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

By

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Key words: Uncertainty, hot spot, landscape scale, spatial dependency, sample number.

Summary


Current estimation of the fluxes of major greenhouse gases (GHGs; CO₂, CH₄ and N₂O) 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.

CO₂ flux showed a spatial dependency in both periods, but their forms were different. N₂O flux showed spatial dependency only during PF, and CH₄ 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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The sample mean was within $\pm 20\%$ 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$_2$O. It is very difficult to carry out such a large number of samples for N$_2$O 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$_2$O. 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$_2$O. 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$_2$O, 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$_2$O 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$_2$O flux. FOLORUNSO & ROLSTON 1984 reported that 88 samples were required (at 95% confidence level for $\pm 20\%$ of the true mean of the flux) when N$_2$O 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 $\pm 10\%$ of the true mean of the flux) when N$_2$O 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$_2$O 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 °C, and annual
mean precipitation is 1,200 mm. The soil of this area is classified as Aquic Humic Udidentand (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\(_2\)O 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\(_2\)O 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\(_2\)O 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 geostatistical 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:

\[
f(Z) = \frac{1}{\sqrt{2\pi}} e^{-\frac{z^2}{2}}, \quad Z_i = \frac{\bar{x} - p/100}{s/\sqrt{n}}, \quad Z_{1-0.95} = \frac{\bar{x} - p/100}{s/\sqrt{n}}
\]

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$_4$ (µg C m$^{-2}$ h$^{-1}$), and N$_2$O (µg N m$^{-2}$ h$^{-1}$) from the 2 km line transect were estimated by using all flux data in whole line transect as follows:

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

where $i$ is the sampling point number on the transect, $R_i$ is the flux value of $i$th, $D_i$ 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$_4$ (µg C m$^{-2}$ h$^{-1}$), and N$_2$O (µg N m$^{-2}$ h$^{-1}$) by sample extraction were estimated as follows:

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

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 µg C m$^{-2}$ h$^{-1}$) and at the point of 490 m in PH (5000 µg 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 µg C m$^{-2}$ h$^{-1}$) at 440 m in PF and CH$_4$ uptake (-6.0 µg 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$_2$O fluxes for forest (F), grazing forest (GF), grassland (GL), grazing pasture (GP), corn field (CF), and whole data on the line transect.

<table>
<thead>
<tr>
<th></th>
<th>PF period</th>
<th>PH period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CO$_2$ flux (mg C m$^{-2}$ h$^{-1}$)</td>
<td>CH$_4$ flux (µg N m$^{-2}$ h$^{-1}$)</td>
</tr>
<tr>
<td>n</td>
<td>Mean</td>
<td>CV, %</td>
</tr>
<tr>
<td>All</td>
<td>98</td>
<td>62.4</td>
</tr>
<tr>
<td>F</td>
<td>6</td>
<td>36.9$^a$</td>
</tr>
<tr>
<td>GF</td>
<td>30</td>
<td>36.8$^a$</td>
</tr>
<tr>
<td>GL</td>
<td>14</td>
<td>70.6$^{ab}$</td>
</tr>
<tr>
<td>GP</td>
<td>38</td>
<td>88.3$^a$</td>
</tr>
<tr>
<td>CF</td>
<td>10</td>
<td>40.1$^{ab}$</td>
</tr>
</tbody>
</table>

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

N$_2$O 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$_2$O 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$_2$O flux at various points in both periods. The high N$_2$O 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$_2$O 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.
CO₂ 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 CO₂ emissions from grassland would cause a periodicity in the semivariogram.

![Graph showing spatial distribution of water content, soil temperature, CO₂ flux, CH₄ flux, and N₂O flux at PF (closed symbol) and PH period (open symbol) on the line transect.](image)

Fig. 1. Spatial distribution of a) water content, b) soil temperature at 10 cm depth, c) CO₂ flux, d) CH₄ flux, and e) N₂O 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 CH₄ 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.

\[
\begin{align*}
\text{PF period} & \quad \text{PH period} \\
\begin{array}{cc}
\text{Semivariance } \gamma(h) & \\text{Semivariance } \gamma(h) \\
0 & 0 \\
0.5 \times 10^4 & 5 \times 10^3 \\
1 \times 10^4 & 1 \times 10^6 \\
1.5 \times 10^4 & 0.8 \times 10^6 \\
2 \times 10^4 & 0.4 \times 10^6 \\
2.5 \times 10^4 & 0.2 \times 10^6 \\
3 \times 10^4 & 0 \end{array}
\end{align*}
\]

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$_2$O fluxes e) at PF and f) at PH, for all flux samples on the line transect.

N$_2$O 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 et al. 1998 and YANAI et al. 2003. N$_2$O flux showed a periodicity of variation at PH (Fig. 2f). The periodicity of N$_2$O 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$_2$O 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 N₂O fluxes, which were measured in a single land use.

Sample number requirement

For CO₂ flux, the required number of samples was 30 at PF and 13 at PH so that the sample mean would 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 (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 CO₂ 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.

<table>
<thead>
<tr>
<th>Χ (%)</th>
<th>CO₂</th>
<th>CH₄</th>
<th>N₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PF</td>
<td>PH</td>
<td>PF</td>
</tr>
<tr>
<td>5</td>
<td>471</td>
<td>196</td>
<td>2009</td>
</tr>
<tr>
<td>10</td>
<td>118</td>
<td>49</td>
<td>503</td>
</tr>
<tr>
<td>20</td>
<td>30</td>
<td>13</td>
<td>126</td>
</tr>
<tr>
<td>50</td>
<td>5</td>
<td>2</td>
<td>21</td>
</tr>
</tbody>
</table>

Table 3. True fluxes and estimated fluxes of CO₂, CH₄, and N₂O from the 2 km line transect repeating extraction of n samples from each land use at PF and PH periods.

<table>
<thead>
<tr>
<th>Period</th>
<th>True flux</th>
<th>Number of extraction each land use</th>
<th>Estimated fluxes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>All land uses</td>
<td>Min</td>
</tr>
<tr>
<td>CO₂ flux (mg C m⁻² h⁻¹)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PF</td>
<td>62</td>
<td>5</td>
<td>49</td>
</tr>
<tr>
<td>PH</td>
<td>144</td>
<td>4</td>
<td>134</td>
</tr>
<tr>
<td>CH₄ flux (µg C m⁻² h⁻¹)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PF with hot spots</td>
<td>28</td>
<td>5</td>
<td>-38</td>
</tr>
<tr>
<td>without hot spots</td>
<td>-21</td>
<td>3</td>
<td>-42</td>
</tr>
<tr>
<td>PH with hot spots</td>
<td>61</td>
<td>3</td>
<td>-35</td>
</tr>
<tr>
<td>without hot spots</td>
<td>-22</td>
<td>5</td>
<td>-34</td>
</tr>
<tr>
<td>N₂O flux (µg N m⁻² h⁻¹)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PF</td>
<td>46</td>
<td>5</td>
<td>24</td>
</tr>
<tr>
<td>PH</td>
<td>144</td>
<td>4</td>
<td>10</td>
</tr>
</tbody>
</table>

The required number of samples for CH₄ flux was 126 for PF and 400 for PH for the sample mean to be within ±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 to 197% of the true flux for PF and 42 to 151% for PH. This means that the hot spots should be eliminated.

For N\textsubscript{2}O, 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\textsubscript{2}O 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\textsubscript{2}O 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\textsubscript{4} and N\textsubscript{2}O.

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**References**


