Title

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Greenhouse Gas Budget in a Larch Forest with Low Atmospheric N Deposition in Hokkaido, Northern Japan

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Abstract
Dissolved inorganic nitrogen (DIN) in throughfall, soil N\textsubscript{2}O and CH\textsubscript{4} fluxes, soil organic matter decomposition (OMD), net primary production (NPP), tree N uptake and net nitrification potential were measured at each one site in five adjacent catchments with fairly identical soil type (Hapludants) and vegetation type (50 to 60 years old larch plantation) for 6 months during the non-snow cover period (June-November) for two years in Mt. Shirahata, Hokkaido, Japan. The net ecosystem production (NEP) was calculated as NPP-OMD and the global warming potential (GWP) was estimated from the negative of NEP, N\textsubscript{2}O and CH\textsubscript{4} emissions using the IPCC recommendation. The throughfall DIN (kg N ha\textsuperscript{-1} 6 months\textsuperscript{-1}) ranged from 0.88 to 1.75 in 2003 and 0.91 to 1.79 in 2004, significantly lower than larch N uptake and nitrification potential. Methane was taken up by soil and N\textsubscript{2}O was emitted from it. Both CH\textsubscript{4} uptake in and N\textsubscript{2}O emission from Mt. Shirahata were significantly lower than previously reported values, which is ascribed to low DIN deposition to this area. A positive GWP was obtained in this study mainly due to a negative NEP, indicating that the forests in Mt. Shirahata enhance global warming.

Key words: atmospheric nitrogen deposition, CH\textsubscript{4}, CO\textsubscript{2}, N\textsubscript{2}O, NEP

Introduction
Forest ecosystem is thought to be an important carbon (C) sink, and its contribution to global C sink is estimated to be 26% (1.9 Gt C), which is identical to the contribution of ocean (IPCC, 2001). Forest soil is second important CH\textsubscript{4} sink following troposphere and its contribution to global CH\textsubscript{4} sink is estimated to be 5% (30 Mt CH\textsubscript{4}) (IPCC, 2001).

The available N for plant growth in a forest ecosystem is supplied by N\textsubscript{2}O fixation and atmospheric N deposition, and it is mainly controlled by N mineralization from litterfall. The mineralized N is readily taken up by plants and is fixed by soil microbes, therefore N runoff from forest ecosystem is generally limited (Vitousek et al., 2002), and the available N essentially governs plant C fixation (Nadelhoffer 2001). Although there are some reports that an increase in atmospheric N deposition stimulated tree growth (Kenk and Fischer, 1988), several reports have shown that an increase in atmospheric N deposition increased NO\textsubscript{3}-N leaching (Disch and Wright, 1995), N runoff to stream (Nakahara et al., 2003), and N\textsubscript{2}O emission from soil (Butterbach-Bahl et al., 2002), decreased CH\textsubscript{4} uptake by soil (Morishita et al., 2004), accelerated soil organic matter decomposition (Kuperman, 1999; Mo et al., 2006), and decreased net primary production (NPP) (Emmett, 1999). Since NO\textsubscript{3}-N leaching relates to indirect N\textsubscript{2}O emission (Mosier et al., 1998), these indicate that atmospheric N deposition stimulates global warming sufficiently.

However, information for the effect of low atmospheric N deposition to forests on global warming is still lacking. Mt. Shirahata in Hokkaido, Northern Japan is received low atmospheric N deposition (Nakahara et al., 2003 and Koide et al., 2005). In this study, we conducted an intensive monitoring of atmospheric N deposition, N\textsubscript{2}O emission from soil, CH\textsubscript{4} uptake by soil, CO\textsubscript{2} budget in ecosystem, and nitrification potential of soil in five adjacent small catchments in Mt. Shirahata with similar soil and vegetation types for two years. We analyzed the influence of N mineralization and atmospheric N deposition on total greenhouse gas budgets.

Materials and Methods
Site description
Mt. Shirahata (N 42°56′, E141°25′), 300 m in elevation and about 1000 ha in area, is located in the south-eastern part of Sapporo City, Japan. The mean annual temperature is 8.2 °C, and the mean annual precipitation is 1130 mm of which 380 mm falls as snow during the period from November to April. The soil type of this mountain is uniformly Hapludants (Soil Survey Staff, 1999) derived from volcanic ashes from Mt. Tarumae and Mt. Eniwa. The dominating vegetation type is 50-60 year old larch stands (Larix leptolepis) covering 72% of the forest area followed by some broad-leaved species (Betula platyphylla var. japonica, Fraxinus mandshurica, and Acer pictum). In 2002, throughfall DIN was measured as atmospheric N deposition at 6 to 8 sites in each of five catchments in the mountain (Nakahara et al., 2003). Based on these results, we selected each one site out of those sites (Received; Feb. 23, 2007: Accepted; Mar. 23, 2007) *Corresponding author: hatano@chem.agr.hokudai.ac.jp
namely A, B, C, D, and E, which showed throughfall DIN close to the average in each catchment, as a representative site. However, a selective felling was done in the catchment E in 2002. At each site in five catchments, we measured throughfall DIN, N\textsubscript{2}O emission from soil, CH\textsubscript{4} uptake by soil, net primary production during the non-snow cover season of 2003 and 2004.

Furthermore, at the same sites where throughfall DIN was measured in 2002 (Nakahara et al., 2003), we took soil samples from O horizons in May 2003 and 2004. However, daily mean soil temperature was measured by a thermometer with data logger from 2003 to 2005. In both methods, regression equations for predicting OMD from soil temperature were made and predicted OMD values between the two methods were compared.

**Throughfall DIN**

Throughfall was taken at each site in five catchments by using a gutter, 180 cm long and 10 cm wide, during the non-snow cover season from June to November. All the gutters were set up at a similar distance from nearby trees to minimize errors. The sampling was carried out once or twice a month. After filtering the samples through membrane filters (0.2 µm) NH\textsubscript{4}-N and NO\textsubscript{3}-N concentrations were measured by indophenol-blue method and by ion-chromatography (Dionex QIC Analyser, Dionex Japan, Osaka, Japan), respectively. The input of inorganic N was calculated as the product of the throughfall water flux and NH\textsubscript{4}-N and NO\textsubscript{3}-N concentrations in the solutions.

**N\textsubscript{2}O and CH\textsubscript{4} fluxes**

N\textsubscript{2}O and CH\textsubscript{4} fluxes from soil were measured once in every three weeks during non-snow cover period of 2003 and 2004 at six replications by a closed-chamber technique in those sites, where throughfall samples were collected. A chamber set of stainless cylinder, 20 cm in diameter and 25 cm in height, with its cover made of acryl, 20 cm in diameter and 3 mm thick, was used. The cylinder had a blade of 2 cm wide around the top in order to place the cover on it. A thin rubber plate was attached on the blade to minimize leakage of air from the chamber. The chamber cover was equipped with a sample collector, pressure regulating bag and a tedlar bag. In order to make the chamber set up easier, a stainless cylindrical base, 20 cm in diameter and 5 cm in height, was used. The base was pushed into the soil at least one day before the gas flux measurement. The upper part of the base has a slight depression to insert the cylinder after filling up water to minimize the leakage of air inside chamber. The vegetations were removed from the chamber base, but the litter covering the base was left inside during the measurement. We took gas samples before and after 60 minutes of closing the chamber. Gas samples were taken using a 50 mL syringe and were filled into the 0.5 L tedlar bags. After these bags were brought to the laboratory, 20 mL of gas samples were immediately transferred into 10 mL vial bottles to measure N\textsubscript{2}O and CH\textsubscript{4} concentrations. Nitrous oxide was analyzed by ECD Gas Chromatography (SHIMADZU GC-14B, Shimadzu, Kyoto, Japan) and CH\textsubscript{4} was analyzed by FID Gas Chromatography (SHIMADZU GC-8A, Shimadzu, Kyoto, Japan). The accuracy of concentration measurement was ±0.01 ppmv for both CH\textsubscript{4} and N\textsubscript{2}O. The gas fluxes were calculated by the following equation as follows.

\[
F = \rho \times V / A \times \Delta c / \Delta t \times 273 / (273 + T) \times P / 760
\]

where F is the flux (mg N m\textsuperscript{-2} h\textsuperscript{-1}), \(\rho\) is the gas density (\(\rho\text{N}_2\text{O-N} = 1.26 \times 10\textsuperscript{4}\) and \(\rho\text{CH}_4-C = 0.539 \times 10\textsuperscript{4}\) mg N m\textsuperscript{-3}), V is the volume of the chamber (m\textsuperscript{3}), A is the area of the chamber (m\textsuperscript{2}), \(\Delta c / \Delta t\) is the ratio of change in the gas concentration inside the chamber (10\textsuperscript{-6} m\textsuperscript{3} h\textsuperscript{-1}), T is the air temperature inside the chamber (°C), and P is the air pressure (mm Hg). The cumulative N\textsubscript{2}O and CH\textsubscript{4} fluxes were calculated assuming linear changes between two sampling occasions. A positive value of the cumulative flux means that gas was emitted from soil and a negative value means that gas was taken up by soil. Generally N\textsubscript{2}O is emitted from and CH\textsubscript{4} is taken up by forest soils (IPCC, 2001).

**Soil organic matter decomposition (OMD)**

The soil OMD was estimated by incubation method in the laboratory and by field method from CO\textsubscript{2} flux measurement at root-cut plot in the field. The CO\textsubscript{2} flux measurement at the root-cut plot was carried out at A and D in 2003 and 2004. However, daily mean soil temperature was measured by a thermometer with data logger from 2003 to 2005. In both methods, regression equations for predicting OMD from soil temperature were made and predicted OMD values between the two methods were compared.

1) Incubation method

The CO\textsubscript{2} production rate was measured using the soil samples taken from O and A horizons at each site of five catchments on a fine day in the beginning of June 2004, when moisture content was almost average in plant growing season. Samples were kept in vinyl bags at 4 °C until the incubation experiment. The samples from A horizon were sieved by using 4 mm mesh sieve just before the incubation experiment. Two g and 20 g of fresh samples from O and A horizons were placed in 1 L Erlenmeyer flasks (actual volume after sealing was 1.15 L), respectively, then inlet of the flask was sealed with a rubber stopper equipped with a sample collector and a pressure regulating bag, and incubated at different temperatures (5, 15 and 25 °C). The soil moisture was not treated, and the incubation was continued for 11 days. CO\textsubscript{2} concentration in the flask was measured with a portable infrared CO\textsubscript{2} gas analyzer (ZFP9GC11; Fuji Electric systems Co. Ltd., Tokyo, Japan) everyday. After measurement of CO\textsubscript{2} concentration, the air inside the flask was exchanged by ambient air containing CO\textsubscript{2} concentration of 370 ppmv.

The organic matter decomposition per gram of soil was calculated from the change in CO\textsubscript{2} concentration inside the incubation flask. The change in CO\textsubscript{2} concentration was generally high for first 5 days after incubation started, and then it became stable. The average value of the change in CO\textsubscript{2} concentration from the 6th to 11th day after starting incubation was used as CO\textsubscript{2} production rate (mg C g\textsuperscript{-1} day\textsuperscript{-1}).

The relation between temperature and CO\textsubscript{2} production rate was well fitted to exponential. The determination of coefficients ranged from 0.921 to
0.993 for O horizon and 0.986 to 1.00 for A horizon. The daily CO₂ production was estimated by substituting the daily mean soil temperature measured by a thermometer with data logger into the exponential equation, and the cumulative CO₂ production both from June 2003 to November 2005 was obtained. The OMD was obtained by multiplying the cumulative CO₂ production, bulk density and depth of O and A horizons as shown in Table 1.

2) CO₂ flux measurement at root cut plot

The root-cut plots of 1 m by 1 m were established in two sites (A and D) in October 2002. As roots were found in upper 50 cm depth during the soil survey, a 1 m deep trench was made surrounding the plot. The soil column was immediately lapped with a vinyl sheet and the trench was filled with the soil. All vegetations were removed from the root-cut plots. CO₂ flux from soil was measured by using the same chamber as used for N₂O and CH₄ flux measurements 16 times (once or twice a month) each from June 2003 to November 2004 at A and D sites. However, the period of closing chamber was 6 min. for CO₂ flux measurements. Soil temperature at 4 cm depth was measured at every CO₂ flux measurement. Significant exponential relations between soil temperature at 4 cm depth (T) and CO₂ flux (mg C m⁻² hr⁻¹) were obtained in both sites. The equation is: CO₂ = 33.9 exp(0.079×T), R² = 0.749, P<0.01 for site A and CO₂ = 41.4 exp(0.065×T), R² = 0.576, P<0.01 for site D. The daily CO₂ flux from June to November in 2003 to 2005 was estimated by substituting the daily mean soil temperature measured by thermometer with data logger at each site of five catchments into the regression equation. The OMD from June to November in 2003 and 2005 was estimated by integrating the daily CO₂ fluxes. The OMD from June 2003 to November 2005 was obtained. The OMD from incubation + 2332, R² = 0.882, P<0.01.

The OMD at 5 catchments was estimated.

Net primary production (NPP) in the growing season

The NPP was estimated as a sum of difference between the total biomass in fall and spring and litterfall. The litterfall was assumed as the increment of the leaf. The aboveground total biomass (kg ha⁻¹) was calculated by using the following allometric relation as recommended by the Research group of four University (1964):

Log (total aboveground biomass) = -1.262+0.883log (D²H), R²=0.987

where D is the diameter at breast height (cm), and H is the tree height (m). Root biomass was assumed as 1/3 of above ground biomass (Ono, 2002). Tree inventory for D and H was made in an area of 50 m by 50 m in each site of five catchments. Litterfall was taken by the box, 540 cm by 370 cm by 20 cm in height, covered by a 1mm mesh net at ten replicates at each site of five catchments in 2004.

NPP in unit of (kg C ha⁻¹) was calculated as TB×C_TB + LF×C_L, where TB is the difference in total biomass in fall and spring, LF is litterfall, and C_TB and C_L are mean C contents of TB and leaf, respectively. The N uptake (kg N ha⁻¹) was also calculated as TB×N_TB + LF×N_L, where N_TB and N_L are mean N contents of TB and leaf, respectively. One tree of catchment D was felled to measure the biomass and C and N contents of stem, bark, branch, root and leaf. The plant samples were dried for 48 hours at 70 °C, weighed then ground. The ground samples were analyzed for N and C contents using NC analyser (Sumigraph NC-1000, Sumika Chemical Analysis Service, Osaka, Japan). The mean C and N contents were 0.502 g g⁻¹ and 0.000882 g g⁻¹, respectively. Carbon and N contents of leaf were 0.483 and 0.0221 g g⁻¹, respectively.

Global Warming Potentials (GWP)

The GWP of each site was computed based on its GHG emissions. While any period can be selected, the 100 year GWPs recommended by the IPCC was used in this study (IPCC, 2001).

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Horizon</th>
<th>Thickness (cm)</th>
<th>Bulk density (Mg m⁻³)</th>
<th>C (%)</th>
<th>N (%)</th>
<th>C/N</th>
<th>pH(H₂O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>O</td>
<td>3.7</td>
<td>0.073</td>
<td>42.3</td>
<td>1.61</td>
<td>26.3</td>
<td>5.8</td>
</tr>
<tr>
<td>A</td>
<td>A</td>
<td>4.3</td>
<td>0.755</td>
<td>6.9</td>
<td>0.43</td>
<td>16.0</td>
<td>5.5</td>
</tr>
<tr>
<td>B</td>
<td>O</td>
<td>3.3</td>
<td>0.058</td>
<td>45.7</td>
<td>1.56</td>
<td>29.3</td>
<td>5.1</td>
</tr>
<tr>
<td>B</td>
<td>A</td>
<td>5.7</td>
<td>0.807</td>
<td>6.5</td>
<td>0.45</td>
<td>14.4</td>
<td>4.7</td>
</tr>
<tr>
<td>C</td>
<td>O</td>
<td>2.7</td>
<td>0.111</td>
<td>41.2</td>
<td>1.74</td>
<td>23.7</td>
<td>6.0</td>
</tr>
<tr>
<td>C</td>
<td>A</td>
<td>4.3</td>
<td>0.622</td>
<td>7.4</td>
<td>0.54</td>
<td>13.7</td>
<td>6.1</td>
</tr>
<tr>
<td>D</td>
<td>O</td>
<td>4.8</td>
<td>0.065</td>
<td>44.1</td>
<td>1.85</td>
<td>23.8</td>
<td>4.9</td>
</tr>
<tr>
<td>D</td>
<td>A</td>
<td>7.0</td>
<td>0.670</td>
<td>16.2</td>
<td>0.75</td>
<td>21.6</td>
<td>4.9</td>
</tr>
<tr>
<td>E</td>
<td>O</td>
<td>3.0</td>
<td>0.123</td>
<td>47.2</td>
<td>1.97</td>
<td>24.0</td>
<td>5.4</td>
</tr>
<tr>
<td>E</td>
<td>A</td>
<td>4.0</td>
<td>0.444</td>
<td>6.4</td>
<td>0.44</td>
<td>14.5</td>
<td>4.6</td>
</tr>
</tbody>
</table>
The GWP was calculated as follows:

\[ \text{GWP}_{\text{CO}_2} (\text{kg CO}_2 \text{ ha}^{-1}) = \text{NEP} (\text{kg C ha}^{-1}) \times (1\text{g CO}_2) \times (44\text{g CO}_2 / 12\text{g CO}_2-C) \]

\[ \text{GWP}_{\text{CH}_4} (\text{kg CO}_2 \text{ ha}^{-1}) = \text{CH}_4 \text{ emission} (\text{kg C ha}^{-1}) \times (23\text{g CO}_2 / 1\text{g CH}_4) \times (16\text{g CH}_4 / 12\text{g CH}_4-C) \]

\[ \text{GWP}_{\text{N}_2\text{O}} (\text{kg CO}_2 \text{ ha}^{-1}) = \text{N}_2\text{O} \text{ emission} (\text{kg N ha}^{-1}) \times (296\text{g CO}_2 / 1\text{g N}_2\text{O}) \times (44\text{g N}_2\text{O} / 28\text{g N}_2\text{O-N}) \]

where \( \text{GWP}_{\text{CO}_2}, \text{GWP}_{\text{CH}_4} \) and \( \text{GWP}_{\text{N}_2\text{O}} \) are GWP due to \( \text{CO}_2, \text{CH}_4 \) and \( \text{N}_2\text{O} \) emissions, respectively. The negative value of NEP was used for \( \text{CO}_2 \) emission. The positive GWP indicates the enhancement of global warming while the negative indicates its mitigation.

Nitrification potential

Soil samples were taken from O horizons at 28 sites (each 5 to 6 sites in five catchments) in June 2004. Soil samples were kept at 4 °C until the incubation study. Ten g at dry soil basis of sample was placed into 500 mL plastic bottle and distilled water was added to adjust soil moisture content of 2.50 g g\(^{-1}\). Six bottles were prepared for one site. Those bottles were covered by thin aluminum foil with small holes, and were incubated at 25 °C. The moisture content was adjusted every 3 days by measuring the weight of bottle. After pre-incubation for 11 days, each 10g of samples from three bottles for one site was extracted with 50 ml of distilled water, and NO\(_3\)-N concentration was measured by ion-chromatography (Dionex QIC Analyser, Dionex Japan, Osaka, Japan). The remaining were further incubated for 41 days at 25 °C and then NO\(_3\)-N concentration was measured in the same manner. The nitrification potential was obtained as:

\[ (\text{NO}_3-N \text{ content after incubation (mg N g}^{-1}) - \text{NO}_3-N \text{ content at starting incubation (mg N g}^{-1})) / \text{incubation period.} \]

Statistical analyses

Statistical analyses were performed by using Excel statistics. One way and two way analysis of variance and simple regression analysis were performed. For this study, effects with probabilities of \( p < 0.05 \) were assumed to be significant.

Results and discussion

The throughfall DIN deposition at the sites during the non-snow cover season at Mt. Shirahata was 1.191 ± 0.339 (mean±SD) kg N ha\(^{-1}\) 6 months\(^{-1}\) (Table 2). NH\(_4\)–N was the major component in DIN deposition, which was 0.618±0.112.

Soil CH\(_4\) flux at Mt Shirahata was negative (-6.44±0.601 kg C ha\(^{-1}\) 6 months\(^{-1}\)), indicating that CH\(_4\) was taken up by soil (Table 3). The CH\(_4\) uptake was significantly higher than those in other sites in Hokkaido (-2.27±1.05 kg C ha\(^{-1}\) 6 months\(^{-1}\)) (Morishita et al., 2004) and in Europe (-2.54±1.87 kg C ha\(^{-1}\) y\(^{-1}\)) (Borken et al., 2000; Bradford et al., 2001; Butterbach-Bahl and Papen, 2002; Macdonald et al., 1997; Steinkamp et al., 2001). There was a significant positive correlation between CH\(_4\) flux and logarithmic DIN deposition (CH\(_4\) flux = 1.469 ln(DIN) - 5.777, \( R^2 = 0.532, P<0.01 \)), and CH\(_4\) flux was much better correlated with logarithmic NH\(_4\)-N deposition than DIN (CH\(_4\) flux = 2.228 ln(NH\(_4\)-N) - 5.113, \( R^2 = 0.765, P<0.01 \)) (Fig. 1). This is supported by the findings of decrease in CH\(_4\) uptake associated with NH\(_4\)-N fertilization which can be attributed to inhibition of CH\(_4\) oxidation by nitrification (Steudler et al., 1989; Gulledge et al., 1997; Hu et al., 2002). High CH\(_4\) uptake in Mt. Shirahata could possibly be due to low atmospheric DIN deposition compared to those in other sites.

Table 3. CH\(_4\) and N\(_2\)O fluxes from the soil to the atmosphere at Mt. Shirahata.

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Year</th>
<th>DIN</th>
<th>NO(_3)-N</th>
<th>NH(_4)-N</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2003</td>
<td>0.88</td>
<td>0.40</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>1.31</td>
<td>0.46</td>
<td>0.85</td>
</tr>
<tr>
<td>B</td>
<td>2003</td>
<td>1.18</td>
<td>0.55</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>1.20</td>
<td>0.33</td>
<td>0.85</td>
</tr>
<tr>
<td>C</td>
<td>2003</td>
<td>1.04</td>
<td>0.38</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>0.94</td>
<td>0.33</td>
<td>0.60</td>
</tr>
<tr>
<td>D</td>
<td>2003</td>
<td>0.91</td>
<td>0.44</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>0.91</td>
<td>0.14</td>
<td>0.73</td>
</tr>
<tr>
<td>E</td>
<td>2003</td>
<td>1.75</td>
<td>0.68</td>
<td>1.07</td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>1.79</td>
<td>0.48</td>
<td>1.31</td>
</tr>
</tbody>
</table>

*Negative value indicates gas uptake by the soil from the atmosphere.
†Same letter indicates no significant difference at 5 % level.
The soil \( \text{N}_2\text{O} \) flux at Mt Shirahata was positive \((0.0443 \pm 0.0231 \text{ kg N ha}^{-1} \text{ 6 months}^{-1}) \), indicating that \( \text{N}_2\text{O} \) was emitted from the soil (Table 3). The \( \text{N}_2\text{O} \) emission was significantly lower than in other Japanese sites \((0.244 \pm 0.201 \text{ kg N ha}^{-1} \text{ y}^{-1}) \) (Oura et al., 2001, 2005) and European sites \((1.07 \pm 1.61 \text{ kg N ha}^{-1} \text{ y}^{-1}) \) (Borken and Beese, 2005; Brumme and Beese, 1992; Brumme et al., 1999; Butterbach-Bahl et al., 2002; Horvath, 2004; Klemedtsson et al., 1997; Macdonald et al., 1997; Mogge et al., 1998). Broad-leaved forests showed significantly higher \( \text{N}_2\text{O} \) emission \((0.290 \pm 0.139 \text{ kg N ha}^{-1} \text{ y}^{-1}) \) than coniferous forests \((1.537 \pm 4.501 \text{ kg N ha}^{-1} \text{ y}^{-1}) \). There was a significant positive relationship between \( \text{N}_2\text{O} \) emission and DIN deposition in broad-leaved forests \((\text{N}_2\text{O} \text{ emission} = 0.0605 \exp(0.124 \times \text{DIN}), R^2 = 0.612, P<0.01) \) and in coniferous forests \((\text{N}_2\text{O} \text{ emission} = 0.0169 \text{ DIN} + 0.0479, R^2 = 0.480, P<0.01) \) (Fig. 2). The low \( \text{N}_2\text{O} \) emission from Mt. Shirahata could possibly be due to the low atmospheric DIN deposition compared to that from other sites.

The larch NEP at Mt Shirahata was negative \((-1830 \pm 1082 \text{ kg C ha}^{-1} \text{ 6 months}^{-1}) \) (Table 4). However, a positive NEP has been reported for larch forests, Hirano et al. (2003) reported a positive NEP \((2930 \text{ to } 3890 \text{ kg N ha}^{-1} \text{ y}^{-1}) \) in a 40 year old larch forest near Tomakomai city in Hokkaido. Sawamoto et al. (2003) also showed a positive NEP \((1400 \text{ and } 1240 \text{ kg N ha}^{-1} \text{ y}^{-1}) \) in two 200-year-old larch forests in Central Yakutia, Russia. On the other hand, Law et al. (2003) showed a negative NEP at some of different aged pine forests in central Oregon, USA \((-320 \text{ to } -2240 \text{ kg N ha}^{-1} \text{ y}^{-1}) \).

The OMD at Mt. Shirahata was 4118\( \pm \)222 kg C ha\(^{-1}\) 6 months\(^{-1}\) (Table 4), which was significantly higher than that at pine forests in central Oregon \((3064\pm812 \text{ kg C ha}^{-1} \text{ y}^{-1}) \) (Law et al., 2003). However, The OMD at Mt. Shirahata had considerably lower soil respiration (OMD+root respiration) at the larch forest in Tomakomai \((7000 \text{ kg C ha}^{-1} \text{ y}^{-1} \text{ in maximum}) \) as reported by Kim et al. (2005).

The larch NPP at Mt Shirahata was 2384\( \pm \)1126 kg C ha\(^{-1}\) 6 months\(^{-1}\) (Table 4), which was significantly lower than that of the middle aged pine forests \((60-100 \text{ years old}) \) in central Oregon \((4425\pm1448 \text{ kg C ha}^{-1} \text{ y}^{-1}) \). There might be possible factors to reduce the NPP at Mt. Shirahata. One of possible factors might be phosphorous because Andosols have high phosphorous retention (Koide et al., 2005).

The N uptake by larch in Mt. Shirahata was 38.91\( \pm \)7.87 kg N ha\(^{-1}\) 6 months\(^{-1}\) (Table 5), which was significantly higher than DIN deposition. Using the value of nitrification potential in O horizon (Table 5), the potential NO\(_3\)-N supply from O horizon for 6 months was estimated to be 22.54\( \pm \)4.40 kg N ha\(^{-1}\) 6 months\(^{-1}\), which is about half of the larch N uptake. Taking into N mineralization from mineral horizons, the source for larch N uptake was inorganic N mineralized from litter and soil organic matter. Although there was a tendency that larch N uptake
increased with an increase in nitrification potential in the catchments other than catchment E (Table 5). Nitrogen mineralization might be a limiting factor for larch growth. The total GWP at Mt. Shirahata was 6538±3955 kg CO2 ha-1 6 months-1 (Table 6), indicating that the forests in Mt. Shirahata enhance global warming. The contribution of GWP CO2 (NEP) to the total GWP was more than 100%. On the other hand, GWP CH4 contributed negatively to the total GWP, ranging from -2 to -14%. The contribution of GWP NO2 was low ranging from 0.1 to 2%. These results indicate that an increase in CO2 fixation by trees is the most important for mitigating global warming in the site with low DIN deposition.

**Conclusion**

An increase in atmospheric DIN deposition decreases CH4 uptake and increases N2O emission from forest soils. Tree growth in forest is the most important factor for mitigating global warming. However, tree growth seemed to depend on the N mineralization from litter and soil organic matter in the case of significantly lower atmospheric DIN deposition compared to N mineralization.

**References**


**Table 5. Nitrification potential in O horizon and Larch N uptake at Mt. Shirahata in 2004.**

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Mean</th>
<th>sd</th>
<th>Larch N uptake kg N ha^-1 6 months^-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.147</td>
<td>0.051</td>
<td>48.6</td>
</tr>
<tr>
<td>B</td>
<td>0.136</td>
<td>0.055</td>
<td>44.7</td>
</tr>
<tr>
<td>C</td>
<td>0.096</td>
<td>0.059</td>
<td>28.8</td>
</tr>
<tr>
<td>D</td>
<td>0.102</td>
<td>0.064</td>
<td>37.8</td>
</tr>
<tr>
<td>E</td>
<td>0.145</td>
<td>0.061</td>
<td>34.7</td>
</tr>
</tbody>
</table>

†Same letter indicates no significant difference at 5 % level.

**Table 6. Global warming potential (GWP)* at Mt. Shirahata in 2004.**

<table>
<thead>
<tr>
<th>Catchment</th>
<th>GWP CO2 kg CO2 ha^-1 6 months^-1</th>
<th>GWP CH4 kg CO2 ha^-1 6 months^-1</th>
<th>GWP N2O kg CO2 ha^-1 6 months^-1</th>
<th>Total GWP kg CO2 ha^-1 6 months^-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1212</td>
<td>-161</td>
<td>23</td>
<td>1075</td>
</tr>
<tr>
<td>B</td>
<td>4615</td>
<td>-198</td>
<td>10</td>
<td>4427</td>
</tr>
<tr>
<td>C</td>
<td>7894</td>
<td>-217</td>
<td>20</td>
<td>7696</td>
</tr>
<tr>
<td>D</td>
<td>8135</td>
<td>-180</td>
<td>9</td>
<td>7964</td>
</tr>
<tr>
<td>E</td>
<td>11696</td>
<td>-204</td>
<td>35</td>
<td>11527</td>
</tr>
</tbody>
</table>

*Positive value indicates enhancement of global warming. † It was obtained as the negative of NEP value.


Research group of four University (Hokkaido Univ., Tokyo Univ., Kyoto Univ. and Osaka City Univ.) and Shinshu Univ. (1964) Studies on the productivity of the forest. Part II. Larch (Larix leptolepis Cord.) forests of Shinshu District. Forest Technology Association, Tokyo.


