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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_2O and CH_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_2O and CH_4 emissions using the IPCC recommendation. The throughfall DIN (kg N ha^{-1} 6 $months^{-1}$) 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_2O was emitted from it. Both CH_4 uptake in and N_2O 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_4, CO_2, N_2O, 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_4 sink following troposphere and its contribution to global CH_4 sink is estimated to be 5% (30 Mt CH_4) (IPCC, 2001).

The available N for plant growth in a forest ecosystem is supplied by N_2 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 showed that an increase in atmospheric N deposition increased NO_3-N leaching (Dise and Wright, 1995), N runoff to stream (Nakahara et al., 2003), and N_2O emission from soil (Butterbach-Bahl et al., 2002), decreased CH_4 uptake by soil (Morishita et al., 2004), accelerated soil organic matter deposition (Kuperman, 1999; Mo et al., 2006), and decreased net primary production (NPP) (Emmett, 1999). Since NO_3-N leaching relates to indirect N_2O 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_2O emission from soil, CH_4 uptake by soil, CO_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

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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_2O emission from soil, CH_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 to measure nitrification potential in the laboratory and also measured throughfall DIN in 2004.

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_4-N and NO_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_4-N and NO_3-N concentrations in the solutions.

N_2O and CH_4 fluxes

N_2O and CH_4 fluxes from soil were measured once in every three weeks during non-snow cover period of 2003 and 2004 at 6 replications by a closed-chamber technique in those sites, where throughfall samples were collected. A chamber set of stainless cylinder, 20cm in diameter and 25cm 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, 20cm in diameter and 5cm 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, 20mL of gas samples were immediately transferred into 10mL vial bottles to measure N_2O and CH_4 concentrations. Nitrous oxide was analyzed by ECD Gas Chromatography (SHIMADZU GC-14B, Shimadzu, Kyoto, Japan) and CH_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_4 and N_2O. 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^{-2} h^{-1}), ρ is the gas density (ρN_2O-N = 1.26×10^6 and ρCH_4-C = 0.539×10^6 mg N m^{-3}), V is the volume of the chamber (m^3), A is the area of the chamber (m^2), $\Delta c/\Delta t$ is the ratio of change in the gas concentration inside the chamber (10^{-6} m^3 m^{-3} h^{-1}), T is the air temperature inside the chamber (°C), and P is the air pressure (mm Hg). The cumulative N_2O and CH_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_2O is emitted from and CH_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_2 flux measurement at root-cut plot in the field. The CO_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_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 11days. CO_2 concentration in the flask was measured with a portable infrared CO_2 gas analyzer (ZFP9GC11; Fuji Electric systems Co. Ltd., Tokyo, Japan) everyday. After measurement of CO_2 concentration, the air inside the flask was exchanged by ambient air containing CO_2 concentration of 370 ppmv.

The organic matter decomposition per gram of soil was calculated from the change in CO_2 concentration inside the incubation flask. The change in CO_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_2 concentration from the 6th to 11th day after starting incubation was used as CO_2 production rate (mg C g^{-1} day^{-1}).

The relation between temperature and CO_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 CO_2 production was estimated by substituting the daily mean soil temperature measured by a thermometer with data logger into the exponential equation, and the cumulative CO_2 production both from June 2003 to November 2005 was obtained. The OMD was obtained by multiplying the cumulative CO_2 production, bulk density and depth of O and A horizons as shown in Table 1.

2)CO_2 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. CO_2 flux from soil was measured by using the same chamber as used for N_2O and CH_4 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 CO_2 flux measurements. Soil temperature at 4 cm depth was measured at every CO_2 flux measurement. Significant exponential relations between soil temperature at 4 cm depth (T) and CO_2 flux (mg C m^{-2} hr^{-1}) were obtained in both sites. The equation is: $CO_2 = 33.9 \exp(0.079\times T)$, $R^2 = 0.749$, $P<0.01$ for site A and $CO_2 = 41.4 \exp(0.065\times T)$, $R^2 = 0.576$, $P<0.01$ for site D. The daily CO_2 flux from June to November in 2003 to 2005 was estimated by substituting the daily mean soil temperature at 4 cm depth 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 obtained by integrating the daily CO_2 fluxes. However, the OMD estimated at root-cut plot was significantly lower than that from the laboratory incubation. This is probably due to the sum of CO_2 production in only O and A horizons for OMD estimation in laboratory incubation method. However, there was a significant correlation between the values from laboratory incubation and field measurement at the root-cut plot (OMD from root-cut plot = 0.975 OMD from incubation + 2332, $R^2 = 0.882$, $P<0.01$). Using this correlation and the results from the incubation study, 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 (D^2H) , $R^2=0.987$

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 $TB\times C_{TB} + LF\times C_L$, 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 $TB\times N_{TB} + LF\times N_L$, 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 in total biomass were calculated by using the proportion of stem, bark, branch and root in total biomass and C and N contents. 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 1. Properties of soils at study sites at Mt. Shirahata.

Catchment	Horizon	Thickness	Bulk density	C	N	C/N	pH(H_2O)
		cm	Mg m^{-3}	g g^{-1}, %	g g^{-1}, %		
A	O	3.7	0.073	42.3	1.61	26.3	5.8
	A	4.3	0.755	6.9	0.43	16.0	5.5
B	O	3.3	0.058	45.7	1.56	29.3	5.1
	A	5.7	0.807	6.5	0.45	14.4	4.7
C	O	2.7	0.111	41.2	1.74	23.7	6.0
	A	4.3	0.622	7.4	0.54	13.7	6.1
D	O	4.8	0.065	44.1	1.85	23.8	4.9
	A	7.0	0.670	16.2	0.75	21.6	4.9
E	O	3.0	0.123	47.2	1.97	24.0	5.4
	A	4.0	0.444	6.4	0.44	14.5	4.6

The GWP was calculated as follows:

GWP_{CO2} (kg CO_2 ha^{-1}) = -NEP (kg C ha^{-1}) × (1g CO_2) × (44g CO_2 / 12g CO_2-C)

GWP_{CH4} (kg CO_2 ha^{-1}) = CH_4 emission (kg C ha^{-1}) × (23g CO_2 / 1g CH_4) × (16g CH_4 / 12g CH_4-C)

GWP_{N2O} (kg CO_2 ha^{-1}) = N_2O emission (kg N ha^{-1}) × (296g CO_2 / 1g N_2O) × (44g N_2O / 28g N_2O-N)

where GWP_{CO2}, GWP_{CH4} and GWP_{N2O} are GWP due to CO_2, CH_4 and N_2O emissions, respectively. The negative value of NEP was used for 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:

(NO_3-N content after incubation (mg N g^{-1}) - NO_3-N content at starting incubation (mg N g^{-1})) / 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 2. Throughfall dissolved inorganic nitrogen (DIN) and NO_3-N and NH_4-N in the DIN at Mt. Shirahata.

Catchment	Year	DIN	NO_3-N	NH_4-N
		kg N ha^{-1} $6month^{-1}$		
A	2003	0.88	0.40	0.47
	2004	1.31	0.46	0.85
B	2003	1.18	0.55	0.63
	2004	1.20	0.33	0.85
C	2003	1.04	0.58	0.46
	2004	0.94	0.33	0.60
D	2003	0.91	0.44	0.47
	2004	0.91	0.14	0.73
E	2003	1.75	0.68	1.07
	2004	1.79	0.48	1.31

Table 3. CH4 and N2O fluxes from the soil to the atmosphere at Mt. Shirahata.

Catchment	Year	CH_4 flux* kg C ha^{-1}6 $months^{-1}$			N_2O flux* kg N ha^{-1}6 $months^{-1}$		
		Mean	sd	†	Mean	sd	†
A	2003	-7.36	0.21	a	0.045	0.03	ab
	2004	-5.24	1.19	a	0.050	0.03	ab
B	2003	-6.17	0.98	a	0.020	0.01	a
	2004	-6.46	1.34	a	0.023	0.02	a
C	2003	-6.65	1.81	a	0.046	0.03	ab
	2004	-7.09	1.21	a	0.043	0.02	ab
D	2003	-6.63	0.39	a	0.032	0.00	a
	2004	-5.88	0.84	a	0.020	0.01	a
E	2003	-6.33	0.88	a	0.088	0.01	b
	2004	-6.64	1.30	a	0.076	0.01	b

*Negative value indicates gas uptake by the soil from the atmosphere.

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

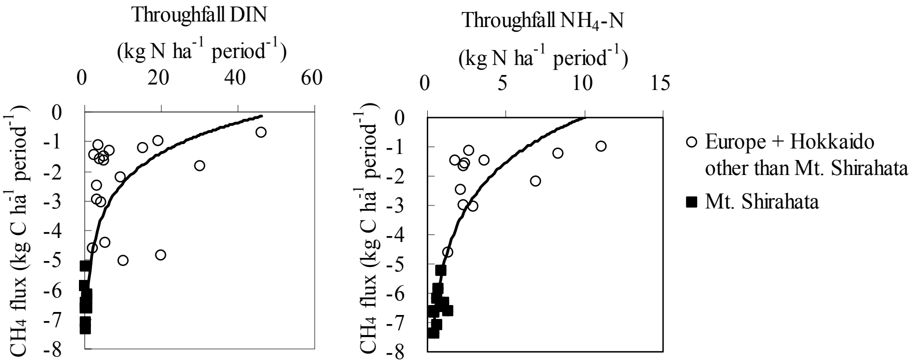

Fig. 1. Relationship between CH_4 flux and throughfall DIN and NH_4-N.

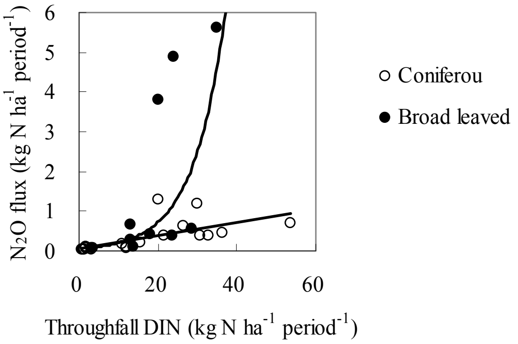

Fig. 2. Relationship between N_2O flux and throughfall DIN.

Table 4. Organic matter decomposition (OMD), net primary production (NPP) and net ecosystem production (NEP) at Mt. Shirahata.

Catchment	Year	OMD	NPP	NEP
		kg C ha^{-1}6 $months^{-1}$		
A	2003	4051		
	2004	4232	3901	-331
B	2003	4242		
	2004	4470	3211	-1259
C	2003	3811		
	2004	4018	1865	-2153
D	2003	3833		
	2004	3960	1742	-2219
E	2003	4170		
	2004	4391	1201	-3190

The soil N_2O flux at Mt Shirahata was positive (0.0443 ± 0.0231 kg N ha^{-1} 6 $months^{-1}$), indicating that N_2O was emitted from the soil (Table 3). The N_2O emission was significantly lower than in other Japanese sites (0.244±0.201 kg N ha^{-1} y^{-1}) (Oura et al., 2001, 2005) and European sites (1.07±1.61 kg N ha^{-1} 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 N_2O emission (0.290±0.139 kg N ha^{-1} y^{-1}) than coniferous forests (1.537±4.501 kg N ha^{-1} y^{-1}). There was a significant positive relationship between N_2O emission and DIN deposition in broad-leaved forests (N_2O emission = 0.0605 exp(0.124×DIN), $R^2 = 0.612$, $P<0.01$) and in coniferous forests (N_2O emission = 0.0169 DIN + 0.0479, $R^2 = 0.480$, $P<0.01$) (Fig. 2). The low N_2O 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±1082 kg C ha^{-1} 6 $months^{-1}$) (Table 4). However, a positive NEP has been reported for larch forests. Hirano et al. (2003) reported a positive NEP (2930 to 3890 kg N ha^{-1} y^{-1}) in a 40 year old larch forest near Tomakomai city in Hokkaido. Sawamoto et al. (2003) also showed a positive NEP (1400 and 1240 kg N ha^{-1} 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 to -2240 kg N ha^{-1} y^{-1}).

The OMD at Mt. Shirahata was 4118±222 kg C ha^{-1} 6 $months^{-1}$ (Table 4), which was significantly higher than that at pine forests in central Oregon (3064±812 kg C ha^{-1} 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 kg C ha^{-1} y^{-1} in maximum) as reported by Kim et al. (2005).

The larch NPP at Mt Shirahata was 2384±1126 kg C ha^{-1} 6 $months^{-1}$ (Table 4), which was significantly lower than that of the middle aged pine forests (60-100 years old) in central Oregon (4425±1448 kg C ha^{-1} 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±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±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

Table 5. Nitrification potential in Ohorizon and Larch N uptake at Mt. Shirahata in 2004.

Catchment	Nitrification potential in O horizon $kg\ N\ ha^{-1}d^{-1}$ Mean	sd	†	Larch N uptake $kg\ N\ ha^{-1}6\ months^{-1}$
A	0.147	0.051	a	48.6
B	0.136	0.055	a	44.7
C	0.096	0.059	a	28.8
D	0.102	0.064	a	37.8
E	0.145	0.061	a	34.7

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

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

Catchment	GWP_{CO2}†	GWP_{CH4}	GWP_{N2O}	TotalGWP
	$kg\ CO_2\ ha^{-1}6\ months^{-1}$			
A	1212	-161	23	1075
B	4615	-198	10	4427
C	7894	-217	20	7696
D	8135	-180	9	7964
E	11696	-204	35	11527

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

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 CO_2 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 CO_2 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 CH_4 uptake and increases N_2O 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.

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