CH_4 Flux in an Alas Ecosystem Formed by Forest Disturbance near Yakutsk, Eastern Siberia, Russia

Tomoaki Morishita, Ryusuke Hatano*, and Roman V. Desyatkin**

*Graduate School of Agriculture and *Field Science Center for Northern Biosphere, Hokkaido University, Sapporo, 060–8589 Japan; and **Institute of Biological Problems of Cryolithzone, Russian Academy of Sciences, Yakutsk 677891, Republic of Sakha, Russia*

Received July 22, 2002; accepted in revised form March 24, 2003

Alas is a round area of grassland with a pond at the center, formed by subsidence associated with permafrost thawing in Taiga forests in eastern Siberia. Some Alases have a Pingo, which is a round mound formed by the refreezing of the Alas pond. To characterize the relationship between the CH_4 dynamics and soil properties in a forest-Alas ecosystem, we investigated 2 line transects in an Alas near Yakutsk: one transect from the forest to the pond (300 m), and the other from the top of the Pingo to the pond (26 m). Both soil pH and EC in the topsoil were higher in the grassland and the Pingo (5.8–7.1 for pH and 7–141 mS m^{-1} for EC) than in the forest (4.3 for pH and 1–17 mS m^{-1} for EC). The organic carbon contents of the soils were also higher in the grassland and the Pingo than in the forest. CH_4 uptake in the forest soils ranged from −13 to −17 μg C m^{-2} h^{-1}. On the other hand, CH_4 emission in the grassland increased from −8 to 3.8 × 10^3 μg C m^{-2} h^{-1} with the approach to the pond. Large CH_4 emissions of 0.6 to 7.0 × 10^3 μg C m^{-2} h^{-1} were observed at the edge of the pond. The values of the CH_4 fluxes were similar to those previously reported −25 to −5 μg C m^{-2} h^{-1} for forests and 0.1 to 5.2 × 10^3 μg C m^{-2} h^{-1} for wetlands in Alaska and northern Europe. CH_4 fluxes were strongly correlated with the soil moisture content, but not with the soil temperature. No CH_4 flux was observed in the Pingo soils, probably due to the large accumulation of salts. These results suggest that Alas formation with forest disturbance increases CH_4 production and decreases CH_4 consumption due to the accumulation of salts and the increase in the soil moisture and organic carbon content in the Alas soil.

Key Words: **Alas, forest fire, methane, permafrost, Taiga.**

CH_4 is an important greenhouse gas with a contribution of about 20% to the radiative forcing of the global climate (IPCC 2001). Total CH_4 emission is estimated of 598 Tg $year^{-1}$ (IPCC 2001). Major sources of atmospheric CH_4 include the production and use of energy, biomass burning, rice fields, natural wetland systems, landfills, and enteric fermentation in animals and termites. The major sinks are considered to be the atmosphere and soils: 470 Tg $year^{-1}$ is estimated to be consumed by the reaction of CH_4 with hydroxyl radicals in the atmosphere, while forest soils consume 30 Tg $year^{-1}$ (IPCC 2001). However, little or no information is available about the CH_4 dynamics in the vast low-rainfall coniferous forests of eastern Siberia (Smith et al. 2000).

Eastern Siberia is characterized by a low precipitation (209 mm as annual average, Robert 1997) and low temperature (−10.4°C as annual average, Robert 1997), presence of permafrost (Desyatkin 1993), and occasional wildfires (Goldammer and Furyaev 1996). Larch species, *Larix gmelinii* and *Larix cajander*, are predominant because of their high regeneration ability after wildfire (Abaimov 1995; Schulze et al. 1995; Kajimoto et al. 1999). However, some fires are strong enough to completely destroy the forest ecosystems due to subsidence after permafrost thawing. Isaev et al. (2002) using remote sensing data and forest inventory data showed that, 22% of a studied forest area of 24,700 ha in eastern Siberia was damaged by high-intensity ground fires which completely destroyed forest ecosystems. They stared their 70–80% of the fires were caused by human activity with the remainder caused by natural events such as lightning (Goldammer and Stocks 2000). After severe forest fires, Alases are formed (Desyatkin 1993). Alases are thermokarsts and water supplied from the thawing permafrost flows laterally into the Alas, forming ponds with diameters ranging from several tens of

meters to 100 m. Some Alases have a Pingo which is a small hill (10–20 m in diameter, 10–20 m in height) formed by the refreezing of water in the pond (Fitzpatrick 1983). CH_4 flux from soils is affected by the soil temperature and moisture (Castro et al. 1994; Whalen and Reeburgh 1996; Primè and Christensen 1997; Bowden et al. 1998). Microbiological processes regulate the production and consumption of CH_4 in soil (Mer and Roger 2001). In general, forest soils take up CH_4 (Smith et al. 2000), whereas wetlands emit CH_4 (Mer and Roger 2001). As the land-cover modifies often changes the thermo-hydrological conditions of soil, forest disturbance is generally considered to decrease the CH_4 consumption activity of soil (Dobbie et al. 1996). The disappearance of forest may decrease CH_4 uptake in the Taiga ecosystem, and the appearance of ponds may increase CH_4 emission.

The purpose of this study was to characterize the relationship between the CH_4 dynamics and soil properties in a forest-Alas ecosystem near Yakutsk, eastern Siberia.

MATERIALS AND METHODS

Site description. This study was conducted in an Alas and adjacent forest in Neleger, located 30 km north-northwest from the city of Yakutsk (lat 62°05′ N, long 129°45′ E), Russia (Fig. 1). The Alas is about 500 m × 1,000 m, in size with a pond 100 m in diameter and 1 m deep. All the measurements were carried out in July 2000, and June and July 2001.

The forest consists mainly of Larch (*Larix gmelinii*) trees more than 200 years old, with *Vaccinium vitis-idaea* predominatily on the forest floor. The grassland of the Alas consists predominantly of *Elytriga repens* near the forest and *Carex resucata* near the pond. *Potentilla anserina* predominates on the Pingo.

Measurements.

Set up of line transects: The location and topography of the 2 line transects are shown in Figs. 1, 2, and 4. One transect (300 m) was set up from the forest to the pond through the grassland (the FG-line), and the other transect (26 m) was set up from the top of the Pingo to the pond (the P-line). The location of the grassland was 2 m lower than that of the forest and there was a steep slope at the edge of the forest (Fig. 2). One of the measuring points was set up in the forest (A) and the other points were set up through the grassland at every 10 to 20 m from the edge of the forest to the pond (B–E in 2000, B–F in 2001) (Figs. 1 and 2). The water depth at E in 2000 or F in 2001 was 10 cm. In 2001, E was in the grassland because the area of the pond in 2001 had decreased compared to the area in 2000. On the P-line, 14 measurement points were set up at every 2 m intervals from the top of the Pingo to the edge of the pond (P_0, P_2, P_4, …, P_{22}, P_{24}, P_{26}; numbers represent the distance in m from the top of the Pingo). The top of the Pingo was located on 5 m above the pond surface (Fig. 4).

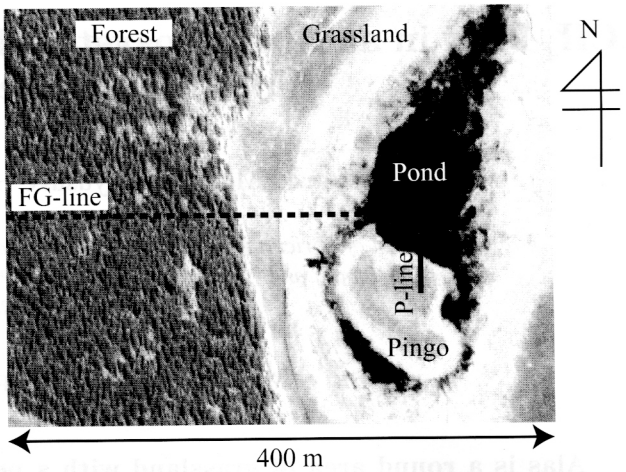

Fig. 1. IKONOS image of Neleger on July 11, 2001 provided by (C) Japan Space Imaging Corporation.

Soil environment: Examination of the soil profile and soil sampling were conducted in the forest (near A), in the grassland (between B and C, and near D), and on the top of the Pingo (Fig. 1). Intact 100-mL cores (5 cm diameter, 3 replications) and bulk samples (PVC bag: about 500 mL) were collected from each horizon of each soil profile. Using the intact cores, the bulk density was determined gravimetrically by drying to a constant weight at 105°C overnight. Bulk samples were air-dried for more than 3 weeks in the laboratory, and then sieved through a 2-mm-mesh sieve for use for chemical analysis.

Soil pH was determined with a glass electrode pH meter in a supernatant suspension of 1 : 2.5 (O horizon, 1 : 20) soil : deionized water mixture. EC was determined with a EC meter in a 1 : 5 soil : deionized water mixture. The EC value was modified by multiplying by 5 to approximate the EC value for a water-saturated soil paste. After the soil samples were air-dried and ground, total carbon and nitrogen contents were determined by using a C / N analyzer (NC-1000, Sumika Chemical Analysis Service, Ltd., Osaka, Japan). Carbonate-carbon content was analyzed by measuring the amount of CO_2 produced from 0.3 to 0.8 g of soil samples to which 15 mL of 2 M HCl solution was added in an Erlenmeyer flask. Organic carbon content was calculated by subtracting the carbonate-carbon content from the total carbon content (Loeppert and Suarez 1996; Sawamoto et al. 2002).

Soil temperature and moisture: Soil temperature and soil moisture were measured at each point on the line

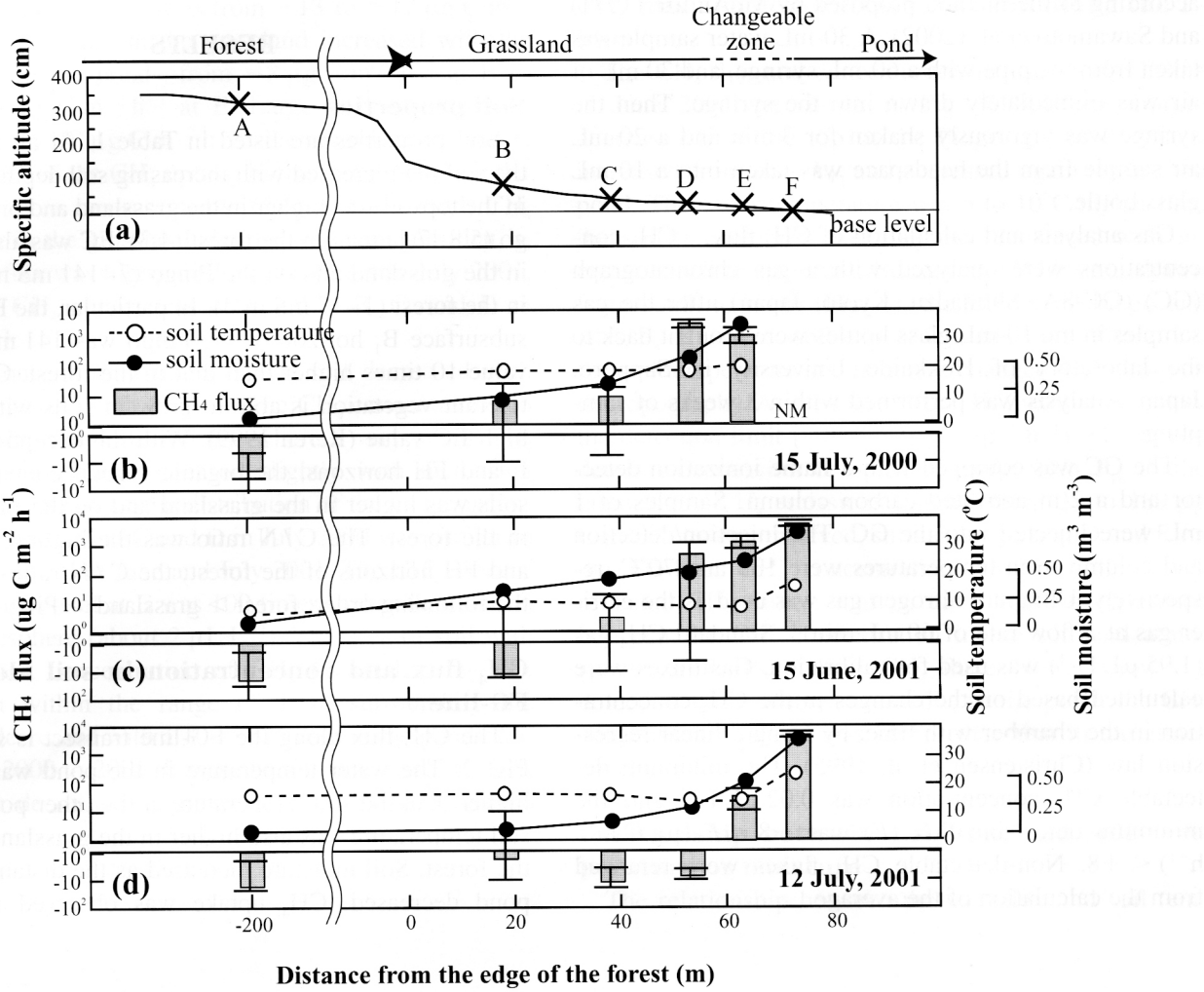

Fig. 2. Topography and CH_4 fluxes along FG-line. (a) Topography. Base level of specific altitude is located on the surface of the pond. (b), (c), and (d) CH_4 fluxes with soil temperature and moisture in July 2000; June 2001; and July 2001; respectively. CH_4 fluxes are indicated on a log scale and vertical bars denote maximum and minimum values of CH_4 flux. NM, not measured.

transects (A–F, P_0–P_{26}). Soil temperature was measured with a digital thermometer at a depth of 4 cm. Soil moisture was measured as volumetric water content with a FDR (ML2 Theta Probe, Delta-T Devices, Co., Cambridge, UK) at a depth of 0 to 7 cm. All the measurements were taken with 5 replications.

CH_4 flux: CH_4 flux measurements were carried out by applying a closed chamber technique. To transport the chambers into the field more conveniently, the chambers were constructed so as to allow 6 chambers of slightly differing sizes to fit into the largest of them in the same way as a Russian matryoshka doll. That is, the height of each of the 6 chambers was similar (25 cm), but the diamaeter was different (18.5, 19, 19.5, 20, 20.5, and 21.0 cm). The CH_4 fluxes were measured at A–F on the FG-line (3 to 6 replications) and at P_0–P_{26} on the P-line (no replication). CH_4 fluxes on the P-line were measured only in June 2001. On the day before the measurement, chambers were installed at 3 cm depth into the soil. At 0, 10, 20, and 40 min after the chamber was set up, a 20-mL gas sample was taken into a 10-mL glass bottle vacuum-sealed with a butyl rubber stopper and a plastic cap.

CH_4 concentration in the soil: To collect gases in the soil, stainless steel pipes 9-mm in diameter were installed at depths of 5, 10, 15, 20, 30, and 50 cm (3 pipes at each depth). After the pipes were set up, 50 mL of air was exhausted from each pipe. The pipes were then sealed by using a 3-way cock and kept overnight to allow gas concentrations in the pipes to equilibrate with the soil air. From each of the pipes installed at each depth, air samples (50 mL) were taken into a Tedlar bag. At the same time, air on the soil surface was taken into a Tedlar bag as a sample of soil air at a depth of 0 cm. Within the same day, 20-mL air samples from each of the Tedlar bags were transferred to 10-mL glass bottles.

Sometimes we could get only water from the pipes. In that case, dissolved CH_4 concentrations were measured,

according to the method proposed by McAullife (1971) and Sawamoto et al. (2002). A 30-mL water sample was taken from the pipe with a 60-mL syringe, and 30 mL of air was immediately drawn into the syringe. Then the syringe was vigorously shaken for 3 min and a 20-mL air sample from the headspace was taken into a 10-mL glass bottle.

Gas analysis and calculation of CH_4 flux: CH_4 concentrations were analyzed with a gas chromatograph (GC) (GC-8A; Shimadzu, Kyoto, Japan) after the gas samples in the 10-mL glass bottles were brought back to the laboratory of Hokkaido University in Sapporo, Japan. Analysis was performed within 3 weeks of sampling.

The GC was equipped with a flame ionization detector and a 2-m activated carbon column. Samples of 1 mL were injected into the GC. The injection/detection and column oven temperatures were 130 and 70°C, respectively. Ultrapure nitrogen gas was used as the carrier gas at a flow rate of 60 mL min^{-1}. Standard CH_4 gas (1.95 μL L^{-1}) was used for calibration. Gas fluxes were calculated based on the changes in the CH_4 concentration in the chamber with time, by using a linear regression law (Christensen et al. 1995). The minimum detectable CH_4 concentration was 0.02 μL L^{-1} and the minimum detectable flux (F) was $-8 < F$ (μg C m^{-2} h^{-1}) $< +8$. Non-detectable CH_4 fluxes were removed from the calculation of the average.

RESULTS

Soil properties

Soil properties are listed in Table 1. At all the sites, the soil pH increased with increasing soil depth. Soil pH in the topsoil was higher in the grassland and on the Pingo (5.8–7.1) than in the forest (4.3). EC was also higher in the grassland and on the Pingo (7–141 mS m^{-1}) than in the forest (1–17 mS m^{-1}). In particular, the EC in the subsurface B_1 horizon of the Pingo was 141 mS m^{-1}, a value 10 times higher than that in the forest. Only salt-tolerant vegetation is able to grow in soils with such a high EC value (Keren 1999). With the exception of the L and FH horizons, the organic carbon content of the soils was higher in the grassland and on the Pingo than in the forest. The C / N ratio was the highest in the L and FH horizons of the forest; the C / N ratios were in the following order: forest > grassland > Pingo.

CH_4 flux and concentration in soil along the FG-line

The CH_4 flux along the FG-line transect is shown in Fig. 2. The water temperature in the pond was always higher than the soil temperature at the other points. The soil temperature was also higher in the grassland than in the forest. Soil moisture increased as the distance to the pond decreased. CH_4 uptake was observed in forest

Table 1. Properties of forest and grassland soils in Neleger.

Layer	Depth (cm)	Soil texture	Bulk density (Mg m^{-3})	pH	EC (mS m^{-1})	Org-C (%)	T-C (%)	T-N (%)	C / N
Forest									
L	−10	SiCL		4.3	17	50.3	50.3	0.58	86
FH	−7	SiCL		4.5	7	52.0	52.0	1.43	36
E1	2	SiCL	1.12	4.8	1	1.8	1.8	0.04	47
E2	25	SiCL	1.51	6.3	1	0.6	0.6	0.03	22
$B2_h$	56	SiCL	1.51	8.7	9	0.5	0.5	0.03	17
B3	73	SiCL	1.50	9.2	10	0.4	0.9	0.03	35
C	108+	SiCL	1.52	9.1	11	0.5	1.0	0.03	40
Grassland									
A1	12	SiC	0.72	6.7	7	10.4	10.4	0.98	11
A2	19	SiC	1.52	8.7	12	1.2	2.0	0.06	35
$B2_{ir}$	31.5	SiC	1.55	9.0	18	0.9	1.8	0.04	52
$B2_h$	49	SiC	1.60	8.7	29	0.2	0.9	0.03	32
$B3_g$	78	SiC	1.53	8.5	31	0.2	0.8	0.03	31
C_g	120+	SiC	1.50	8.3	26	0.9	1.1	0.05	23
Grassland									
A	20	SiC	1.08	7.1	36	13.3	13.7	1.06	13
AB	28	SiC	1.36	8.8	21	1.7	1.98	0.13	15
$B1_g$	50	SiC	1.63	8.8	36	0.7	0.74	0.05	15
$B2_g$	130+	SiC	1.60	8.4	42	0.5	1.12	0.04	28
Pingo									
A	7	SiC	0.95	5.8	12	4.4	4.41	0.33	13
B1	36	SiC	0.84	4.5	141	5.1	5.07	0.41	12
B2	130+	SiC	1.14	8.2	19	1.2	1.66	0.05	33

soils; the CH_4 flux ranged from -13 to -17 μg C m^{-2} h^{-1}. CH_4 emission in the grassland increased with the approach to the pond—from -8 μg C m^{-2} h^{-1} at B to 3.8×10^3 μg C m^{-2} h^{-1} at E. Large CH_4 emissions of 0.6 to 7.0×10^3 μg C m^{-2} h^{-1} were recorded at E and F. The values of the CH_4 uptake in the forest were similar in these three measurements. On the other hand, CH_4 emission in the grassland significantly changed; that is, the CH_4 flux was higher in July 2000 than in July 2001. Notably, CH_4 uptake was observed at B, C, and D in July 2001.

CH_4 concentration in the forest soil decreased with increasing soil depth (Fig. 3). The CH_4 concentration in the grassland soil (B and C), where a very small CH_4 flux was observed, increased slightly with increasing soil depth. However, the distribution of the CH_4 concentration in the soil at C and D in July 2000 was similar to that at D and E in June and July 2001. The CH_4 concentration in the soil at E was 100 times higher than that in the atmosphere (about 2 μL L^{-1}). The area of soil with the highest concentration of CH_4 (>10 μL L^{-1})—i.e., the area within the range of 10 m surrounding the pond—decreased with a 10-m decrease in the pond radius from 2000 to 2001. It was also observed that the CH_4 emission decreased as the area of the pond decreased (Fig. 2).

CH_4 flux and concentration in soil along the P-line

The CH_4 flux and concentration in soil on the P-line in June 2001 are shown in Fig. 4. Soil temperature decreased from the top of the Pingo (P_0) to P_6, but it increased from P_8 to P_{12} and decreased again toward the pond. The water temperature was 5 to 10°C higher than the soil temperature. Soil moisture decreased with increasing soil temperature. Because the P-line was drawn from south to north (Fig. 1), the top of the Pingo and sites P_8–P_{12} were well exposed to sunshine. Therefore, the soil temperature and moisture changed depending on the topography. At sites P_0 to P_{16}, CH_4 fluxes were below the detection limit [$-8 < F$ (μg C m^{-2} h^{-1}) $< +8$] (no detectable emission or uptake), while from P_{18} to the pond, large CH_4 emissions ranging from 21 to 189 μg C m^{-2} h^{-1} were observed, similar to those at D and E on the FG-line. CH_4 concentrations in the soil closely reflected CH_4 fluxes; that is, there was no difference between the CH^4 concentration in the soil and atmosphere at P_0–P_{16}, where CH_4 fluxes were below the detection limit, whereas from P_{14} to the pond, the CH_4 concentration in soil was higher than that in the atmosphere.

Relationship between CH_4 flux and soil temperature or moisture

The relationship between the CH_4 flux and soil tem-

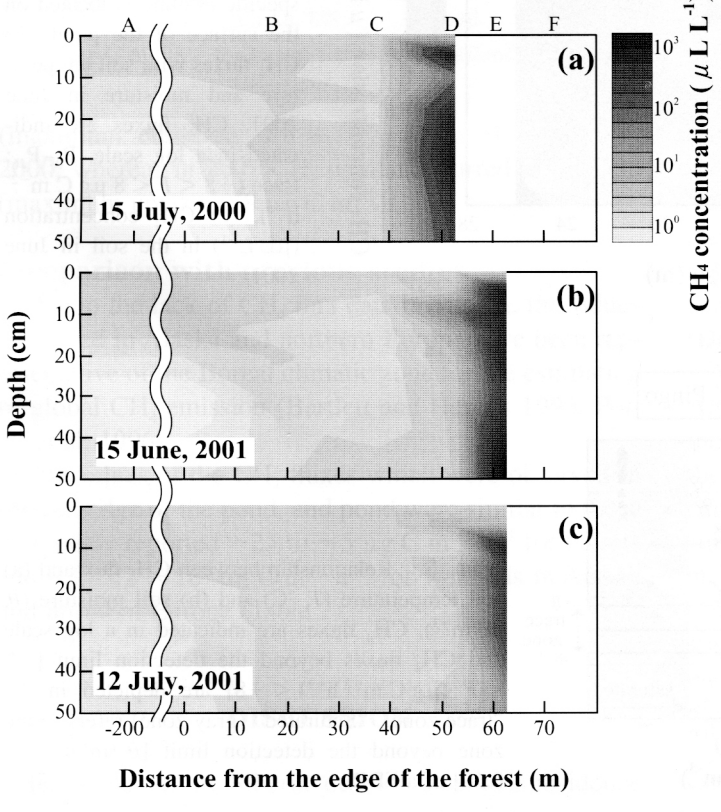

Fig. 3. CH_4 concentration (μL L^{-1}) in soil or water along the FG-line in July 2000 (a); June 2001 (b); and July 2001 (c); respectively.

perature or soil moisture is shown in Fig. 5. The CH_4 fluxes outside the detection limit [$-8 < F$ (μg C m^{-2} h^{-1}) $< +8$] are depicted in the "trace zone"; there were many such fluxes in this study. There was no relationship between the CH_4 flux and soil temperature (Fig. 5a). On the other hand, there was a close relationship between the CH_4 flux and soil moisture (Fig. 5b). CH_4 uptake occurred in the forest where the soil moisture content was low, and CH_4 emissions occurred in the pond and the edge of the pond where the soil moisture content was high; both uptake and emission of CH_4 occurred in the grassland where the soil moisture conditions varied. The CH_4 flux on the Pingo showed a similar tendency to that in the grassland. However, at a low soil moisture, CH_4 uptake was observed in the grassland, but not on the Pingo. Soil moisture contents at A, B, and C in July 2000 were lower than in June 2001 and higher than in July 2001, but there was no conspicuous difference in the CH_4 flux among them (Fig. 6a). On the other hand, CH_4 emissions at D and E decreased (Fig. 6b) with decreasing soil moisture from July 2000 to July 2001. At D in particular, CH_4 emission was observed

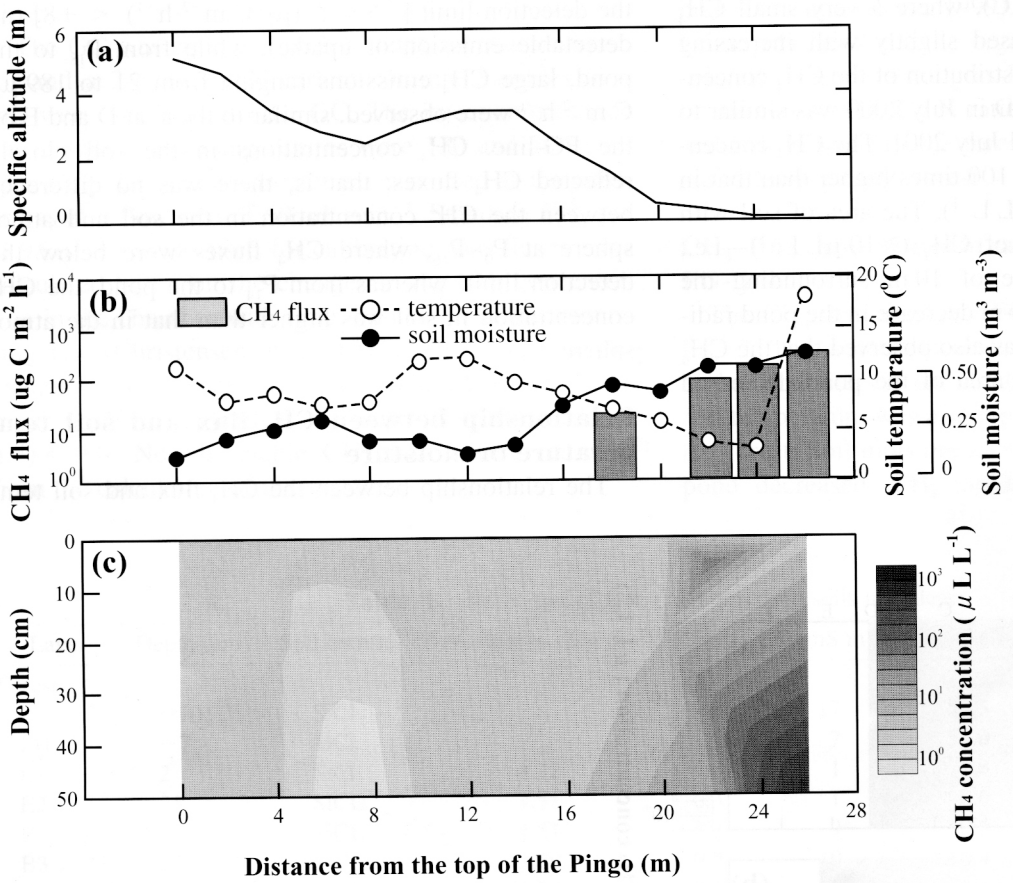

Fig. 4. Topography, CH_4 flux, and soil CH_4 concentration along the P-line. (a) Topography. Base level of specific altitude is located on the surface of the pond. (b) CH_4 fluxes with soil temperature and moisture in June 2001. CH_4 fluxes are indicated in a log scale. P_0–P_{16}: trace ($-8 < F < 8$ μg C m^{-2} h^{-1}). (c) CH_4 concentration (μL L^{-1}) in the soil in June 2001.

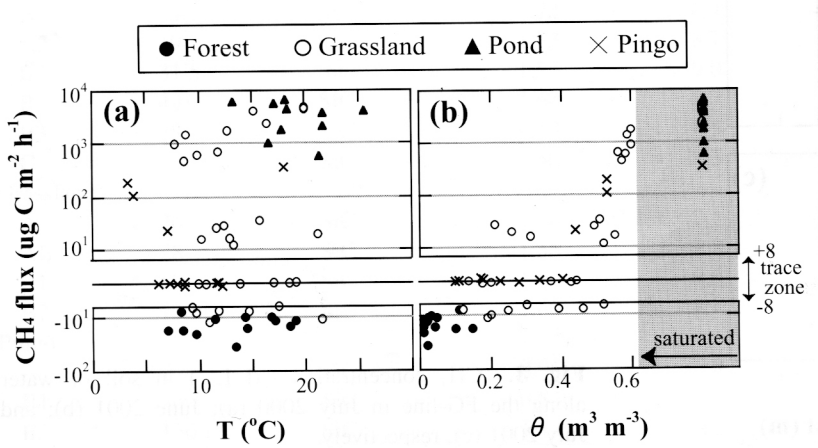

Fig. 5. Relationship between CH_4 flux and (a) soil temperature (T, °C) and (b) soil moisture (θ, m^3 m^{-3}). CH_4 fluxes are indicated in a log scale and CH_4 fluxes beyond the detection limit [$-8 < F$ (μg C m^{-2} h^{-1}) $< +8$] are depicted in the "trace zone." "Saturated" (gray zone) refers to the zone beyond the detection limit [θ (m^3 m^{-3}) $>$ 0.60] of a FDR.

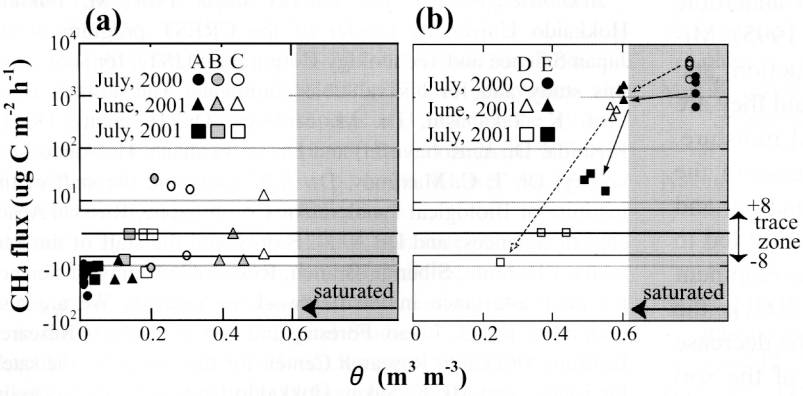

Fig. 6. Relationship between CH_4 flux and soil moisture θ ($m^3\ m^{-3}$) obtained in the FG-line. (a) Relatively drier plots (A, B, and C). (b) Relatively wetter plots (D and E). CH_4 fluxes are indicated in a log scale and CH_4 fluxes beyond the detection limit [$-8 < F$ ($\mu g\ C\ m^{-2}\ h^{-1}$) $< +8$] are depicted in the "trace zone." "Saturated" (gray zone) refers to thezone beyond the detection limit [θ ($m^3\ m^{-3}$) > 0.60] of a FDR. Arrows in (b) indicate seasonal changes, in CH_4 flux at D (dotted line) and E (solid line).

Table. 2. CH_4 flux from high-latitude ecosystems (>60° N).

Lati.	Longi.	Location	Soil	Vegetation	Study period	CH_4 flux range[a]	Reference
Boreal forest							
N 64	W 148	Alaska, US	Silt loam	Spruce	Jun.–Sep.	−25 to −11	Gulledge and Schimel 2000
N 62	E 130	Nelegal, Russia	Loamy soil	Larch	Jun.–Jul.	−17 to −13	This study
N 60	E 18	Norrliden, Sweden	Orthic podzol	Pine	Annual	−17 to −5	Klemedtsson and Klemedtsson 1997
Grassland							
N 69	E 161	Chersky, Russia	Silts and clays	*Festuca* spp.	Jul.–Aug.	−130–47	Nakano et al. 2000
N 62	E 130	Nelegal, Russia	Loamy soil	*Elytriga repens*	Jun.–Jul.	−11–28	This study
Wetland							
N 69	E 161	Chersky, Russia	Floodplain	Horsetail, *Carex*	Jul.	2.3–5.2	Tsuyuzaki et al. 2001
N 67	−N 77		Wet Tundra	—	Jul.–Aug.	1.5 ± 2.2	Christensen et al. 1995
>N 60		Alaska, US	Wet Tundra	—	Warm season	0.3 ± 0.1	Bartlett et al. 1992
N 62	E 130	Nelegal, Russia	Edge of the pond	—	Jun.–Jul.	2.2–4.8	This study
N 62	E 130	Nelegal, Russia	Pond	—	Jun.–Jul.	0.6–2.4	This study
N 60	W 161	Alaska, US	Pond	—	Jul.	0.1–2.4	Bartlett et al. 1992

[a] Unit: $\mu g\ C\ m^{-2}\ h^{-2}$ for boreal forest and glassland, $\times 10^3\ \mu g\ C\ m^{-2}\ h^{-1}$ for wetland.

(maximum emission: $4.8 \times 10^3\ \mu g\ C\ m^{-2}\ h^{-1}$) in July 2000, whereas in 2001 CH_4 uptake occurred at this site (maximum uptake: $-8\ \mu g\ C\ m^{-2}\ h^{-1}$).

Comparison with previous studies

Due to the lack of CH_4 flux data in Siberia, the values measured in Alaska and northern Europe have been representative of the Boreal climatic zone for the estimation of global CH_4 emission (Bartlett and Harriss 1993; Potter et al. 1996).

The values of the CH_4 fluxes which were observed in forests, edge of the pond, and pond were similar to those previously reported -25 to $-5\ \mu g\ C\ m^{-2}\ h^{-1}$ for forests and $0.1–5.2 \times 10^3\ \mu g\ C\ m^{-2}\ h^{-1}$ for wetlands in Alaska and northern Europe (Table 2).

DISCUSSION

Thermokarsts in Siberia develop due to subsidence associated with melting permafrost after the occurrence of severe forest fires (Desyatkin 1993). At the initial stage of Alas formation, a pond is formed in the Alas; the pond then gradually dries up due to the small amount of precipitation. As the pond dries up, heavy accumulation of salts takes place in the Alas soil (Desyatkin 1993).

We ascribed the increase in the soil moisture in the Alas grassland to the thermokarst geomorphology. The increase in EC occurred due to salt accumulation and the low precipitation; the increase of the pH and organic carbon content was associated with the forest fires that supplied ash and organic matter to the soil (Sawamoto et al. 2000).

The CH_4 dynamics in the Alas, as determined in this study, showed that, although no detectable CH_4 flux occurred on the salt-accumulated Pingo (Fig. 4), overall the Alas acted as a source of CH_4 emission (Fig. 2).

CH_4 flux from soil occurs as a net CH_4 production and consumption in soil, because an aerobic zone develops

at the surface of the soil aggregates and an anaerobic zone develops inside the aggregates (Conrad 1995). Microbiological processes regulate CH_4 production and consumption in soil (Mer and Roger 2001), and they are strongly affected by the soil temperature and moisture. Dunfield et al. (1993) reported that the increase of the soil temperature promoted both CH_4 production and consumption in soil. Increase in the soil moisture led to the increase of CH_4 production due to the development of anaerobic conditions (Mer and Roger 2001); the increase in the soil moisture also resulted in the decrease of CH_4 consumption due to the depression of the soil gas diffusivity (Castro et al. 1995; MacDonald et al. 1997; Hu et al. 2001). Our study did not reveal any relationship between the CH_4 flux and soil temperature (Fig. 5), presumably due to the positive temperature dependency of both CH_4 production and consumption in the soil. The forest soil with a low moisture showed a steady CH_4 uptake, while a large CH_4 emission was observed near and in the pond (Figs. 2 and 5). These facts clearly indicate that CH_4 production and consumption strongly depended on the soil moisture.

On the other hand, soils at the top of the Pingo did not show any detectable CH_4 fluxes, in spite of the low soil moisture content which was similar to that of the forest soil (Figs. 2 and 4), presumably due to the higher EC values in the Pingo soil than in the forest soil (Table 1). Nesbit and Breitenbeck (1992) reported that KCl (3.5 $cmol_c\ kg^{-1}$) inhibited CH_4 oxidation in soil. In addition, MacDonald et al. (1997) showed that sodium inhibited CH_4 oxidation in soil. In this study, the EC was very high (141 $mS\ m^{-1}$) at a 30 cm depth in the Pingo soil. EC is an indicator of total cation concentration, and an EC of 141 $mS\ m^{-1}$ corresponds to a total cation concentration of 14 $cmol_c\ kg^{-1}$ (Kamewada 1991). Furthermore, salt-tolerant vegetation, such as *Puccinellia tenuiflora* and *Artemisa commutata*, was dominant at the top of the Pingo. However, although the pH on the surface of the Pingo soil was about 6—favorable conditions for the growth of methanotrophs (Hütsch et al. 1994)—CH_4 uptake was not observed. Therefore, salinity rather than pH may influence the CH_4 flux. Christensen et al. (1995) reported that CH_4 production increased with increasing organic carbon content, and Dunfield et al. (1993) showed that both CH_4 production and consumption were highest at the top of mineral soils. Therefore, a higher CH_4 production may occur in the grassland compared with the forest.

These results suggest that Alas formation due to with forest disturbance increases CH_4 production and decreases CH_4 consumption due to the accumulation of salts and the increase of the soil moisture and organic carbon content in the Alas soil.

Acknowledgments. The authors thank Prof. M. Fukuda, Hokkaido University, Leader of the CREST program of the Japan Science and Technology Corporation (JST), for supporting this study and for his valuable comments. The authors thank Prof. K. Takahashi, Dr. M. Shibuya, Dr. H. Saito, Dr. K. Kushida, Dr. Y. Kobayashi, and Dr. G. Iwahana, Hokkaido University; Dr. T. C. Maximov, Dr. A.P. Isaev, and the staff of the Institute of Biological Problems of Cryolithzone, Russian Academy of Sciences; and Dr. A. N. Fedrov and the staff of the Permafrost Institute, Siberian Branch, Russian Academy of Science for their assistance in the fieldwork in Yakutsk. We are also grateful to Dr. G. Takao, Forestry and Forest Products Research Institute, Hokkaido Research Center, for the supply of the satellite image, and Mr. K. Sakai, Hokkaido University, for his assistance in the fieldwork and laboratory work. This study was supported by the CREST program of the Japan Science Technology Corporation (JST).

REFERENCES

Abaimov AP 1995: The larches of Siberia permafrost zone and their species peculiarities in progressive succesions, *In* Larch Genetics and Breeding: Research Findings and Ecological-Silvicultural Demands, Ed. O Martinsson, p. 11–15, Swedish University of Agricultural Sciences, Stockholm, Sweden

Bartlett KB, Crill PM, Sass RL, Harriss RC, and Dise NB 1992: Methane emissions from Tundra environments in the Yukon-Kuskokwim delta, Alaska. *J. Geophys. Res.*, **97**, 16645–16660

Bartlett KB and Harriss RC 1993: Review and assessment of methane emissions from wetlands. *Chemosphere*, **26**, 261–320

Bowden RD, Newkirk KM, and Rullo GM 1998: Carbon dioxide and CH_4 fluxes by a forest soil under laboratory-controlled moisture and temperature conditions. *Soil Biol. Biochem.*, **30**, 1591–1597

Castro MS, Melillo JM, Steudler PA, and Chapman JW 1994: Soil moisture as a predictor of CH_4 uptake by temperate forest soils. *Can. J. For. Res.*, **24**, 1805–1810

Castro MS, Steudler PA, and Melillo JM 1995: Factors controlling atmosphere CH_4 consumption by temperate forest soils. *Global Biogeochem. Cycles*, **9**, 1–10

Christensen TR, Jonasson S, Callaghan TV, and Hvstrom M 1995: Spatial variation in high-latitude CH_4 flux along a transect across Siberian and European tundra environments. *J. Geophys. Res.*, **100**, 21035–21045

Conrad R 1995: Soil microbial processes involved in production and consumption of atmospheric trace gases. *Adv. Microb. Ecol.*, **14**, 207–250

Desyatkin RV 1993: Syngenetic soil salinization during themokarst Alas formation. *Eurasian Soil Sci.*, **25** (4), 38–46

Dobbie KE, Smith KA, Primè A, Christensen S, Degorska A, and Orlanski P 1996: Effect of land use on the rate of CH_4 uptake by surface soils in northern Europe. *Atmos. Environ.*, **30**, 1005–1011

Dunfield P, Knowles R, Dunmont R, and Moore TR 1993: CH_4 production and consumption in temperate and subarctic peat

soils: response to temperature and pH. *Soil Biol. Biochem.*, **25**, 321–326

Fitzpatrick EA 1983: Soils, p. 215–224, Longman, New York

Goldammer JG and Furyaev VV 1996: Fire in ecosystems of boreal Eurasia. Ecological impacts and links to the global system. *In* Fire in Ecosystems of Boreal Eurasia, Ed. JG Goldammer and VV Furyaev, p. 1–20, Kluwer Academic Publishers, Dordrecht, The Netherlands

Goldammer JG and Stocks BJ 2000: Eurasian perspective of fire: Dimension, management and policies, and scientific requirements. *In* Fire, Climate Change, and Carbon Cycling in the Boreal Forest, Ecological Studies 138, Ed. ES Kasischke and BJ Stocks, p. 49–65, Springer-Verlag, New York

Gulledge J and Schimel JP 2000: Control on soil carbon dioxide and methane fluxes in a variety of Taiga forest stands in interior Alaska. *Ecosystems*, **3**, 269–282

Hu R, Kusa K, and Hatano R 2001: Soil respiration and CH_4 flux in adjacent forest, grassland, and cornfield soils in Hokkaido, Japan. *Soil Sci. Plant Nutr.*, **47**, 621–628

Hütsch BW, Webstar CP, and Powlson DS 1994: CH4 oxidation in soil as affected by land use, soil pH and N fertilization. *Soil Biol. Biochem.*, **26**, 1613–1622

IPCC 2001: Climate Change 2000: The Scientific Basis. http://www.ipcc.ch

Isaev AS, Korovin GN, Bartalev SA, Ershov DV, Janetos A, Kasischke ES, Shugart HH, French NHF, Orlick BE, and Murphy TL 2002: Using remote sensing to assess Russian forest fire carbon emissions. *Clim. Change*, **55**, 235–249

Kajimoto T, Matsuura Y, Sofronov MA, Volokitina AV, Mori S, Osawa A, and Abaimov AP 1999: Above- and belowground biomass and net primary productivity of a *Larix gmelinii* stand near Tura, central Siberia. *Tree Phys.*, **19**, 815–822

Kamewada K 1991: Estimation of EC of soil solution from ion composition and influences of differences of anion composition on EC and hydrostatic pressure. *Jpn. J. Soil Sci. Plant Nutr.*, **62**, 634–640 (in Japanese)

Keren R 1999: Salinity. *In* Handbook of Soil Science, Ed. ME Sumner, p. G4–G25, CRC Press, New York

Klemedtsson AK and Klemedtsson L 1997: Methane uptake in Swedish forest soil in relation to liming and extra N-deposition. *Biol. Fertil. Soils*, **25**, 296–301

Loeppert RH and Suarez DL 1996: Carbonate and gypsum. *In* Method of Soil Analysis Part 3—Chemical Methods, SSSA Book Series: 5, Ed. DL Sparks, p. 437–474, ASA, Madison, USA

MacDonald JA, Skiba U, Sheppard LJ, Ball B, Roberts JD, Smith KA, and Fowler D 1997: The effect of nitrogen deposition and seasonal variability on CH_4 oxidation and nitrous oxide emission rates in an upland spruce plantation and moorland. *Atmos. Environ.*, **31**, 3693–3706

McAullife C 1971: GC determination of solutes by multiple phase equilibration. *Chem. Technol.*, **1**, 46–51

Mer JL and Roger P 2001: Production, oxidation, emission and consumption of CH_4 by soils: A review. *Eur. J. Soil Biol.*, **37**, 25–50

Nakano T, Kuniyoshi S, and Fukuda M 2000: Temporal variation in methane emission from tundra wetlands in a permafrost area, northeastern Siberia. *Atmos. Environ.*, **34**, 1205–1213

Nesbit SP and Breitenbeck GA 1992: A laboratory study of factors influencing CH_4 uptake by soils. *Agric. Ecosyst. Environ.*, **41**, 39–54

Potter CS, Davidson EA, and Verchot lV 1996: Estimation of global biogeochemical controls and seasonality in soil methane consumption. *Chemosphere*, **32**, 2219–2246

Primè A and Christensen S 1997: Seasonal and spatial variation of CH_4 oxidation in a Danish spruce forest. *Soil Biol. Biochem.*, **29**, 1165–1172

Robert H 1997: Climate com http://www.worldclimate.com/climate/

Sawamoto T, Hatano R, Yajima T, Takahashi K, and Isaev AP 2000: Soil respiration in Siberian Taiga ecosystems with different histories of forest fire. *Soil Sci. Plant Nutr.*, **46**, 31–42

Sawamoto T, Kusa K, Hu R, and Hatano R 2002: Dissolved nitrous oxide, CH_4 and carbon dioxide in pipe drainage, seepage, and stream water in a livestock farm in Hokkaido, Japan. *Soil Sci. Plant Nutr.*, **48**, 433–439

Schulze ED, Schulze W, Kelliher FM, Vygodskaya NN, Ziegler W, Kobak KI, Koch H, Arneth A, Kusnetsova WA, Sogatchev A, Issajev A, Bauer G, and Hollinger DY 1995: Aboveground biomass and nitrogen nutrition in a chronosequence of pristine Dahurian *Larix* stands in eastern Siberia. *Can. J. For. Res.*, **25**, 943–960

Smith KA, Dobbie KE, Ball BC, Bakken LR, Sitaula BK, Hansen S, Brumme R, Borken W, Christensen S, Priemè A, Fowler D, Macdonald JA, Skiba U, Klemedtsson L, Kasimir-Klemedtsson A, Degorska A, and Orlanski P 2000: Oxidation of atmospheric methane in Northern European soils, comparison with other ecosystems, and uncertainties in the global terrestrial sink. *Global Change Biol.*, **6**, 791–803

Tsuyuzaki S, Nakano T, Kuniyoshi S, and Fukuda M 2001: CH_4 flux in grassy marshlands near Kolyma river, north-eastern Siberia. *Soil Biol. Biochem.*, **33**, 1419–1423

Whalen SC and Reeburgh WS 1996: Moisture and temperature sensitivity of CH_4 oxidation in boreal soils. *Soil Biol. Biochem.*, **28**, 1271–1281