CO₂, CH₄, and N₂O fluxes from a larch forest soil in Central Siberia

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1. INTRODUCTION

The Russian Federation includes about 8.5×10^6 km² of forest, the largest continuous forest in the world, accounting for 22% of the world's total forest area (FAO 2003). The forested area in Asian Russia (Siberia and the Far East) comprises 6.0×10^6 km² and accounts for 70% of the Russian total (Shividenko and Nilsson 1996). Larch is the dominant conifer species in 2.6×10^6 km² of the Russian forest (Shividenko and Nilsson 1996). Kudeyarv (2004) estimated that the territory of Russia fixes 1.08×10^{15} g yr⁻¹ (1 Gt yr⁻¹) of carbon, accounting for about 50% of NEP in the terrestrial biosphere. The CO₂ flux from the soil is a very important component of the carbon budget.

The CO₂ flux from the soil derives from both soil microbial respiration and plant root respiration. Therefore, both soil temperature and moisture control the CO₂ flux. Generally, the soil temperature strongly affects the CO₂ flux (e.g., Hibbard et al. 2005). The CO₂ flux is also affected by soil moisture; very high soil moisture can block soil pores (Bouma and Bryla 2000), and very low soil moisture limits microbial and root respiration (Yuste et al. 2003). In some cases, however, the CO₂ flux is not related to soil moisture (e.g., Palmroth et al. 2005).

In general, forest soils function as a sink for CH_4 and a source for N_2O (IPCC 2001). The CH_4 uptake is also influenced by soil temperature and moisture, because microbiological processes regulate the consumption of CH_4 in the soil (Mer and Roger 2001). Generally, the CH_4 uptake increases (e.g., Castro et al. 1994) with an increase in soil temperature or a decrease in soil moisture (e.g., Whalen and Reeburg 1996). The N_2O flux from the soil is the sum of N_2O derived from nitrification and that derived from denitrification (Sahrawat and Keeny 1986). Increasing soil moisture increases N_2O production by nitrification, but too much soil moisture decreases the amount produced by denitrification, because of oxygen limitation (Sahrawat and Keeny 1986).

The Russian forest, because of its large area, might be expected to play an important role in controlling the dynamics of these greenhouse gases. Most studies of CO_2 , CH_4 , and N_2O fluxes from boreal forests have been conducted in northern Europe and Alaska. Central Siberia, however, is characterized by low air temperature and precipitation and the presence of permafrost. In particular, the ground surface is characterized by a low hummocky microtopography on which various lichens and mosses grow. These conditions are different from those in Europe and Alaska. Thus, the purpose of this study was to characterize the relationships between fluxes of these gases and soil properties as they relate to the vegetation of a larch forest floor in central Siberia.



Fig. 1. Air temperature and precipitation in the site. a) Daily mean temperature and precipitation from June to August. b) Hourly mean temperature and precipitation before , during-, and after the measurement period.

2. MATERIALS AND METHODS

2.1 Study site

The study was conducted in Tura ($64^{\circ}12'N$, $100^{\circ}27'E$), central Siberia, in mid-July 2005. The annual mean air temperature and precipitation are $-9.2 \,^{\circ}C$ and 334 mm, respectively (Robert 1997). The soil type is a Gelisol, with permafrost below 70 to 100 cm depth, and poor drainage. The soil is frozen from mid-October to the beginning of May. The forest consists mainly of larch (*Larix gmelinii*) trees about 100 years old. Patches of lichens and mosses, 10 to 20 cm thick and composed mainly of *Cladina* sp., *Pleurozium* sp., and *Aulacomnium* sp., cover the forest floor.

2.2 CO₂, CH₄, and N₂O flux measurements

The CO₂, CH₄, and N₂O fluxes were measured by using a closed-chamber technique according to the method of Sawamoto et al. (2000) and Morishita et al. (2003). Six stainless steel chambers, 25 cm in height and 20 cm in diameter, were used. Six patches were selected, two each of *Cladina stellaris*, *Pleurozium schreberi*, and *Aulacomnium palustre*, and a chamber was installed in each patch. Before the measurement of the gas fluxes, all green parts of the plants on the forest floor were carefully removed in order to exclude plant respiration. Then, the chamber collars were installed in the soil at 5 cm depth and left overnight to eliminate disturbance.

First, for CO₂ flux measurement, a 500-mL gas sample was collected in a Tedlar[®] bag on the

day following chamber collar installation, but before the chamber lid was installed, and another was collected 6 min after the lid was installed. The CO_2 flux was measured nine times each day.

After the measurement of CO₂ flux was finished, samples for CH₄ and N₂O flux measurements were collected from the chamber 0, 10, 20, 40, and 60 min after the chamber lid was installed. A 20-mL gas sample was collected in a 10-mL glass bottle vacuum-sealed with a butyl rubber stopper and a plastic cup. CH₄ and N₂O fluxes were measured four times each day.

Soil temperature and moisture were measured in each patch. Soil temperature was measured with a digital thermometer at a depth of 10 cm. Soil moisture was measured as volumetric water content with a TDR (HydrosenseTM, Campbell Scientific Australia Pty. Ltd.) at depths of 0 to 12 cm near the chambers. All the measurements were taken with three replications.

2.3 Gas analysis and calculation of CO₂, CH₄, and N₂O fluxes

 CO_2 concentrations in the bags were analyzed with a portable gas analyzer (LI-820, LI-COR). The CO_2 flux was calculated using the following equation:

CO₂ flux (mg C m⁻² h⁻¹) = $d \times h \times (C_6 - C_0) \times 273/(T + 273) \times 60$ where *d* is the density (0.536 × 10³ g m⁻³ for carbon); *h* is the height of chamber from the soil surface; C_0 and C_6 are the CO₂ concentrations (m³ m⁻³) in the chamber after 0 and 6 min, respectively; and *T* is the temperature inside the chamber (°C).

CH₄ concentrations in the bottle were analyzed with a gas chromatograph (GC) (GC–8A; Shimadzu, Kyoto, Japan) equipped with a flame ionization detector (FID) and a 2-m-long Univeads C column in the laboratory of FFPRI in Tsukuba, Japan. Analyses were performed within 1 month of sampling. Samples of 2 mL were injected into the GC. The injection/detection and column oven temperature were 120 °C. Helium gas was used as the carrier at a flow rate of 40 mL min⁻¹. A standard gas (1.985 μ L L⁻¹) was used for calibration. N₂O concentrations were measured with a GC (GC–14B; Shimadzu) equipped with a electron capture detector (ECD) and a 2-m-long Porapak N column. Samples of 1 mL were injected into the GC. The injection/detection and column oven temperature were 50 and 340 °C, respectively, and 5% CH₄ in Ar was used as the carrier at a flow rate of 10 mL min⁻¹. Standard N₂O gases (0.301 and 0.510 μ L L⁻¹) were used for calibration.

 CH_4 and $\mathrm{N}_2\mathrm{O}$ fluxes were calculated from the change in the gas concentration in the chamber after closure:

CH₄ or N₂O flux (µg C or N m⁻² h⁻¹) = $-d \times h \times \Delta c/\Delta t \times 273/T$

where *d* is the density of CH₄ (0.536 × 10³ g m⁻³ for carbon) or N₂O (1.25 × 10³ g m⁻³ for nitrogen); $\Delta c/\Delta t$ (10⁻⁶ m³ m⁻³ h⁻¹) is the change in the CH₄ or N₂O concentration in the chamber during a given period. A positive value denotes the CH₄ and N₂O emission from the soil, whereas a negative value denotes the CH₄ or N₂O uptake from the atmosphere.

2.4 Statistical analysis

Mean temperatures, soil moistures, and gas fluxes in each patch were calculated from 8 to 18 measurements. Two-way analysis of variance followed by Fisher's test was used to compare the means of temperatures, moisture values, and CO_2 fluxes. The Kruskal–Wallis test followed by Scheffe's test was used for multiple-group comparison of CH₄ and N₂O fluxes. Excel Toukei (SSRI, Japan) was used for all statistical analyses.

3. RESULTS

3.1 Environmental variables at the site

Air temperature and precipitation from June to August and during the measurement period



are shown in Fig. 1. The daily mean temperature of 20 °C during the measurement period was similar to that recorded throughout July (19.0 °C). The daily range in air temperature was very

Fig. 2. measurement period data: soil temperature (a), and soil moisture (b); CO₂ (c), CH₄ (d), and N₂O (e) flux.

large (max, 26.1 °C at 19:00; min, 11.4 °C at 4:00). A total of about 2.0 mm of rain fell before and during the measurement period.

The highest and lowest soil temperatures in the patches were observed in the evening (16:00 or 19:00) and early morning (4:00), respectively (Fig. 2). The mean soil temperature in the *Aulacomnium* ($6.4 \pm 2.5 \text{ °C}$) patch was significantly lower than that in the *Pleurozium* ($9.0 \pm 3.4 \text{ °C}$) or *Cladina* ($8.6 \pm 3.2 \text{ °C}$) patches (Table 1). Soil moisture was slightly higher at night than during the day (Fig. 2). But no clear effect of the rainfall, which occurred at around 20:00, on soil moisture, was observed. Soil moisture in the *Aulacomnium* ($0.31 \pm 0.10 \text{ m}^3 \text{ m}^{-3}$) patches was significantly higher than that in the *Pleurozium* ($0.17 \pm 0.10 \text{ m}^3 \text{ m}^{-3}$) or *Cladina* ($0.20 \pm 0.09 \text{ m}^3 \text{ m}^{-3}$) patches (Table 1).

3.2 Gas fluxes

The highest CO₂ flux was observed at 16:00 (99 mg C m⁻² h⁻¹, *Aulacomnium* patches) or 22:00 (169 mg C m⁻² h⁻¹, *Pleurozium*; 119 mg C m⁻² h⁻¹, *Cladina*). The lowest CO₂ flux was observed at 4:00 (58 mg C m⁻² h⁻¹, *Pleurozium*; 34 mg C m⁻² h⁻¹, *Aulacomnium*) or 7:00 (53 mg C m⁻² h⁻¹, *Cladina*) (Fig. 2). There were significant differences among the mean CO₂ fluxes in the different patches. CO₂ fluxes in the patches decreased in the order *Pleurozium* (110 ± 36 mg C m⁻² h⁻¹) > *Cladina* (85 ± 21 mg C m⁻² h⁻¹) > *Aulacomnium* (68 ± 21 mg C m⁻² h⁻¹) (Table 2).

No clear pattern of daily changes in the CH₄ flux was found. CH₄ tended to be taken up by the soil (*Pleurozium*; $-3.0 \pm 2.4 \ \mu g \ C \ m^{-2} \ h^{-1}$, *Cladina*; $-1.6 \pm 3.8 \ \mu g \ C \ m^{-2} \ h^{-1}$, *Aulacomnium*; $-3.4 \pm 3.7 \ \mu g \ C \ m^{-2} \ h^{-1}$) (Table 2). N₂O tended to be emitted from the soil in the *Pleurozium* ($1.0 \pm 1.7 \ \mu g \ N \ m^{-2} \ h^{-1}$) and *Cladina* ($1.2 \pm 1.1 \ \mu g \ N \ m^{-2} \ h^{-1}$) patches, but it was taken up by the soil in the *Aulacomnium* patches ($-0.4 \pm 2.8 \ \mu g \ N \ m^{-2} \ h^{-1}$). There were no significant differences in the CH₄ and N₂O fluxes among the different patches.

Table 1. Summary of son temperature and moisture data.											
		Sc	oil			Soil					
	temperature				r	moisture					
		$m^{3} m^{-3}$									
Pleurozium	9.0	±	3.4	а	0.17	±	0.10	b			
Cladina	8.6	±	3.2	а	0.20	±	0.09	b			
Aulacomnium	6.4	±	2.5	b	0.31	±	0.10	а			
different letters above a gigniferent defference among the vegetation											

Table 1. Summary of soil temperature and moisture data.

different letters show a signifcant defference among the vegetetion at 5%

	CO ₂ flux				CH ₄ flux	N ₂ O flux		
	mg C m ⁻² h ⁻¹			-1	$ug C m^{-2} h^{-1}$	ug N $m^{-2} h^{-1}$		
Pleurozium	110	±	36	а	-3.0 ± 2.4 a	1.0 =	± 1.7 a	
Cladina	85	±	21	b	-1.6 ± 3.8 a	1.2 =	± 1.1 a	
Aulacomnium	68	±	21	c	-3.4 ± 3.7 a	-0.4	± 2.8 a	

Table 2. Summary of CO₂, CH₄, and N₂O flux data.

different letters show a signifcant defference among the vegetetion at 5% level

3.3 Relationship between gas fluxes and soil temperature and moisture

The CO₂ flux was positively correlated with soil temperature (r = 0.79 P < 0.01) and negatively correlated with soil moisture (r = -0.50 P < 0.01) (Fig. 3). However, neither the CH₄ nor the N₂O flux was correlated with soil temperature or moisture (Fig. 3).



Fig. 3. Relationship between the gas fluxes and soil temperature and soil moisture.

3.4 Comparison with results of previous studies in Russia

The measured CO₂ fluxes (68–110 mg C m⁻² h⁻¹) were lower than those previously reported: 64–389 mg C m⁻² h⁻¹ for a larch forest in eastern Siberia (Sawamoto et al. 2000), 200–280 mg C m⁻² h⁻¹ for a birch forest in western Siberia (Nakano et al. 2004), and 108–130 mg C m⁻² h⁻¹ for a mixed and broad-leaved forest in the southern taiga zone of Russia (Lopes de Gerenyu et al. 2001). The amount of CH₄ uptake (-3.0 to -1.4 µg C m⁻² h⁻¹) was also lower than values previously reported: -17 to -13 µg C m⁻² h⁻¹ for a forest in eastern Siberia, -280 to -92 µg C m⁻² h⁻¹ for a birch forest in western Siberia (Nakano et al. 2004), and -60 to -48 µg C m⁻² h⁻¹ data from Russia were available, but the measured N₂O fluxes (-0.4 to 1.2 µg N m⁻² h⁻¹) were lower than values of 5.6–50 µg N m⁻² h⁻¹ reported for various forests in Alaska (Kim and Tanaka 2003), where the climate is similar.

4. DISCUSSION

4.1 Differences in the gas fluxes among the patches

There were significant differences in the mean CO_2 flux among the different patches (Table 2). The CO_2 flux was smallest in the *Aulacomnium* patches. This result can be attributed to the lower soil temperature and higher soil moisture in the Aulacomnium patch compared with the other patches, because the CO₂ flux was positively correlated with soil temperature and negatively correlated with soil moisture (Fig. 3). Generally, the CO₂ flux increases with an increase in soil temperature (e.g., Hibbard et al. 2005), and high soil moisture can cause the CO₂ flux to decrease (e.g., Bouma and Bryla 2000). The Aulacomnium patches were in relatively lower parts of the microtopography. Thus, rain and meltwater might collect there and prevent CO₂ from diffusing from the soil into the atmosphere and might also prevent an increase in soil temperature. As a result, the CO_2 flux in the Aulacomnium patch was small. On the other hand, no clear effect of low soil temperature and high soil moisture on CH₄ or N₂O emissions was observed. CH₄ and N₂O fluxes tend to correlate with soil temperature, because microbiological processes regulate the production and consumption of CH₄ (Mer and Roger 2001) and N₂O (Sahrawat and Keeny 1986) in soil. Moreover, the CH₄ flux from soil represents the net of CH_4 production and consumption in the soil (Conrad 1995). The forest floor with relatively lower microtopography is flooded by meltwater in the spring, and sometimes remains flooded till the summer, allowing anaerobic sites to develop at the soil surface. Therefore, both CH₄ production and denitrification can occur as a result of this flooded condition. Both production and consumption of CH_4 are promoted by an increase in temperature (Dunfield et al. 1993). The positive temperature dependency of both CH_4 production and consumption may account for there being no relationship observed between the CH_4 flux and temperature. N₂O is produced by both nitrification and denitrification (Sahrawat and Keeny 1986), but the positive temperature dependency of N_2O production via nitrification is different from that via denitrification (Castaldi 2000). At this site, both nitrification and denitrification might occur because of the microtopography. As a result, we found no relationship between CH₄ or N₂O fluxes and soil temperature.

4.2 Assessment of gas emission and consumption values

 CO_2 and N_2O emissions and CH_4 uptake were relatively smaller than values obtained by previous studies. Especially, CO_2 emission and CH_4 uptake in this study were relatively lower than those at Yakutsk even though almost the same method of measuring gas fluxes was used (Sawamoto et al. 2000; Morishita et al. 2003). The air temperature at Yakutsk (annual mean: $-10.4^{\circ}C$) is similar to that at Tura, so temperature was not a main factor causing the lower CO_2 flux in this study. The C/N ratio in the soil may also influence CO_2 emission. Matsuura et al. (1997) reported that the C/N ratio within 1 m depth in a larch forest at Tura (20.5 to 20.9) was higher than that at Yakutsk (around 10). Generally, when the C/N ratio is high, nitrogen is immobilized and the organic decomposition rate decreases (Lavelle and Spain 2001). Moreover, a high C/N ratio in the soil may decrease the N₂O flux from the soil because of low nitrification. Thus, the C/N ratio in a soil may be an important controller of CO₂ and N₂O emission.

The lower CH₄ uptake in this study compared to that at Yakutsk (Morishita et al. 2003) may have been caused by the microtopography of the forest floor. The ground surface was almost

flat at Yakutsk (Morishita et al.2003), but was characterized by a hummocky microtopography at this site. Thus, as mentioned above, CH_4 production might have occurred owing to the development of an anaerobic zone at the surface of the soil. In addition, the removal of lichens and mosses can decrease CH_4 uptake at the forest floor. Raghoebarsing et al. (2005) showed that CH_4 oxidation occurred in within mosses in peat bogs in the Netherlands. *Aulacomnium* is a kind of moss, and it likes wet conditions and sometimes grows with *Sphagnum* species (Li and Vitt 1995). Thus, *Aulacomnium* may be able to oxidize CH_4 . Therefore, the next step in evaluating the CH_4 dynamics in this region is to measure the CH_4 uptake rate including by mosses where thick mosses are present.

5. CONCLUSION

The CO₂ flux was positively correlated with soil temperature and negatively correlated with soil moisture. The CO₂ flux was lowest in the *Aulacomnium* patch among the patches because of the low soil temperature and high soil moisture. The CO₂ emission and CH₄ uptake were smaller than previously reported values. The C/N ratio in the soil might be an important factor explaining the low CO₂ emission, and the low CH₄ production may be related to the microtopography at the site.

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