth from the soil surface and volumetric water content having the highest R^2 values. Again there was a highly developed spatial structure as suggested by C/(C_0+C) values equal or close to unity. Data were detrended only for soil volumetric water content and soil temperature since these are the only soil physical properties having significant polynomial trends. Detrending the data did not change the R^2 values and spatial structure. However, the variogram models fitted to volumetric water content and soil temperature at 5 cm depth changed for the detrended residuals.

Mapping Soil Physical Properties Distribution Across the Field

The distribution of soil physical properties in an onion field in Mikassa in 1999 and 2000 with first degree trend surface and contoured residuals are shown in Fig. 6-10. Estimation of soil physical properties at unsampled locations was made using the geostatistical technique of Inverse Distance Weighing (IDW). A default grid spacing was used for interpolation purposes. After estimation of soil physical properties, isarithmic maps were produced with different contour levels. In 1999, maps showed that as for soil chemical properties and N_2O fluxes, there was a systematic variability with spatial patterns for all soil physical properties in the onion field. However, maps produced after detrending data (contoured residuals) did not change these spatial patterns. Finally, the distribution patterns for soil volumetric water content and soil temperature differed for both years.

Relationship Between Soil Physical Properties and Nitrous Oxide Emissions

The relationship between nitrous oxide emissions and soil physical properties is shown in Table 5. As for soil chemical properties, soil physical properties were significantly correlated with N_2O emissions with coefficients of correlation ranging from 0.21 to 0.42, but only when data was

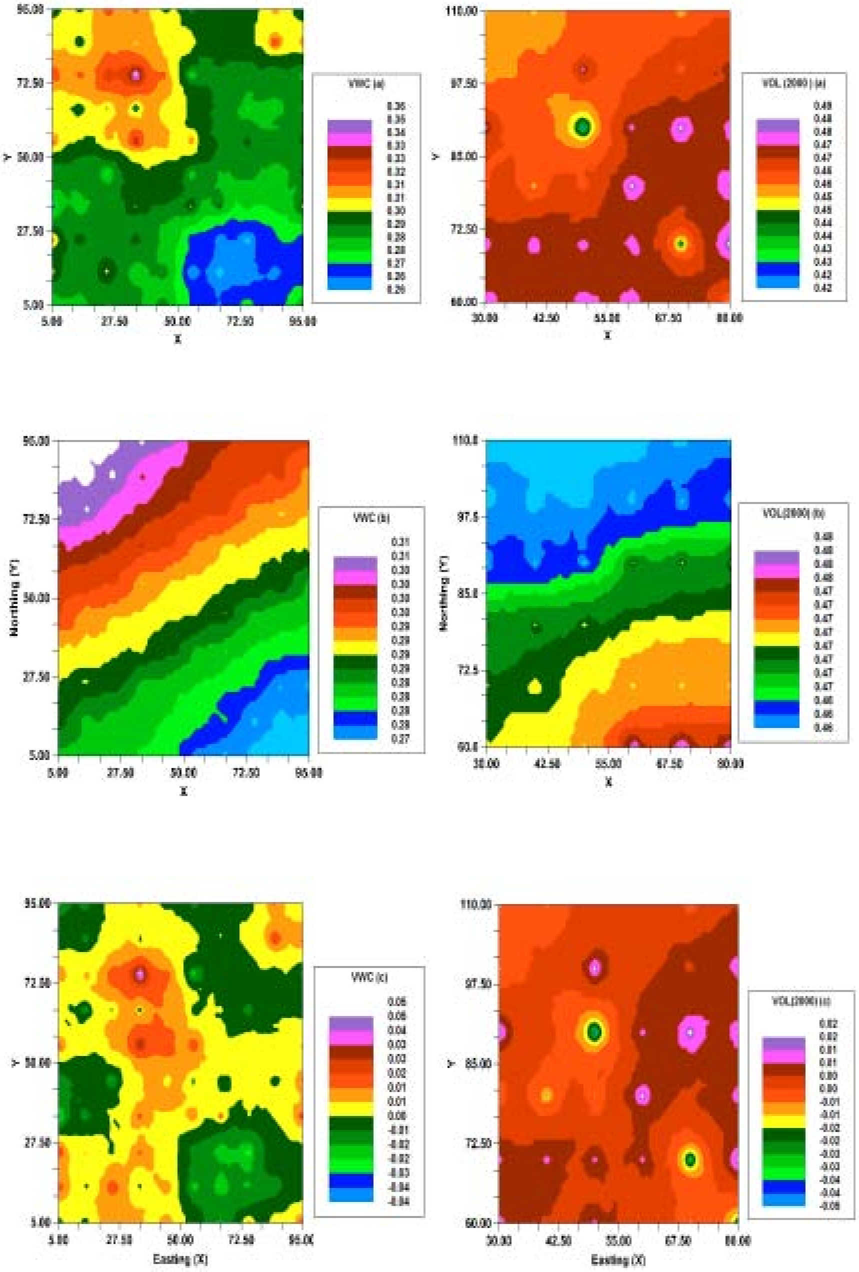


Fig. 6: Maps of soil volumetric water content in an onion field in Mikassa in 1999 and 2000, (a) contour maps, (b) first degree surface and (c) contoured residuals

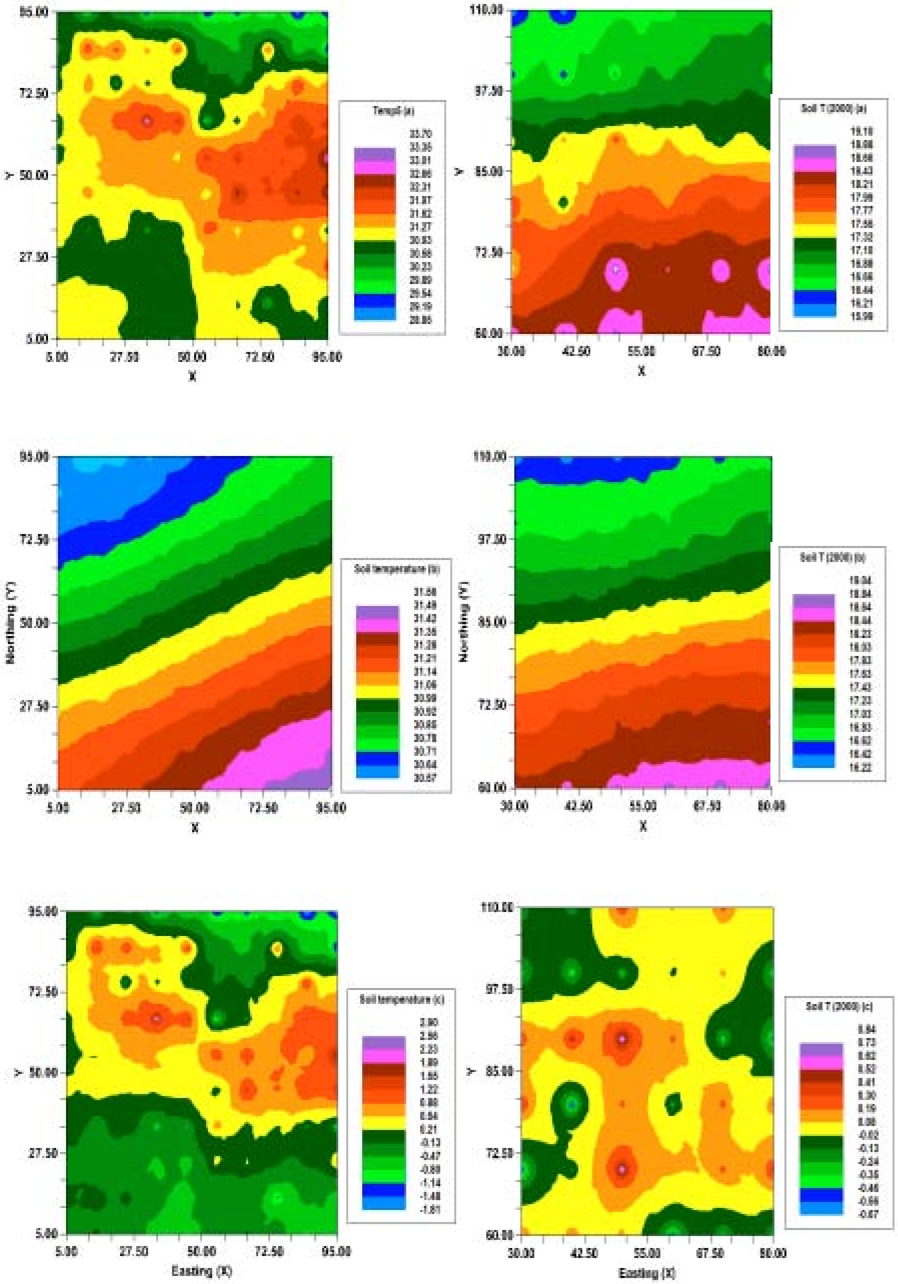


Fig. 7: Maps of soil temperature at 5 cm depth in an onion field in Mikassa in 1999 and 2000, (a) contour maps (b) first degree surface and (c) contoured residuals

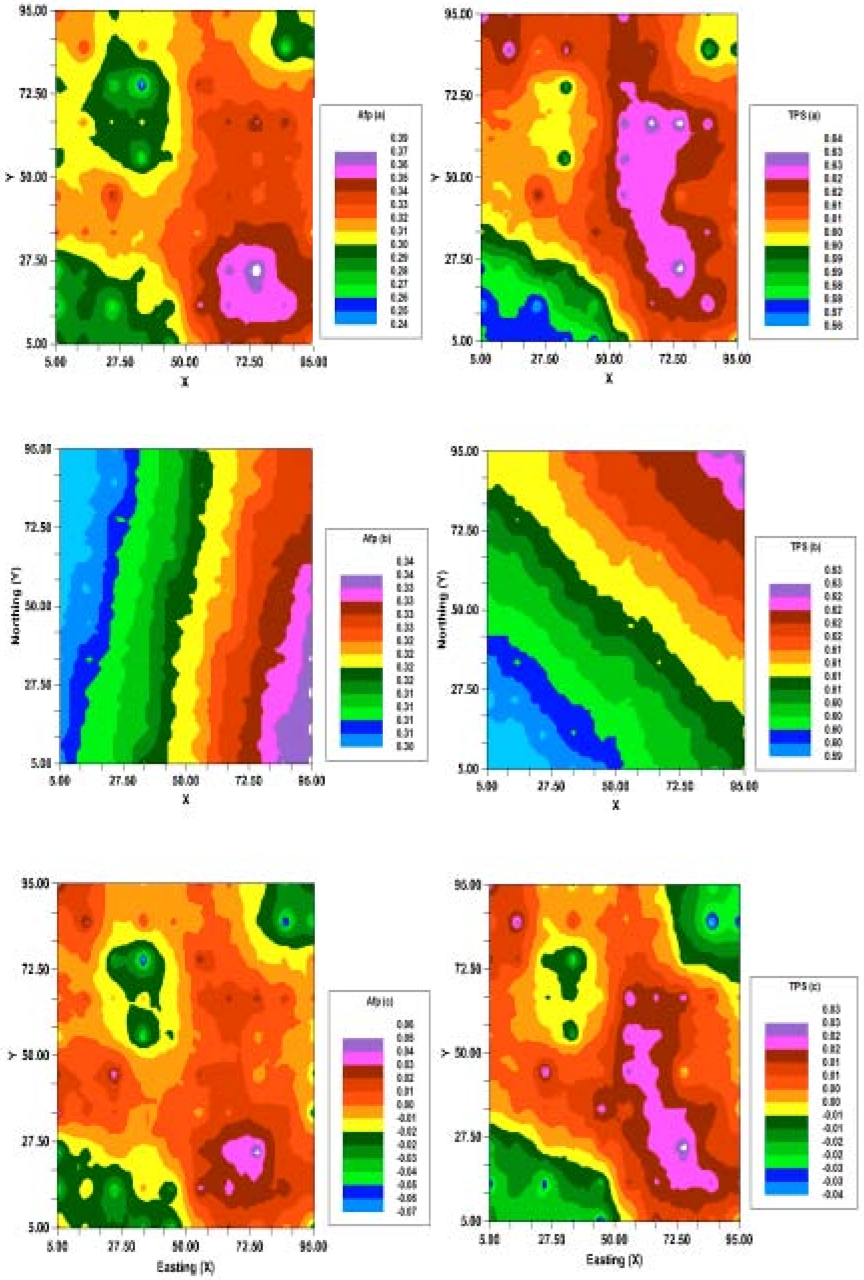


Fig. 8: Maps of soil air-filled porosity and total pore space in an onion field in Mikassa in 1999, (a) contour maps, (b) first degree surface and (c) contoured residuals

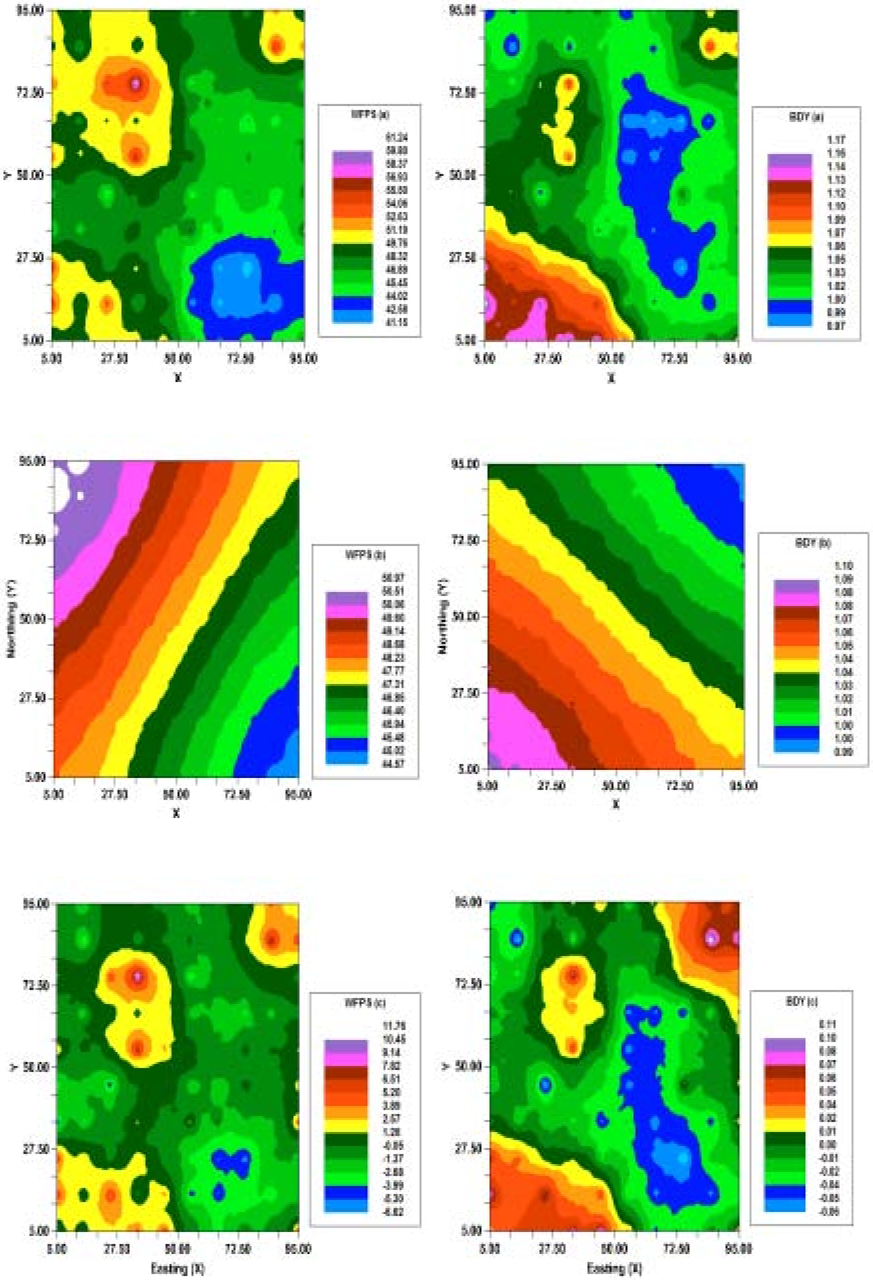


Fig. 9: Maps of soil water-filled porosity and bulk density in an onion field in Mikassa in 1999, (a) contour maps, (b) first degree surface and (c) contoured residuals

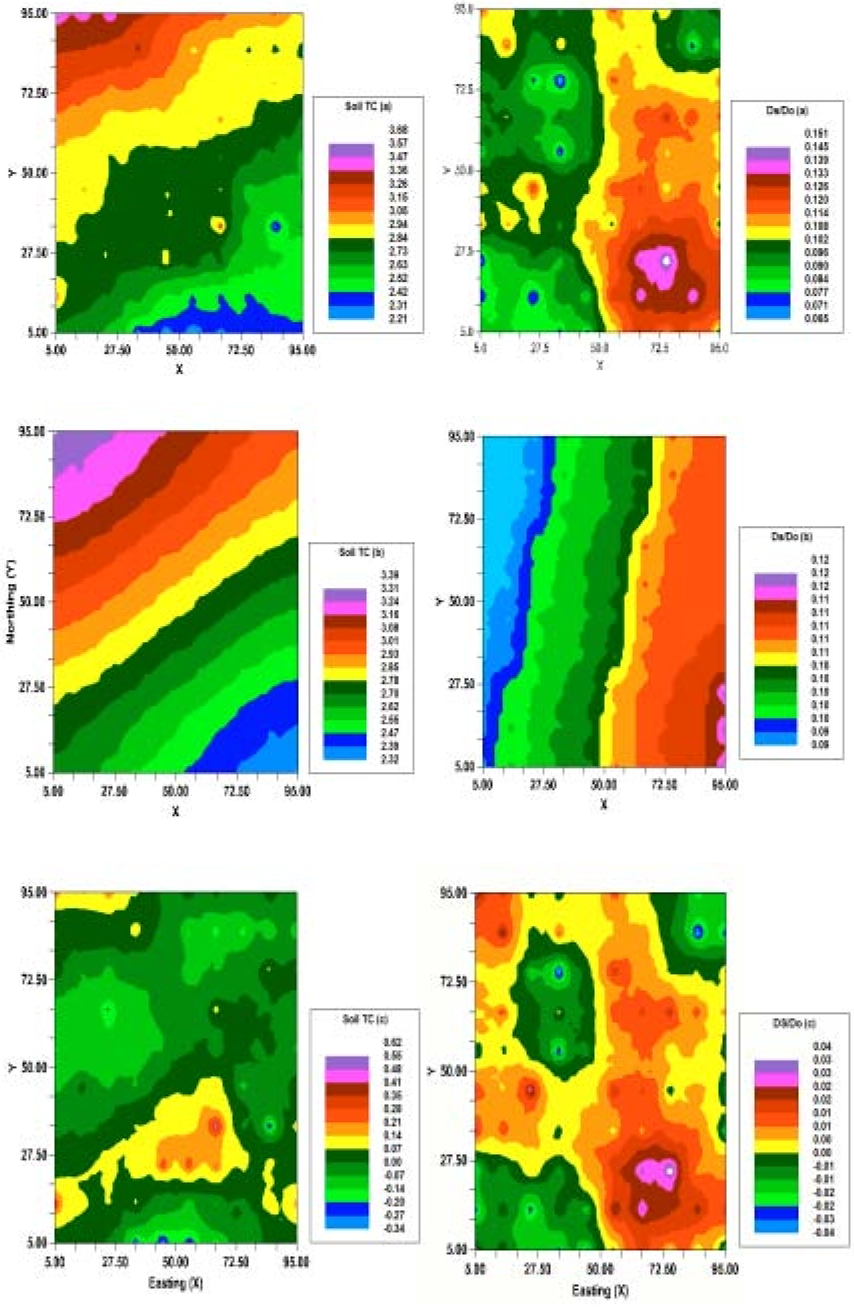


Fig. 10: Maps of soil pore tortuosity and relative gas diffusion coefficient in an onion field in Mikassa in 1999, (a) contour maps, (b) first degree surface and (c) contoured residuals

Table 5: Correlation between soil physical properties and N_2O emissions in an onion field in Mikassa

	1999				2000	
	Ln (N_2O) ($\mu g\ N_2O\ Nm^{-2}\ h^{-1}$)		N_2O ($\mu g\ N_2O\ Nm^{-2}\ h^{-1}$)		Ln (N_2O) ($\mu g\ N_2O\ Nm^{-2}\ h^{-1}$)	
Physical properties	r	p	r	p	r	p
f_a	-	-	-	-	0.37	0.026
ρ_b	-0.21	0.038	-	-	-0.48	0.003
WFPS	-	-	-	-	-0.40	0.016
TPS	0.29	0.003	-	-	-0.48	0.003
D_s/D_o	-0.22	0.027	-	-	0.34	0.05
Log (D_s/D_o)	-0.22	0.032	-	-	-	-
τ	-	-	-	-	-0.49	0.002
T_5 (°C)	-	-	-0.49	0.003	-0.37	0.027

transformed into logarithmic scale. Soil temperature was the only parameter to directly correlate to N_2O emissions without prior transformation in 2000. However, in 1999, soil temperature was not correlated to N_2O emissions. Conflicting results have been reported about the relationship between soil temperature and N_2O emissions in various ecosystems. Paro *et al.* (2007) studied the spatial variability of soil thermal properties and CO_2, CH_4 and N_2O emissions in a forest soil of central Missouri. They reported a significant correlation between soil temperature and CO_2 and N_2O emissions, but no correlation with CH_4. However, Johnson *et al.* (2007) conducted a similar study in a pasture in central missouri, but could not relate CO_2 and N_2O to soil temperature. This lack of correlation was probable a consequence of other soil properties. In fact, Hatano and Liepic (2004) suggested that fact soil moisture and availability of NO_3^- and NH_4^+ were the most important factors regulating N_2O emissions in more controlled environments. Davidson and Swank (1986) also suggested that the effects of soil temperature were sometimes confounded by factors such as moisture, i.e., when soil moisture was favorable, temperature was important and vice versa. In fact, present data show that in 1999, 48% only of the total pore space was filled with water (WFPS), while in 2000, the water-filled pore space was 80%. Furthermore, water-filled pore space (WFPS) was not correlated with N_2O emissions in 1999 while it significantly correlated with N_2O emissions in 2000 ($p = -0.016$, $r = 0.40$). These results are in strong agreement with those of other researchers who reported positive correlation between N_2O emissions with changes in WFPS up to 50-60% (Kiese and Butterbach-Bahl, 2002). Furthermore, it has been suggested that the correlation between N_2O emission and WFPS even further increases at WFPS higher than 60% (Simojoski and Jaakkola, 2000). Davidson and Swank (1986) found that the status WFPS explained 66% of the seasonal variability in denitrification N_2O emissions at a forested study site in North Carolina. Van Kessel *et al.* (1993) concluded that an adequate supply of soil water was the triggering event for N_2O emission, with other soil factors being of secondary importance. This has also been suggested by Werner *et al.* (2007) who investigated the soil-atmosphere exchange of N_2O, CH_4 and CO_2 and controlling environmental factors for tropical rain forest sites in western Kenya. They reported that the spatial differences in N_2O emissions could be explained by differences in soil texture and topsoil C: N-ratio (CO_2: subsoil C and N concentrations), whereas the temporal variability of N_2O and CO_2 emissions was primarily driven by soil moisture. Dong *et al.* (1998) studied the effects of leaves and humus layers on fluxes of CO_2, CH_4 and N_2O from a temperate forest soil. They found that CO_2 and CH_4 fluxes were significantly dependent on changes in ambient temperature, whereas N_2O fluxes were more affected by soil moisture. A good correlation between CO_2 production and CH_4 uptake was observed, but no relationship was found between N_2O emissions and either CO_2 or CH_4 fluxes. Despite the importance of water-filled pore space in N_2O emissions, this study also found that soil bulk density, total pore space and the gas diffusion coefficient to correlate with N_2O emissions consistently in both years. In 2000, some of these correlations such as that between soil bulk density and N_2O emissions were better than the correlation with water-filled pore space. Furthermore, the most significant correlation between soil physical properties and N_2O emissions were obtained with bulk density, total pore space and the pore tortuosity factor. Ball *et al.* (2000) characterized the spatial heterogeneity of N_2O flux at short distances (0.1-2 m) in relation to various soil physical and chemical properties and the location of incorporated crop residues in arable soils. They found that most properties of compacted soils did not correlate with N_2O flux. Smith *et al.* (2003) cited several studies where gases fluxes could or could not be correlated to either soil moisture, temperature or other soil properties.

CONCLUSION

The objective of this study was to assess the spatial distribution soil physical properties and relate these properties to N_2O emissions. The study was conducted in June 1999 and September 2000 in Mikassa, northern Hokkaido, Japan. This study confirms that fact N_2O emissions and soil properties vary considerably in space and time, which make their studies more complicated. Variability of N_2O emissions and soil properties in space may be influenced by site-specific potential problems (producing trends) related to the unknown regionalized variable (i.e., soil property under investigation). Therefore, removal of a potential trend was used in this study to improve variogram fitting. However, the results showed that in many cases, the variogram fitted to data after trend removal had poor spatial structure and low R^2. In some cases however, both the spatial structure and R^2 improved. The study has also showed that there are other soil physical properties that better correlate with N_2O emissions than water-filled pore space and soil temperature. Further investigations are therefore needed to study the relationship between N_2O emissions and soil pore tortuosity (τ) and gas diffusion coefficient (D_s/D_o), which appear important soil controlling factors.

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