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Spatial Variability of Greenhouse Gas Fluxes from Soils of Various Land Uses on a Livestock Farm in Southern Hokkaido, Japan

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Summary

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Current estimation of the fluxes of major greenhouse gases (GHGs; CO_2, CH_4 and N_2O) from soils includes large uncertainty. Accurate estimation, therefore, is required to develop better mitigation technology. Thus, the objective of this study was to evaluate the spatial variability of GHG fluxes from soils on a landscape scale with multiple land uses.

The investigation was carried out at the Shizunai Experimental Livestock Farm in Southern Hokkaido, Japan. A 2 km line transect was set up across five land uses of forest, grazing forest, grassland, grazing pasture, and corn field. GHG fluxes were measured by using a closed-chamber technique at 100 points during the periods of post-fertilization (PF) and pre-harvesting of maize (PH). The semivariogram for the all data of GHG fluxes obtained in a 2 km line transect was analysed to evaluate the effect of land uses on the spatial dependency of GHG fluxes. The number of flux samples needed to estimate the mean of fluxes at 95% confidence level for various percentages of error from a true mean of the all measured fluxes in the line transect was also calculated. Furthermore, the minimum error range of each gas flux in the line transect was estimated by repeating the extraction of measured samples with increasing the number of extraction in each land use.

CO_2 flux showed a spatial dependency in both periods, but their forms were different. N_2O flux showed spatial dependency only during PF, and CH_4 flux did not show any spatial dependencies in both periods. These results suggest that no improvement of the accuracy for estimating mean value of GHG fluxes can be expected by taking account of spatial dependency. The number of samples in the 2 km line transect required to increase the accuracy in order that the

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sample mean was within ±20% of the true mean of the flux at 95% confidence level was 30 and 13 in each period for CO_2, 126 and 400 for CH_4 and 477 and 696 for N_2O. It is very difficult to carry out such a large number of samples for N_2O and CH_4. The number of samples required to obtain the narrowest range of the estimated flux was determined to be 3 to 5 for each land use type, which was estimated by repeating the extraction of measured samples. The largest error was 25% for CO_2, 513 % for CH_4, and 94% for N_2O. The error for CH_4 could be reduced to 97% by eliminating the samples identified as hot spots of which the values were higher than the average of whole data. Thus, the measurement of GHG fluxes in consideration of land use types and hot spots was recommended.

Introduction

Soil is considered to be a major source of greenhouse gases (GHGs) such as CO_2, CH_4, and N_2O. However, there is still a large uncertainty in estimating GHG fluxes from soils. These GHG fluxes are due to the microbial activities in the soil (MOSIER 1998) and these activities are dominated by many soil properties, which show spatial variability (PARKIN 1993). The spatial variability of GHG fluxes from field soils have been reported in several studies (FOLORUNSO & ROLSTON 1984, VELTHOF & al. 1996, VAN DEN POL-VAN DASSELAAR & al. 1998, YANAI & al. 2003). VAN DEN POL-VAN DASSELAAR & al. 1998 had reported that N_2O, CO_2 and CH_4 fluxes showed different spatial dependency in each sampling day when measured in grids at an interval of 7.5 to 15 m. They described that it showed 50 to 1400 % of CV value and spatial dependency from 50 to more than 200 m. YANAI & al. 2003 had evaluated spatial variability of N_2O flux and soil properties in grids at an interval of 10 m, which showed 217% of CV value and spatial dependency beyond 75 m. FOLORUNSO & ROLSTON 1984 and VELTHOF & al. 1996 have also estimated the number of samples required for precise estimation for N_2O flux. FOLORUNSO & ROLSTON 1984 reported that 88 samples were required (at 95% confidence level for ±20% of the true mean of the flux) when N_2O fluxes was measured on 36 m strip at the interval of 1 m. VELTHOF & al. 1996 reported, on the other hand, that 375 to 1240 samples were required (at 95% confidence level for ±10% of the true mean of the flux) when N_2O fluxes were measured for 144 samples at the interval of 1 m. All these studies were conducted at a single site and there is still no study conducted for multiple land uses. Therefore, the objectives of this study were to investigate spatial distribution and magnitude of CO_2, CH_4, and N_2O fluxes at post-fertilization and pre-harvesting periods, and to determine sample number requirements for various degrees of precision for multiple land uses.

Material and Methods

Site description

This study was carried out at the Shizunai Experimental Livestock Farm (N42° 25'9'', E142° 29'1''), in Southern Hokkaido, Japan. The annual mean temperature is 7 ℃, and annual mean precipitation is 1,200 mm. The soil of this area is classified as Aquic Humic Udivitrand (USDA Soil Taxonomy).

Measurement of gas fluxes

A 2 km line transect was set up across five land uses: forest, grazing forest, grassland, grazing pasture, and corn field. N fertilizers of 88, 25, and 89 kg N ha^{-1} were applied to grassland, grazing pasture, and corn field, respectively between April and August 2000. The measurements of spatial variability on the line transect were conducted twice, i.e. 21 June 2000, a month after fertilization (post-fertilization; PF), and 31 August 2000, a month before harvesting of maize (pre-harvesting; PH). The intervals of flux measurements were 20 m at PF and 5, 10, 20 and 40 m at PH. 100 samples were taken during each measurement. GHG fluxes were measured by using a closed-chamber technique. A cylindrical stainless steel chamber (diameter 0.3 m, height 0.35 m) was used for measurements. The chamber lid was made by white-painted acrylic plastic with a gas-sampling tube and a bag to control air pressure inside the chamber. Between the chamber and the lid, 1 mm thick silicon packing was installed. One day before the measurement, plants on the forest floor, grassland and grazing pasture were carefully removed to exclude plant respiration. In the corn field, the chambers were installed on the exposed soil surface between two corn plants. CO_2 gas was sampled at 0 and 6 minutes and CH_4 and N_2O gases were sampled at 0 and 20 minutes after closing the lid. Air temperature inside the chamber and soil temperature at 10 cm depth were measured with a digital thermometer. Volumetric water content at 0-10cm depth was measured with TDR (TRIME-FM, probe-P2, IMKO Micromodultechnik GmbH). CO_2 was analyzed by an infrared CO_2 gas analyzer (Fuji Electric, ZFP-5), CH_4 by gas chromatography with FID (Shimadzu, GC8A), and N_2O by gas chromatography with ECD (Shimadzu, GC 14B). Fluxes were calculated by linear regression (KUSA & al. 2002). In this study, positive flux indicates GHG emission from the soils, while negative flux indicates GHG uptake from the atmosphere.

Statistical and geostatistical analyses

The mean value and coefficient of variation of CO_2, CH_4, and N_2O fluxes in each land use were calculated. Significant difference of the mean value of the fluxes among the land uses were evaluated by Tukey-Kramer test (P=0.05).

The degree of spatial dependence of gas fluxes throughout the 2 km line transect was evaluated by a semivariogram to evaluate the effect of land use on the spatial variability of the gas fluxes. Semivariogram is described by plotted semivariance $\gamma(h)$ against lag distance h. In general, $\gamma(h)$ increases with an increase of h between the sampling points within a "range", when constant is called "sill". The semivariance at h=0 is called "nugget". $\gamma(h)$ of each gas flux was estimated by the following equation:

$$\hat{\gamma}(h) = \frac{1}{2m(h)} \sum_{i=1}^{m(h)} \{z(x_i) - z(x_i + h)\}^2$$

where m(h) is the total number of pairs of data (z(x_i) and z(x_i+h)) separated by h. The range, sill and nugget were estimated by a curve fitting method (WEBSTER & OLIVER 1990). In this study, semivariance was estimated by using all gas flux values, on the basis of assuming that they could not be divided by land uses. For the geostatisitical analysis, the software, GS+ Version 5.1 for Windows (Gamma Design Software), was used.

Estimation of sample numbers

The number of samples to estimate mean value of various degrees from a true mean at 95% confidence level were calculated by using the following equation:

$$95(\%) = f(Z_1) - f(Z_2)$$

$$f(Z) = \frac{1}{\sqrt{2\pi}} e^{-\frac{z^2}{2}}, \quad Z_1 = \frac{\bar{x} \times p/100}{s/\sqrt{n}}, \quad Z_2 = \frac{\bar{x} \times -p/100}{s/\sqrt{n}}$$

where f(z) is cumulative distribution function, $\bar{x}$ is the sample mean, p is the deviation of the sample mean from the 'true' mean of fluxes, s is standard deviation, and n is the required number of samples.

Calculation of gas flux in whole line transect

True fluxes for CO_2 (mg C m^{-2} h^{-1}), CH_4 (μ g C m^{-2} h^{-1}), and N_2O (μ g N m^{-2} h^{-1}) from the 2 km line transect were estimated by using all flux data in whole line transect as follows:

$$\text{True flux} = \sum_{i=1}^{n} \frac{1}{2}(R_i + R_{i+1})(D_{i+1} - D_i)$$

where i is the sampling point number on the transect, R_i is the flux value of ith, D_i is the distance initial sampling point (m). In the calculation, width of the transect was assumed to be 1 m.

On the other hand, the estimated fluxes for CO_2 (mg C m^{-2} h^{-1}), CH_4 (μ g C m^{-2} h^{-1}), and N_2O (μ g N m^{-2} h^{-1}) by sample extraction were estimated as follows:

$$\text{Estimated flux} = \sum \bar{x} \times D$$

where $\bar{x}$ is the mean of fluxes, calculated using the samples extracted randomly from all samples in each land use, and D is the length of each land use in the transect. The maximum and minimum estimated fluxes were obtained by repeating extraction of the sample 50 times with increasing the number of extracted samples. The number of samples for the narrowest range of the maximum and minimum values was determined by testing the significant difference between the means of the range for each extraction.

Results and Discussion

Spatial and temporal distribution of gas fluxes

CO_2 fluxes during PF were lower in forest, grazing forest, and corn field than in grassland and grazing pasture (Table 1, Fig. 1c). However, CO_2 fluxes at PH period were higher in grassland than others (Table 1). Almost all the plots showed higher fluxes during PH than PF (Fig. 1c). Correlation between CO_2 flux and soil temperature was observed in most of the plots (Fig. 1b, c) which were also observed in other studies (RAICH & SCHLESINGER 1992, DAVIDSON & al. 1998). However, a few grassland plots had showed higher flux at PH than PF (Fig. 1c), even though the soil temperature at PH was lower or similar to PF (Fig. 1b). This may be due to the higher root activities at PH than PF. The difference in seasonal pattern of CO_2 flux and soil temperature was also reported by HU & al. 2001. There was no significant difference ($P<0.05$) between forest and grazing forest for both periods (Table 1). Thus both land uses can be estimated without distinction. However, there was a significant difference in the flux between grassland and pasture at PH. The high CO_2 flux in grassland at PH may be due to higher root respiration. Thus both grassland and pasture need to be distinguished for estimating CO_2 fluxes.

Spatial variability of CH_4 fluxes was similar for both periods (Fig. 1d). CH_4 uptake was observed at both forest and grazing forest, whereas CH_4 emissions were observed at some sampling points of grazing pasture. Only few CH_4 uptake and emission were observed in grassland and corn field. The high CH_4 emissions at 420 m in PF (2100 μ g C m^{-2} h^{-1}) and at the point of 490 m in PH (5000 μ g C m^{-2} h^{-1}) were observed in grazing pasture. Those sampling points had almost saturated soil moisture conditions. However, at the next sampling points, low CH_4 emission (308 μ g C m^{-2} h^{-1}) at 440 m in PF and CH_4 uptake (-6.0 μ g C m^{-2} h^{-1}) at 495 m in PH was observed. The soil moisture content also decreased from water saturation. CH_4 emission generally occurred when the activity of the methanogens dominated with an increase in soil moisture content, and methane consumption was prominent when the methanotrophs dominated with a decrease in soil moisture (TOPP & PATTEY 1997). Thus, these soils with high moisture content due to its microtopography were "hot spots" of CH_4 emission. The hot spots were also observed in grazing forest. However, the CH_4 emission was still lower than that in grazing pasture, suggesting the effect of N fertilization on CH_4 emission. There was no significant difference between each land use (Table 1) for both periods suggesting that the "hot spot" are needed to be distinguished from the other points.

Table 1. The mean value and coefficient of variation of CO_2, CH_4, and N_2O fluxes for forest (F), grazing forest (GF), grassland (GL), grazing pasture (GP), corn field (CF), and whole data on the line transect.

	PF period								PH period					
		CO_2 flux (mg C m^{-2} h^{-1})		CH_4 flux (µg C m^{-2} h^{-1})		N_2O flux (µg N m^{-2} h^{-1})			CO_2 flux (mg C m^{-2} h^{-1})		CH_4 flux (µg C m^{-2} h^{-1})		N_2O flux (µg N m^{-2} h^{-1})	
	n	Mean	CV, %	Mean	CV, %	Mean	CV, %	*n*	Mean	CV, %	Mean	CV, %	Mean	CV, %
All	98	62.4	57	18	1298	46	228	100	146^{a}	36	124	502	51	275
F	6	$36.9^{a,b}$	52	-77	-23	0.49^{a}	1115	3	104^{a}	15	-53	-28	3.1^{a}	132
GF	30	36.8^{a}	56	-31	-265	9.0^{a}	181	24	131^{a}	35	-45	-131	3.0^{a}	110
GL	14	$70.0^{b,c}$	40	11	-371	18^{a}	162	11	218^{b}	17	-2	-283	23^{a}	129
GP	38	88.3^{c}	37	85	420	37^{a}	188	54	143^{a}	36	254	326	50^{a}	279
CF	10	$40.1^{a,b}$	23	0	1765	261^{b}	76	8	125^{a}	22	-5	-192	253^{b}	104

Difference in small letter denote significant difference in flux, using Tukey-Kramer test on fluxes ($P=0.05$).

N_2O fluxes were higher in corn field and grazing pasture than in other land uses (Fig. 1e). Corn fields showed high flux points, but they varied with time. Grasslands and corn field received almost the same amount of N fertilizer (88 and 89 kg N ha^{-1}, respectively), but corn field showed considerably higher emission than grassland. The higher N_2O emission in corn field may be due to its slower and incomplete N uptake and higher denitrification, and this result is consistent with the finding of BOUWMAN 1996. Grazing pasture showed some "hot spots" for N_2O flux at various points in both periods. The high N_2O fluxes at grazing pasture over grassland may be due to the additional N input and compaction of soil by cattle treading, which was also reported by VELTHOF & OENEMA 1995. Significant differences ($P<0.05$) of N_2O fluxes between corn field and other land uses were found for both periods, but there was no difference among other land uses (Table 1).

Spatial dependency of gas fluxes

CO_2 fluxes were spatially dependent for the distance of 778 m at PF (Fig. 2a). This result showed a longer spatial dependency than those reported by VAN DEN POL-VAN DASSELAAR & al. 1998. The CO_2 flux also showed a periodicity of variation at PH (Fig. 2b), which was also reported by AMBUS & CHRISTENSEN 1994.

CO_2 fluxes in grassland at PH were significantly higher than in other land uses (Table 1), but was evenly distributed at the line transect (Fig. 1c). This periodicity of significantly higher CO_2 emissions from grassland would cause a periodicity in the semivariogram.

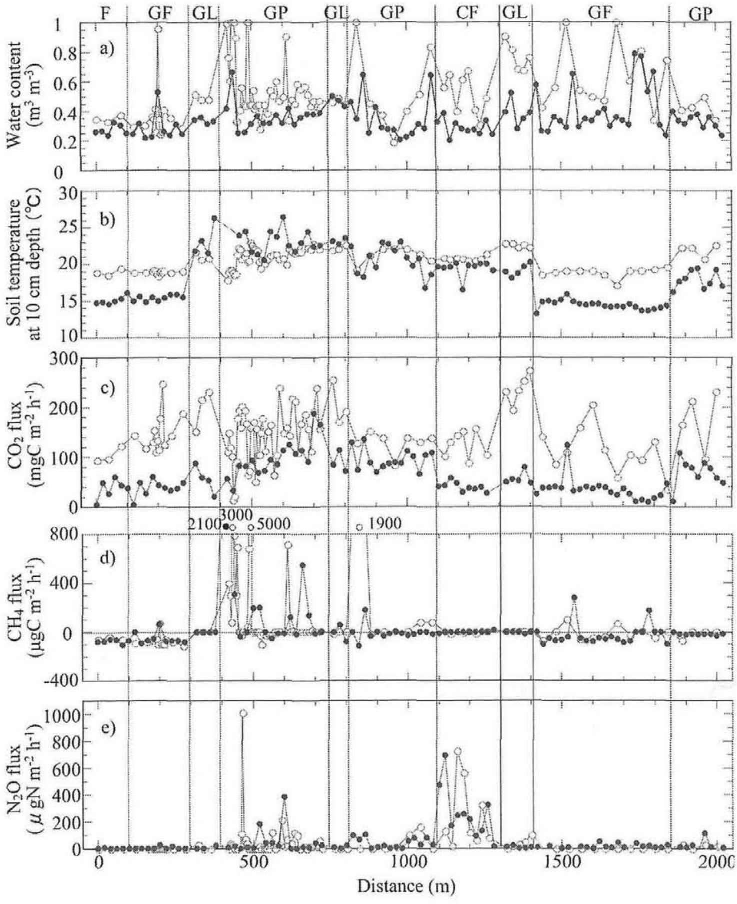

Fig. 1. Spatial distribution of a) water content, b) soil temperature at 10cm depth, c) CO_2 flux, d) CH_4 flux, and e) N_2O flux at PF (closed symbol) and PH period (open symbol) on the line transect. The line transect is across forest (F), grazing forest (GF), grazing pasture (GP), grassland (GL), and corn field (CF).

The semivariance of CH_4 flux at PF increased with an increase of lag distance at PF, but it was separated into two lines (Fig. 2c). The coefficient of determination of a regression model was very low (R^2=0.072), and the range could not be calculated. Until today, there is still no report on such kind of separation in semivariance. The semivariance of CH_4 flux at PH decreased with an increase in lag distance (Fig. 2d), thus a range could also not be obtained. The decrease in semivariance with an increase in lag distance for both measurements may be due to some "hot spots" for CH_4 fluxes. The uneven distribution of large fluxes affected by land uses may increase semivariance at shorter lag range.

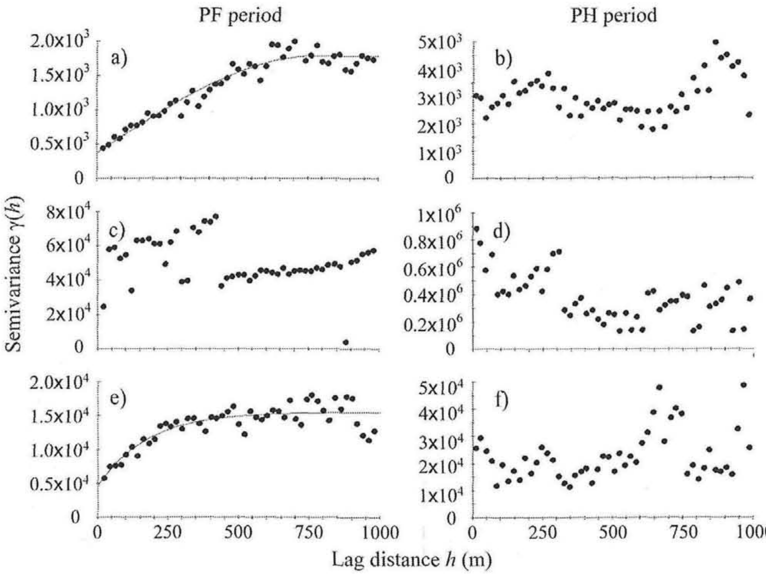

Fig. 2. Variograms of CO_2 fluxes a) at PF and b) at PH, CH_4 fluxes c) at PF and d) at PH, and N_2O fluxes e) at PF and f) at PH, for all flux samples on the line transect.

N_2O fluxes were spatially dependent on distances at 173 m at PF (Fig. 2e). Our results showed longer spatial dependency than those reported by VAN DEN POL-VAN DASSELAAR & al. 1998 and YANAI & al. 2003. N_2O flux showed a periodicity of variation at PH (Fig. 2f). The periodicity of N_2O flux at PH may be due to the periodicity of large emission points similar to CO_2 fluxes. These large emission points were observed in fertilized corn field and wet grazing pasture at both PF and PH. Thus, water and nutrient uptake by plants might have influenced the shape of the semivariogram.

Land uses influence the spatial dependency of CO_2, CH_4, and N_2O fluxes. Therefore, it is difficult to estimate an entire gas flux from a whole area including different land uses and different topography due to their influence on soil moisture and nutrient status. Furthermore, spatial dependency of the gas fluxes was different for both sampling times. VAN DEN POL-VAN DASSELAAR & al. 1998 and VELTHOF

& al. 2000 also reported the difference in spatial dependency for N_2O fluxes, which were measured in a single land use.

Sample number requirement

For CO_2 flux, the required number of samples was 30 at PF and 13 at PH so that the sample mean would be within $\pm$20% of the true mean of the flux at 95% confidence level (Table 2). The number of samples required for each land use (n) to obtain the narrowest range of the estimated flux was 5 for PF and 4 for PH (Table 3). This means that 25 and 20 samples in a whole line transect for two sampling times were required. The estimated fluxes were 79 to 125% of true flux for PF and 93 to 120% for PH (Table 3). Thus, for CO_2 flux estimation, the similar number of samples were required with and without distinguishing land use types.

Table 2. The number of samples required for various degrees of precision at 95% confidence level for PF and PH periods.

x(%)	CO_2		CH_4		N_2O	
	PF	PH	PF	PH	PF	PH
5	471	196	2009	6387	7628	11134
10	118	49	503	1597	1907	2784
20	30	13	126	400	477	696
50	5	2	21	64	77	112

Table 3. True fluxes and estimated fluxes of CO_2, CH_4, and N_2O from the 2 km line transect repeating extraction of n samples from each land use at PF and PH periods.

Period	True flux	Number of extraction		Estimated fluxes	
		Each land use	All land uses	Min	Max
CO_2 flux (mg C m^{-2} h^{-1})					
PF	62	5	25	49	77
PH	144	4	20	134	172
CH_4 flux (μg C m^{-2} h^{-1})					
PF with hot spots	28	5	25	-38	168
without hot spots	-21	3	15	-42	-6
PH with hot spots	61	3	15	-35	371
without hot spots	-22	5	25	-34	-9
N_2O flux (μg N m^{-2} h^{-1})					
PF	46	5	25	24	87
PH	144	4	20	10	67

The required number of samples for CH_4 flux was 126 for PF and 400 for PH for the sample mean to be within $\pm$20% of the true mean at 95% confidence level (Table 2). The number of samples required for each land use to obtain the narrowest range of the estimated flux was 5 for PF and 3 for PH (Table 3). However, estimated fluxes showed a very wide variation due to the presence of hot spots, which were -134 to 594% of true flux for PF and -58 to 613% for PH. The hot spots were identified when the data are greater than the average of each land use sample. The number of hot spot data eliminated for PF was 10 and PH was 28. The true flux without hot spots was estimated to be negative values from positive values in the true flux with hot spots (Table 3). The number of samples required for each land use to obtain the narrowest range of the estimated flux was very small, which improved the estimation being 30 to197% of the true flux for PF and 42 to 151% for PH. This means that the hot spots should be eliminated.

For N_2O, the number of flux samples required was 477 for PF and 696 for PH in order that the sample mean be within ±20% of the true mean of the flux at 95% confidence level (Table 2). The number of samples required for each land use to obtain the narrowest range of the estimated flux was 5 for PF and 4 for PH (Table 3). However, estimated fluxes showed a very wide range, which were 52 to 194% of the true flux for PF and 7 to 47 for PH. This was due to a significantly higher N_2O emission in the corn field than in other land uses (Table 1). Such kind of land use having a significantly high flux needs to be identified. This shows that N_2O fluxes were highly affected by hot spots.

Conclusion

GHG fluxes from soils in multi-land uses showed a spatial dependency, but the dependency condition was influenced by land use, hot spots, and sampling time. GHG fluxes seemed to be different in forests, grasslands, and crop fields. Thus, land use and hot spots need to be distinguished for accurate estimation of GHG fluxes, especially CH_4 and N_2O.

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