

## ORIGINAL ARTICLE

## Temporal variations in soil–atmosphere methane exchange after fire in a peat swamp forest in West Siberia

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Masami FUKUDA<sup>4</sup>, and Yoshifumi YASUOKA<sup>2</sup><sup>1</sup>Department of Geography, Tokyo Metropolitan University, Hachioji 192-0397, <sup>2</sup>Institute of Industrial Science, University of Tokyo, Tokyo 153-8505, <sup>3</sup>National Institute for Environmental Studies, Tsukuba 305-8506 and <sup>4</sup>Institute of Low Temperature Science, Hokkaido University, Sapporo 060-0819, Japan**Abstract**

Temporal variations in methane (CH<sub>4</sub>) exchange between the soil and the atmosphere during a period of 3 years after a forest fire were estimated by combining field measurements of CH<sub>4</sub> flux with an analysis of satellite images. The study area was located in a boreal peat swamp forest in the West Siberian plain that experienced a severe fire in the summer of 1998. The surface of the burned area was classified into bare soil, open water and recovered vegetation. In the summers of 1999 and 2000, CH<sub>4</sub> fluxes, using a closed-chamber method, and environmental variables, such as soil temperature and soil water content, for each of the three surface types in the burned area and in the unburned area were measured. In general, CH<sub>4</sub> fluxes were controlled by the surface moisture in the burned area and by the temperature in the unburned forest. Temporal changes in the areal coverage of soil, water and vegetation in the burned area were investigated using NOAA AVHRR (Advanced Very High Resolution Radiometer) data with subpixel land-cover characterization. Based on the satellite information, temporal changes in the moisture conditions of the burned surface were estimated and temporal variations in the CH<sub>4</sub> fluxes for the entire burned area were calculated. The cumulative CH<sub>4</sub> emission rates from the entire burned area during the summer (from June to August) were estimated to range from 0.39 to 0.48 g C m<sup>-2</sup> during the period from 1999 to 2001. In contrast, unburned forest soils were consistently net CH<sub>4</sub> consumers. The cumulative consumption rate during the summer was calculated to be approximately 0.4 g C m<sup>-2</sup> based on a reanalysis air temperature dataset. As the surface soil had become extremely wet since the fire, the soil had become a net emitter of CH<sub>4</sub> after the fire disturbance, although CH<sub>4</sub> oxidation predominated in the unburned forest.

**Key words:** forest fire, NOAA AVHRR, soil–atmosphere methane exchange, spectral mixture analysis, western Siberia.

**INTRODUCTION**

Soils are major global sources and sinks of methane (CH<sub>4</sub>) and play an important role in regulating atmospheric CH<sub>4</sub> concentrations. Natural wetlands are large sources of CH<sub>4</sub> emission to the atmosphere (e.g. Christensen *et al.* 1995; Nakano *et al.* 2000; Nykänen *et al.* 2003; Whalen and Reeburgh 1992), whereas aerobic

environments such as upland forest soils consume CH<sub>4</sub> owing to microbial oxidation (e.g. Borken *et al.* 2000; Castro *et al.* 1995; Priemé and Christensen 1997; Smith *et al.* 2000). The direction and rate of the net CH<sub>4</sub> exchange between soils and the atmosphere are commonly highly variable both spatially and temporally and are controlled by various environmental factors such as soil moisture, soil temperature and chemical properties (e.g. pH, nitrogen availability). Among these factors, soil moisture is the major determinant of whether soils are net CH<sub>4</sub> emitters or consumers because it directly influences the availability of oxygen.

Fire is ubiquitous in the boreal region and is extremely common in boreal forests (Kasischke 2000). Fire is associated with important consequences for carbon

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storage in boreal forests and is linked to immediate pulses of trace gases to the atmosphere through combustion. Fire also causes long-term surface disturbances and changes in the gas exchange between soil and the atmosphere. In many studies, carbon emissions during burning and post-fire release of CO<sub>2</sub> have been investigated using satellite imagery, historical statistics, modeling and/or field soil surveys (Auclair and Carter 1993; Cahoon *et al.* 1994; Conard *et al.* 2002; Dixon and Krankina 1993; French *et al.* 2000; Isaev *et al.* 2002; Kasischke and Bruhwiler 2003; Kasischke *et al.* 1995; Pitkänen *et al.* 1999; Turetsky and Wieder 2001; Zoltai *et al.* 1998). In addition, changes in the surface CH<sub>4</sub> flux before and after controlled fires (Kim and Tanaka 2003; Levine *et al.* 1990) have been investigated using a chronosequential method (Burke *et al.* 1997). However, continuous variations in the soil-atmosphere CH<sub>4</sub> exchange over several years at a particular burned site have been examined in only a few studies. Another consideration is the need to scale up the CH<sub>4</sub> flux measured at points or in a small area to an entire burned area to evaluate the impact of fire on the soil-atmosphere CH<sub>4</sub> exchange.

Remote sensing is an appropriate technique for monitoring the land surface over a wide area. High-resolution images such as LANDSAT TM, SPOT HRV and Terra ASTER images have been used to map forest fire extent and damage and to estimate carbon emissions from burned areas (Garcia-Haro *et al.* 2001). However, high-resolution images may not cover a target area frequently because of their narrow swath width. Coarse spatial resolution data, such as NOAA AVHRR (Advanced Very High Resolution Radiometer) data, have the advantages of wide coverage and high temporal resolution, although this sensor may not detect fine spatial structures in mixtures of vegetation, soil and water in land ecosystems, which results in the existence of mixed pixels. However, a technique for extracting subpixel cover type reflectance levels from the mixed pixels of a coarse spatial resolution image has been developed (Oleson *et al.* 1995; Takeuchi *et al.* 2003).

The study area was located in a boreal forest in the West Siberian plain that experienced a forest fire in 1998. The surface environment of the burned area consisted of a mosaic of small ponds (open water), bare soil and invading herbaceous plants, whose distribution had varied temporally over the years following the fire. The purpose of the present study was to estimate temporal variations in the CH<sub>4</sub> exchange between soil and the atmosphere after fire disturbance for the entire burned area. To achieve this objective, first we conducted flux measurements at the burned sites and the unburned site and revealed relationships between the CH<sub>4</sub> flux and environmental variables. Second, temporal variations in

the surface environment were analyzed based on NOAA AVHRR images covering the study area. Finally, we estimated temporal variations in CH<sub>4</sub> flux from the entire burned area by combining the results from the field measurements with the results from an analysis of the remotely sensed data.

## MATERIALS AND METHODS

### Study sites

The study area was located in a boreal forest (latitude 56°52'N, longitude 83°17'E) near Plotnikovo, Tomsk Oblast, in the southern part of the West Siberian plain. This plain is an extremely paludinous area characterized by very large carbon stocks resulting from peat accumulation (Yefremov and Yefremova 2001). The study area was covered with a thick organic soil layer derived from peat. In the area, the annual mean air temperature was -1.1°C, mean monthly temperatures ranged between -18.6°C and -17.6°C throughout the year, and the annual precipitation was approximately 530 mm (Lapshina *et al.* 2001). Measurements were conducted in an unburned forest and in an adjacent area that was burnt in August 1998. Based on a comparison between satellite images before and after the fire, the burned area was estimated to extend over 13.8 km<sup>2</sup> (Takeuchi *et al.* 2002).

In the unburned area, the forest consisted of white birch (*Betula pendula*) with occasional Scots pines (*Pinus sylvestris*). The ground vegetation included shrubs (*Ledum palustre*, *Chamaedaphne calyculata*, *Rubus chamaemorus*) and herbaceous plant communities. A 3-cm layer of decomposing litter (L horizon) was underlain by a thick (approximately 90 cm), black, organic layer (H horizon), which overlaid a silty, mineral horizon (B horizon).

In general, forest fires in West Siberia burn organic-rich soils and tree roots, not tree canopies. Thus, most trees in the burned areas fall down during the fire and leave innumerable root scars on the soil surface. The soil surface in the burned study area was uneven (approximately 50-cm high undulation) and was entirely covered with fallen trees (Fig. 1). The burned area was covered with snow until the beginning of May. The surface was flooded after snowmelt and gradually dried out owing to evaporation during the summer. Although most plants were completely burnt in August 1998, the ground surface was gradually invaded by plants in the summer of the following years: first liverwort (*Marchantia* Sp.) and successively other herbaceous plants (mainly *Epilobium angustifolium*). The soil had no litter layer, but the black organic H horizon was approximately 30 cm thick and was underlain by a silty, mineral horizon (B horizon). Some charcoal fragments were included in the upper part of the H horizon. The surface environment in the burned area



**Figure 1** The burned area in August 1999; almost the entire area was covered with fallen trees.

was classified into open water, unvegetated bare soil and plant-covered soil; the distribution and areal coverage of each component varied across seasons and years.

### Methodology of field observations

Measurements of net CH<sub>4</sub> flux were conducted at the following sites: unburned forest (site U), open water (site W), bare soil (site S) and vegetation (site V) sites in the burned area using a closed-chamber method. The system comprised a 0.4-m-tall transparent chamber, stainless-steel collars with an enclosure of 0.152 m<sup>2</sup>, a portable CH<sub>4</sub>/CO<sub>2</sub> analyzer equipped with a semiconductor CH<sub>4</sub> detector, and a 12-V lead-acid battery. The chamber was made of acrylic plastic and was equipped with sampling ports, a Tedlar bag to equalize pressure, a thermometer and a battery-operated fan. Before the initiation of the measurements, two collars were embedded into the soil to a depth of 10 cm at site U, and they remained throughout the study. At sites W, S and V, two or three collars were inserted into the soil at each site on the first day of each study period and remained only for the duration of the period, because the surface environment at the burned sites changed with time. The chamber was closed for 10 min by fitting a water-filled groove into the collar for the measurements. Sample air was continuously pumped at a rate of approximately 1 dm<sup>3</sup> min<sup>-1</sup> from the chamber through a polyethylene tube to the CH<sub>4</sub> analyzer and back to the chamber. Details of the analysis have been described by Nakano *et al.* (2004). The CH<sub>4</sub> concentration in the chamber was recorded at 5 s intervals with a data logger (NR-1000, Keyence Co., Osaka, Japan). CH<sub>4</sub> flux at the drier unburned site was determined from the rate constant of the exponential curve fit to the concentration changes over a 10 min sampling period, whereas the flux was calculated using a linear regression of the

concentration changes over the first 3 min at the wetter burned site that was more prone to ebullition and disturbances. The minimum *r*<sup>2</sup> value for significance was 0.90, and any data that fell below this value were rejected. The detection limit was approximately ± 0.03 mg C m<sup>-2</sup> day<sup>-1</sup>. A positive CH<sub>4</sub> flux represents a transfer from the soil surface to the atmosphere and a negative flux indicates CH<sub>4</sub> uptake by the soil.

Flux measurements were carried out during 1-week periods in August 1999, June 2000 and September 2000. At site U, flux was measured four times per day for each of two collars to examine temporal variations in methane oxidation by boreal forest soil (Nakano *et al.* 2004), and the daily mean flux was calculated based on these data. At sites W and S, flux measurements were conducted three to five times at each site for each period. Flux at site V was measured only in September 2000 because herbaceous plants invaded our observation area after the measurement of June 2000.

Environmental data were collected concurrently with the flux measurements. At sites U, S and V, the soil temperature at a depth of 10 cm and volumetric water content (VWC) at the time of the flux measurements were determined using a handheld digital thermometer (ST-920, Testoterm GmbH & Co., Berlin, Germany) and time domain reflectometry (TDR) probes (0–12 cm depth; HydroSense, Campbell Scientific Inc., Logan, UT, USA) positioned vertically from the surface into the soil, respectively. At site W, the depth of standing water was measured at the time of the flux measurements. Measurements of the soil temperature, soil moisture and water depth were carried out at 5 points around each collar immediately after the flux measurement was recorded and averaged. In addition, air temperatures at 1.5 m above ground level at both the burned and unburned areas were measured every 30 min using data loggers with thermistor probes (SK-L200T, Sato Keiryoki Mfg. Co., Tokyo, Japan). The spatial distribution of soil moisture and the depth of standing water in the burned area were also surveyed every 5 m along two 50-m sampling transects in August 1999, June 2000, September 2000 and August 2001.

Surface soil samples at both the burned and unburned sites were collected in triplicate and brought back to Japan in September 2000. The relative gas diffusion coefficient (*D/D*<sub>0</sub>) was determined using Osozawa's (1987) diffusion chamber method with 100-cm<sup>3</sup> undisturbed soil cores. Soil core porosity was measured with an actual volume meter (DIK-1000, Daiki Rika Kogyo Co., Tokyo, Japan) and the bulk density was determined gravimetrically. The soil cores were also used for cross-checking the TDR results using the gravimetric method. Total carbon and nitrogen contents were determined by dry combustion using a CN analyzer (Vario-EL, Elementar Analysensysteme GmbH,

Hanau, Germany) equipped with a thermal conductivity detector. Soil pH and electrical conductivity (EC) were determined with a glass electrode pH meter and an EC meter, respectively, in a supernatant suspension of 1:10 soil : deionized water mixture.

### Analysis of NOAA AVHRR imagery

A total of 715 AVHRR images from the summers of 1998–2001 were acquired. NOAA AVHRR channels 1 and 2 were calibrated to reflectance values using coefficients based on the NOAA KLM User's Guide (Goodrum *et al.* 1999), and cloud-free areas were selected carefully with visual interpretation. Corrections of the atmospheric conditions and bidirectional reflectance distribution function (BRDF) were not carried out. Pixels over 45° of the sensor scan angle were considered unacceptable for processing. The AVHRR data were geometrically corrected based on ground control point (GCP) matching using PaNDA software, and the registration error over the image was less than 1 pixel. PaNDA is a free software package for NOAA data analysis (Shimoda *et al.* 1998). After screening out inappropriate images, 24 images were selected for analysis (Table 1).

The NOAA AVHRR is one of the few space-borne sensors currently capable of acquiring radiometric data over a broad range of view angles. However, the relatively coarse spatial resolution of AVHRR (1.1–4.3 km

most often results in measurements of mixed land covers and pixel unmixing is required (Asner *et al.* 1997). A linear spectral mixture model based on three end members, vegetation, soil and water (Yamagata *et al.* 1997), was defined by

$$\text{AVHRR}_{\text{CH1}} = a_{11}V + a_{12}S + a_{13}W \quad (1)$$

and

$$\text{AVHRR}_{\text{CH2}} = a_{21}V + a_{22}S + a_{23}W \quad (2)$$

where  $\text{AVHRR}_{\text{CH1}}$  and  $\text{AVHRR}_{\text{CH2}}$  are the reflectance of channels 1 and 2, respectively, and V, S and W are the fractional coverage of vegetation, soil and water;  $a_{ij}$  represents the end members and ranges from 0 to 1. The constraint equation (Eq. 3) requires that the sum of V, S and W in each pixel equal 1.

$$V + S + W = 1 \quad (3)$$

By solving the three equations with the AVHRR reflectance levels of channels 1 and 2 simultaneously, we were able to calculate the fractional coverage of V, S and W within a pixel. Results of the linear spectral mixture model were verified based on the field survey.

## RESULTS

### Field measurements

Summary statistics of the CH<sub>4</sub> flux and environmental variables for the entire study period are presented in Table 2. Soil–atmosphere exchanges of CH<sub>4</sub> were

**Table 1** The NOAA AVHRR data used in this study

No.	Date	Julian Day	Time (GMT)	Satellite
1	24 May 1998	144	0856	NOAA-14
2	4 June 1998	155	0835	NOAA-14
3	17 June 1998	168	0744	NOAA-14
4	9 July 1998	190	0850	NOAA-14
5	25 July 1998	206	0914	NOAA-14
6	10 August 1998	222	0719	NOAA-14
7	23 May 1999	143	0818	NOAA-14
8	6 June 1999	157	0901	NOAA-14
9	22 June 1999	173	0923	NOAA-14
10	7 July 1999	188	0812	NOAA-14
11	30 July 1999	211	0855	NOAA-14
12	10 August 1999	222	0831	NOAA-14
13	19 May 2000	140	1002	NOAA-14
14	19 June 2000	171	0900	NOAA-14
15	25 June 2000	177	0939	NOAA-14
16	9 July 2000	191	1017	NOAA-16
17	31 July 2000	213	0914	NOAA-16
18	7 August 2000	220	0934	NOAA-16
19	26 May 2001	146	1042	NOAA-16
20	24 June 2001	175	1000	NOAA-16
21	6 July 2001	187	0712	NOAA-16
22	19 July 2001	200	0635	NOAA-16
23	3 August 2001	215	0721	NOAA-16
24	17 August 2001	229	0820	NOAA-16

**Table 2** Summary statistics of CH<sub>4</sub> flux and environmental variables at the burned sites and the unburned site

Site <sup>†</sup>	<i>n</i>	Mean	Median	SD	Maximum	Minimum
CH <sub>4</sub> flux (mg C m <sup>-2</sup> d <sup>-1</sup> )						
W	17	11	6.5	8.5	30	2.6
S	14	3.4	0.24	5.1	16	-0.48
V	9	0.27	0.04	0.64	0.07	-0.41
U	43	-3.9	-3.9	1.0	-2.2	-6.8
Soil temperature at 10-cm depth (°C) <sup>‡</sup>						
S		12.5	11.5	1.9	15.5	10.5
V		11.2	11.0	0.4	11.8	10.9
U		13.4	13.9	1.2	14.9	10.3
Water depth (cm) <sup>‡</sup>						
W		10.5	10.0	5.5	20.5	3.0
Volumetric water content (%) <sup>‡</sup>						
S		57.9	50.5	14.8	82.9	43.0
V		25.4	25.0	3.5	32.8	21.7
U		11.2	10.8	2.5	19.7	7.4

<sup>†</sup>Burned sites: W, open water; S, bare soil; and V, vegetated. U, unburned site. <sup>‡</sup>Data collected concurrently with flux measurements. SD, standard deviation.

**Table 3** Summary of air temperature data (°C) recorded automatically at 30-min intervals at the burned and unburned areas

Site	August 1999		June 2000		September 2000	
	Burned	Unburned	Burned	Unburned	Burned	Unburned
Mean	10.7	10.3	18.0	17.2	11.5	11.2
Maximum	21.3	21.0	32.1	30.8	26.5	26.1
Minimum	-1.0	-0.4	2.0	3.1	-0.4	0.3

always negative at site U, indicating that forest soil before the fire was a net consumer of CH<sub>4</sub>. In contrast, CH<sub>4</sub> flux was always positive (net emission) at site W. Both emission and consumption of CH<sub>4</sub> were observed at sites S and V. The flux varied widely at site S, ranging from -0.48 to 16 mg C m<sup>-2</sup> d<sup>-1</sup>, whereas it was close to zero at site V. Soil temperatures at a depth of 10 cm showed slight variations (approximately 10–15°C) at all sites. The VWC of the soils differed markedly among the sites: at site S the values were very high and variable, whereas the soil at site U experienced drought conditions (VWC < 20%) for the entire period.

Air temperature recorded at 30-min intervals was significantly different between the burned area and the unburned area for all the study periods (paired *t*-test, *P* < 0.0001; Table 3). Mean temperatures for each period at the burned area were 0.3–0.8°C higher than those at the unburned area. Temperature variations were also significantly different between the areas; the range of temperature variations was wider in the burned area than in the unburned area.

Table 4 shows the results of the transect measurement of the water depth of pools and VWC of bare and plant-covered soils at the burned area. Measurements were carried out during each period at 22 points every 5 m along the two 50-m transects. The number and depth of the pools were greatest in June 2000, immediately after the snowmelt. Soil moisture level in the bare soil was also highest in June 2000. The soil gradually dried out during summer, and herbaceous plants started to invade the measurement lines in the summer of 2000. The VWC of the plant-covered soils was approximately 25% in both September 2000 and August 2001.

Soil properties of the surface H horizon at the burned area and the unburned area are presented in Table 5. Significant differences in means between the unburned area and the burned area were found for the thickness of the H horizon, relative gas diffusion coefficient (D/D<sub>0</sub>), pH and EC (two-sample *t* test, *P* < 0.05). The thickness of the H horizon decreased by approximately 60 cm after the fire, and D/D<sub>0</sub> also decreased considerably. The values of the pH and EC showed a slight increase and decrease, respectively.

Spearman's rank correlation coefficients (*r<sub>s</sub>*) for the relationship between individual measurements of

**Table 4** Water depth of pools and volumetric water content of bare and plant-covered soils measured along two 50-m transect lines in the burned area

Period	<i>n</i>	Mean	SD
Water depth (cm)			
August 1999	9	6.5	2.1
June 2000	14	13.8	4.5
September 2000	8	10.2	3.6
August 2001	3	4.0	1.4
Volumetric water content (%) of bare soil			
August 1999	13	48.0	7.2
June 2000	8	75.9	6.8
September 2000	8	53.5	5.1
August 2001	4	39.1	5.3
Volumetric water content (%) of plant-covered soil			
August 1999	0	–	–
June 2000	0	–	–
September 2000	6	25.2	3.8
August 2001	15	23.7	4.1

–, no data. SD, standard deviation.

**Table 5** Soil properties of the surface organic layer (H horizon) at the burned and unburned areas

	Unburned	Burned
Thickness (m)	0.89 ± 0.06	0.31 ± 0.16
Bulk density (Mg m <sup>-3</sup> )	0.19 ± 0.02	0.22 ± 0.02
Porosity (%)	90 ± 2	89 ± 3
D/D <sub>0</sub>	0.37 ± 0.05	0.010 ± 0.001
Total C (g g <sup>-1</sup> )	0.43 ± 0.02	0.45 ± 0.01
Total N (g g <sup>-1</sup> )	0.025 ± 0.002	0.025 ± 0.002
pH (H <sub>2</sub> O)	4.9 ± 0.1	5.5 ± 0.2
EC	17 ± 1	12 ± 2

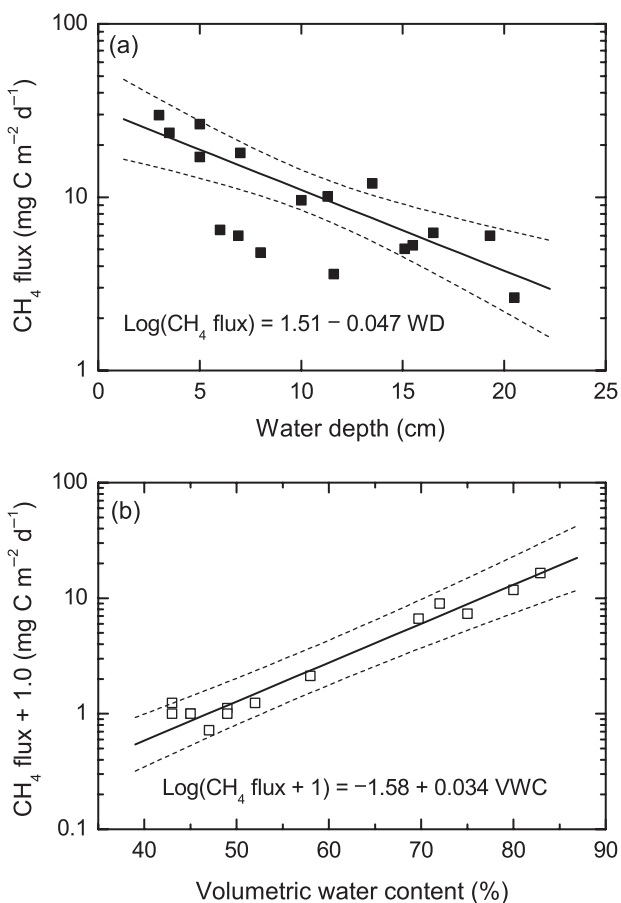
Values represent mean ± SD. D/D<sub>0</sub>, relative gas diffusion coefficient in soil; EC, electrical conductivity.

the CH<sub>4</sub> flux and environmental variables are given in Table 6. At site W, the CH<sub>4</sub> flux showed a negative correlation with water depth. The flux was positively correlated with air and soil temperatures and VWC at site S. There were no significant correlations at site V. Relationships of the CH<sub>4</sub> flux versus water depth and

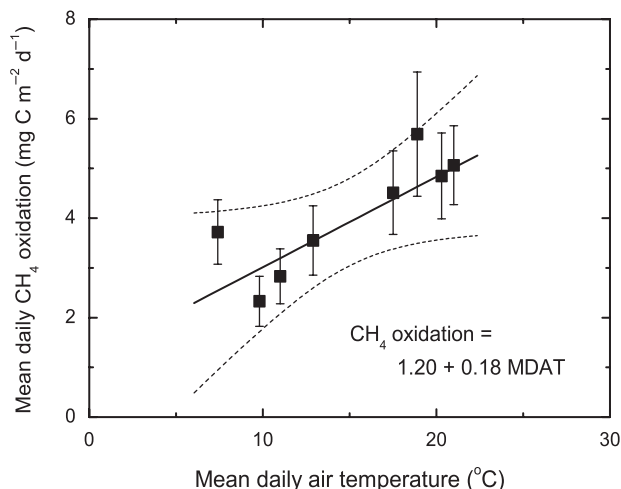
**Table 6** Spearman's rank correlation coefficients ( $r_s$ ) for the relationships between  $\text{CH}_4$  flux and environmental variables for the burned and unburned sites

	Site W	Site S	Site V	Site U
Air temperature	NS	0.74	NS	-0.40
Soil temperature at 10-cm depth	-	0.83	NS	NS
Water depth	-0.60	-	-	-
Volumetric water content	-	0.87	NS	NS

NS, not significant ( $P > 0.05$ ). -, not determined.

**Figure 2** Relationships between  $\text{CH}_4$  flux and (a) water depth (WD) at the open water site and (b) volumetric water content (VWC) at the bare soil site. Lines indicate linear regression (solid line) and the 95% confidence bands (broken lines) for the regression.

VWC are presented in Fig. 2.  $\text{CH}_4$  fluxes after logarithmic transformation were approximated by linear functions of the water depth and VWC.  $\text{CH}_4$  flux in the unburned forest showed a negative correlation with air temperature (Table 6), indicating that  $\text{CH}_4$  oxidation by soil increased as temperature increased. The relationship between mean

**Figure 3** Relationship between mean daily  $\text{CH}_4$  oxidation rate and mean daily air temperature (MDAT) in the unburned birch forest site. Error bars indicate standard deviations. Lines indicate linear regression (solid line) and the 95% confidence bands (broken lines) for the regression.

daily  $\text{CH}_4$  oxidation and mean daily air temperature is shown in Fig. 3. The oxidation rate was approximated by a linear function of air temperature.

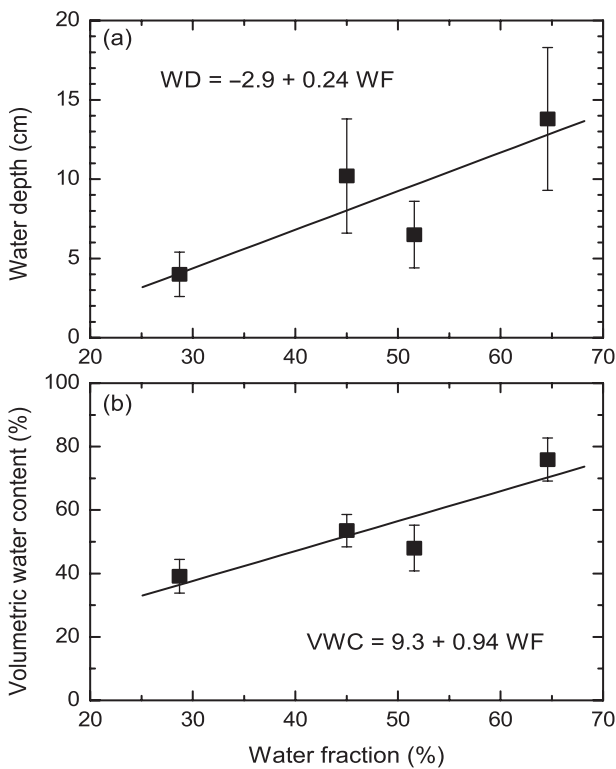
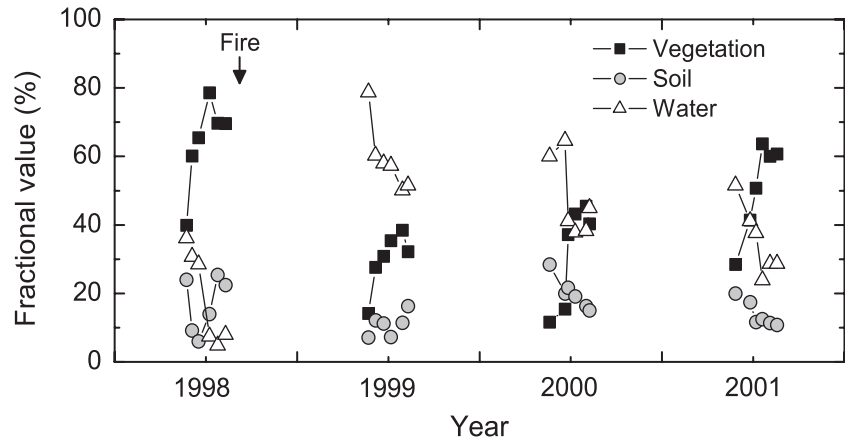
### Monitoring of surface environments by satellite images

Spectral mixture analysis of AVHRR imagery revealed the presence of temporal variations in the areal fractions covered with water, soil and vegetation in the study area (Fig. 4). As each plot represented a value on each day listed in Table 1, this figure showed 4-year variations in the surface coverage. In every year, the vegetation and water fractions showed seasonal variations: the vegetation fraction increased as the season progressed from spring to summer, whereas the water fraction decreased during the same period. Inter-annual variations were also evident (Fig. 4). The annual maximum value for the vegetation decreased from 80% in 1998 to 40% in 1999 owing to the fire, and then gradually increased in the following years. In contrast, the water fraction increased after the fire and decreased thereafter.

### Areal flux estimates

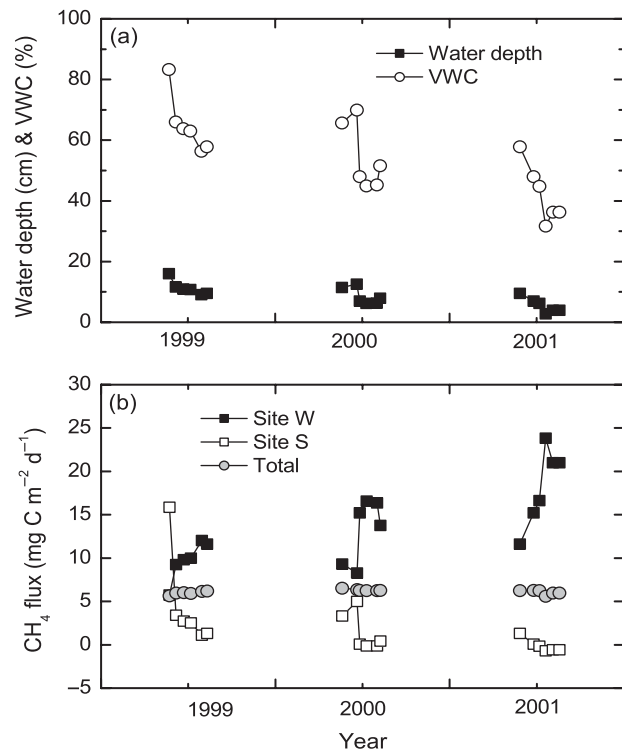
The relationships between the areal fractions of open water deduced from AVHRR imagery and the water depth of the pools obtained from field measurements, and that between the fractions of water and VWC in bare soil are illustrated in Fig. 5a,b, respectively. Both water depth and VWC increased as the fractional value of open water increased, and both relationships were approximated by linear functions.

**Figure 4** Temporal variations in areal fractions of vegetation, bare soil and open water in the study area. The dates of the records for the data plots are listed in Table 1.



**Figure 5** Relationships between areal fractions of open water derived from AVHRR imagery and (a) water depth (WD) of ponds and (b) volumetric water content (VWC) of bare soil. Points represent mean  $\pm$  standard deviations of the values for each measurement period (August 1999, June 2000, September 2000, August 2001). The data for the water fraction (WF) were obtained from four images acquired on 10 August 1999, 19 June 2000, 7 August 2000 and 3 August 2001.

We first estimated the values for water depth of pools and VWC of bare soils from the areal fraction of open water on days for which AVHRR images were available (Table 1) using the linear functions in Fig. 5. Both water depth and VWC decreased with time (Fig. 6a).



**Figure 6** Estimates of temporal variations in (a) water depth of pools and volumetric water content (VWC) of bare soil after the fire, and (b)  $\text{CH}_4$  fluxes from open water, bare soil and the entire burned area.

$\text{CH}_4$  fluxes at sites W and S were calculated by substituting the water depth and VWC given above into the linear functions shown in Fig. 2 (Fig. 6b). The  $\text{CH}_4$  flux at site W increased from spring to summer and with time, whereas that at site S decreased over the years and became almost nil in 2001. The values of the  $\text{CH}_4$  flux from the entire burned area were also computed by weighting the  $\text{CH}_4$  flux at sites W and S with areal coverage of each site and by assuming that the  $\text{CH}_4$  flux

at site V was always zero (Fig. 6b). The integrated CH<sub>4</sub> flux for the entire burned area showed slight variations within and between years and was approximately 5–6 mg C m<sup>-2</sup> day<sup>-1</sup> throughout the study period. Cumulative CH<sub>4</sub> emission rates during the 3-month period from June to August were estimated to be 0.39 g C m<sup>-2</sup> in 1999, 0.45 g C m<sup>-2</sup> in 2000 and 0.48 g C m<sup>-2</sup> in 2001.

### Estimates of CH<sub>4</sub> oxidation in the unburned forest

Using the relationship between CH<sub>4</sub> oxidation and air temperature shown in Fig. 3, seasonal variations in CH<sub>4</sub> oxidation by unburned forest soils were estimated based on the surface air temperature data of the reanalysis dataset of the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) (Kalnay *et al.* 1996). Horizontal resolution of this dataset is latitude 2.5° × longitude 2.5°. Mean daily air temperature data at four grids encompassing Plotnikovo (55.0°N, 82.5°E; 55.0°N, 85.0°E; 57.5°N, 82.5°E; 57.5°N, 85.0°E) from 1998 to 2001 were downloaded from the website (<http://www.cdc.noaa.gov/cdc/reanalysis/>). We averaged temperatures for the four grids and substituted them into the equation in Fig. 3 to represent the temperature at Plotnikovo. Mean daily CH<sub>4</sub> oxidation rates were calculated, and the cumulative rates during the 3-month period from June to August were estimated to be 0.41 ± 0.11 g C m<sup>-2</sup> (mean ± 95% confidence interval) in 1998, 0.39 ± 0.11 g C m<sup>-2</sup> in 1999, 0.40 ± 0.10 g C m<sup>-2</sup> in 2000 and 0.38 ± 0.10 g C m<sup>-2</sup> in 2001.

## DISCUSSION

### Changes in the surface and soil environment after fire

Forest fires result in various changes in the physical, chemical and biological aspects of the surface environment. One important effect of fire is the destruction of the thick organic layer (Lucarotti 1980). Soil organic matter (SOM) consumption associated with wildfires has been studied using peat cores (Pitkänen *et al.* 1999; Turetsky and Wieder 2001), remote sensing analysis of postfire landscapes (Kasischke *et al.* 1995) and modeling (Zhuang *et al.* 2003). The amount of SOM lost during a single fire event has been estimated to be in the range of 2.5–3.0 kg C m<sup>-2</sup> in the boreal forest zone of Alaska (Kasischke *et al.* 1995), 2.5 kg C m<sup>-2</sup> in a peatland of eastern Finland (Pitkänen *et al.* 1999), and 2.2 kg C m<sup>-2</sup> in a peatland of western Canada (Turetsky and Wieder 2001). In the present study area, the thickness of the soil organic layer decreased by approximately 60 cm (Table 5). The amount of SOM, which

was calculated as the product of the thickness, bulk density and total carbon content of the H horizon, was estimated to be 73 kg C m<sup>-2</sup> and 31 kg C m<sup>-2</sup> at the unburned and burned areas, respectively. Assuming that the difference between these amounts corresponds to the loss of soil carbon during the fire, the area lost is 42 kg C m<sup>-2</sup>. This value is considerably larger than the estimates given above, probably because the West Siberian plain is an extremely paludinous area characterized by very large carbon stocks from peat accumulation (Yefremov and Yefremova 2001). Moreover, forest soils in this plain are currently well drained and therefore burn easily.

Our results indicated that soil moisture drastically increased after the disturbance by fire. Desyatkin (1993) reported that, in eastern Siberia, thermokarsts (also called “*alas*”) were formed after severe forest fires by subsidence associated with permafrost thawing. The center of each *alas* was very wet, with the formation of ponds from 10 to 100 m in diameter, because water was supplied from the thawed permafrost. In contrast, a model simulation for black spruce forests in Alaska by Zhuang *et al.* (2003) suggested that the soil moisture of the burned stands would be much lower than that in the unburned stands during approximately the first 50-year period after a fire because of higher evaporation because more radiation reached the soil surface with a reduced canopy and greater drainage was associated with a thicker active layer after the fire. Lucarotti (1980) revealed that soil moisture was unaffected by fire in the *Picea* woodlands of eastern Canada. The present study area became wet after the fire, although it was not located in a permafrost region. A possible explanation is that in the West Siberian plain, surface soil moisture is determined by a balance between precipitation and evapotranspiration because the plain is extremely flat and it is difficult for water to flow laterally in and on the soil. The fire burned trees down and caused a remarkable decrease in transpiration by trees, hence the soil surface became wet.

In several studies, it was noted that soil temperatures at burned sites exceeded those at unburned sites throughout the growing season, and that fire effects may take several years to influence the soil temperature (Burke *et al.* 1997; O'Neill *et al.* 2003; Zhuang *et al.* 2003). Our results indicated that the mean air temperature for each study period in the burned area was 0.3–0.8°C higher than that in the unburned area, although we could not compare soil temperatures because the measurement times differed among the sites. The range of air temperatures was also greater in the burned area than at the unburned site. This higher and more variable temperature in the burned area was attributed to the loss of shading provided by the plant canopy (Fig. 1).



A decrease in latent heat led to a decrease in transpiration because of plant losses and also resulted in a higher air temperature in the burned area.

### Control of CH<sub>4</sub> flux

Studies to date have indicated that factors controlling CH<sub>4</sub> emission from aquatic environments include soil moisture, soil temperature (e.g. Bellisario *et al.* 1999; Bubier *et al.* 1995; Christensen *et al.* 2003), substrate type (Crill *et al.* 1991; Svensson and Sundh 1992) and vegetation (Whiting and Chanton 1992). The most important among these factors is soil moisture because it affects the degree of anaerobicity in the soil profile. In many studies, the relationship between the CH<sub>4</sub> flux and water-table position was reported based on field measurements (Bubier 1995; Dise *et al.* 1993; Fiedler and Sommer 1999; Heikkinen *et al.* 2002; Liblik *et al.* 1997; Nykänen *et al.* 1998; Sebacher *et al.* 1986) and laboratory experiments (Daulat and Clymo 1998; MacDonald *et al.* 1998). Correlation of CH<sub>4</sub> flux and soil VWC has also been reported (Christensen *et al.* 1995; Morishita *et al.* 2003). These studies showed that a higher water-table level and water content led to a higher CH<sub>4</sub> emission. Our results (Fig. 2b) are in agreement with these previous findings.

When the water-table position was above the soil surface, however, the higher water level was associated with a lower CH<sub>4</sub> flux (Fig. 2a). Similar results have been reported previously (Juutinen *et al.* 2001; Kelley *et al.* 1995; Moore *et al.* 1990; Otter and Scholes 2000; Weyhenmeyer 1999). In general, methane-oxidizing bacteria consume a large fraction of the methane formed in methanogenic habitats before it reaches the atmosphere (Kiene 1991). The CH<sub>4</sub> oxidation potential is likely to increase by the longer water-column pathway, resulting in lower diffusive CH<sub>4</sub> fluxes across the sediment–water interface.

The CH<sub>4</sub> flux was almost zero at the plant-invaded site in the burned area and no relationship was found between the flux and environmental variables. Soil moisture at this site was relatively low (approximately 25%) and consistent over time. This low moisture level suppressed the CH<sub>4</sub> emission from the soil to the atmosphere. The limited variations in soil moisture and soil temperature during the study periods may account for the lack of a correlation.

Effects of soil temperature and moisture on the CH<sub>4</sub> oxidation rate at the unburned site were analyzed by Nakano *et al.* (2004). In the present study, a relationship between air temperature and CH<sub>4</sub> oxidation rate was demonstrated (Fig. 3) and temporal variations in CH<sub>4</sub> oxidation were estimated based on the air temperature data from the NCEP/NCAR reanalysis. Although few studies have focused on air temperature as a

controlling factor of CH<sub>4</sub> oxidation rate, we consider that air temperature is a good predictor of CH<sub>4</sub> flux because long-term and global-scale air temperature data, unlike soil temperatures, can be obtained by using datasets such as the NCEP/NCAR reanalysis dataset.

### CH<sub>4</sub> fluxes before and after a fire

In the present study, temporal variations in CH<sub>4</sub> flux during the 3-year period after a fire were investigated based on field measurements and analysis of NOAA AVHRR imagery. In the study area, CH<sub>4</sub> oxidation in the dry soils of the unburned forest predominated and the cumulative CH<sub>4</sub> oxidation rate during the summer (from June to August), which was nearly consistent during the 4-year period (1998–2001), amounted to approximately 0.4 g C m<sup>-2</sup>. The surface soil had become extremely wet after the fire and was covered with numerous small pools. As a result, the soil became a net emitter of CH<sub>4</sub> after the fire disturbance.

The soil gradually dried out and the pools became shallower and then disappeared from spring to summer and over the years. This moisture change in the burned area was apparent from both the field survey and the remote sensing analysis (Table 4, Fig. 6). CH<sub>4</sub> emission per unit area from the pools increased with time because CH<sub>4</sub> emission rate shows an inverse relationship with the depth of standing water. In contrast, the CH<sub>4</sub> flux from bare soils decreased as soil moisture decreased. Areal coverage of the pools and bare soil decreased over the years, as these cover types were replaced by herbaceous plants, whose CH<sub>4</sub> flux was almost zero. By weighting CH<sub>4</sub> fluxes at the pools, bare soils and invaded-plant sites according to their areal fractions and adding these values, we could estimate the soil–atmosphere CH<sub>4</sub> exchange in the entire burned area. The total CH<sub>4</sub> flux showed slight seasonal and interannual variations and amounted to approximately 5–6 mg C m<sup>-2</sup> day<sup>-1</sup> throughout the study period (Fig. 6). The cumulative CH<sub>4</sub> emission rates during the summer were calculated to be in the range of 0.39–0.48 g C m<sup>-2</sup>, values within the same order of magnitude as the CH<sub>4</sub> oxidation rate in the unburned forest. However, because the soil is becoming still drier and the pools are disappearing, we predict that the burned soils will return to CH<sub>4</sub> consumer status in several years.

We are not aware of any published studies on the temporal changes in CH<sub>4</sub> flux after a fire to compare our results with. However, in a few studies, changes in the CH<sub>4</sub> exchange between soils and the atmosphere before and after forest fires were examined (Burke *et al.* 1997; Kim and Tanaka 2003). Burke *et al.* (1997) carried out CH<sub>4</sub> and CO<sub>2</sub> flux measurements at several sites with different fire histories (fires had occurred from 0 to 7 years before the measurements) in black

spruce stands and jack pine stands in Canada. All sites were net sinks of atmospheric CH<sub>4</sub>, and the burned sites tended to be slightly stronger CH<sub>4</sub> sinks than the unburned controls after a few years of recovery. They observed a net CH<sub>4</sub> emission shortly after a fire (a few weeks) and suggested that this emission may have been of pyrogenic origin. Kim and Tanaka (2003) measured the fluxes of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O before and after a prescribed fire in the boreal forest of interior Alaska. They reported that most CH<sub>4</sub> after the fire was oxidized by soil, but that some was emitted to the atmosphere above the burned stand. In addition, the CH<sub>4</sub> flux from soil increased from 7% to 142% after the fire, presumably because thawing of the frozen soil was accelerated by fire, and CH<sub>4</sub> may have been released from permafrost. Unlike these studies, our results indicated that the surface soil changed from a net CH<sub>4</sub> oxidizer to an emitter after the fire.

A key parameter of surface CH<sub>4</sub> exchange before and after the fire was soil moisture. Soil moisture in the burned area varied temporally and from site to site depending on the soil type, microrelief and vegetation cover. Remotely sensed satellite images are appropriate for monitoring surface moisture conditions over broad areas. Combining field measurements with the analysis of satellite images is a good strategy for evaluating the soil-atmosphere CH<sub>4</sub> exchange after fire disturbance.

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## REFERENCES

- Asner GP, Wessman CA, Priette JL 1997: Unmixing the directional reflectances of AVHRR sub-pixel land covers. *IEEE Trans. Geosci, Remote Sensing*, **35**, 868–878.
- Auclair AND, Carter TB 1993: Forest wildfires as a recent source of CO<sub>2</sub> at northern latitudes. *Can. J. For. Res.*, **23**, 1528–1536.
- Bellisario LM, Bubier JL, Moore TR, Chanton JP 1999: Controls on CH<sub>4</sub> emissions from a northern peatland. *Global Biogeochem. Cycles*, **13**, 81–91.
- Borken W, Brumme R, Xu Y-J 2000: Effects of prolonged soil drought on CH<sub>4</sub> oxidation in a temperate spruce forest. *J. Geophys. Res.*, **105D**, 7079–7088.
- Bubier JL 1995: The relationship of vegetation to methane emission and hydrochemical gradients in northern peatlands. *J. Ecol.*, **83**, 403–420.
- Bubier JL, Moore TR, Bellisario L, Comer NT, Crill PM 1995: Ecological controls on methane emissions from a northern peatland complex in the zone of discontinuous permafrost, Manitoba, Canada. *Global Biogeochem. Cycles*, **9**, 455–470.
- Burke RA, Zepp RG, Tarr MA, Miller WL, Stocks BJ 1997: Effect of fire on soil-atmosphere exchange of methane and carbon dioxide in Canadian boreal forest sites. *J. Geophys. Res.*, **102D**, 29 289–29 300.
- Cahoon DR Jr, Stocks BJ, Levine JS, Cofer WR III, Pierson JM 1994: Satellite analysis of the severe 1987 forest fires in northern China and southeastern Siberia. *J. Geophys. Res.*, **99D**, 18 627–18 638.
- Castro MS, Steudler PA, Melillo JM, Aber JD, Bowden RD 1995: Factors controlling atmospheric methane consumption by temperate forest soils. *Global Biogeochem. Cycles*, **9**, 1–10.
- Christensen TR, Jonasson S, Callaghan TV, Havström M 1995: Spatial variation in high-latitude methane flux along a transect across Siberian and European tundra environments. *J. Geophys. Res.*, **100D**, 21 035–21 045.
- Christensen TR, Ekberg A, Ström L, Mastepanov M, Panikov N, Öquist M *et al.* 2003: Factors controlling large-scale variations in methane emissions from wetlands. *Geophys. Res. Lett.* **30**, 1414, doi:10.1029/2002GL016848.
- Conard SG, Sukhinin AI, Stocks BJ, Cahoon DR, Davidenko EP, Ivanova GA 2002: Determining effects of area burned and fire severity on carbon cycling and emissions in Siberia. *Climatic Change*, **55**, 197–211.
- Crill PM, Harriss RC, Bartlett KB 1991: Methane flux from terrestrial wetland environments. In *Microbial Production and Consumption of Greenhouse Gases: Methane, Nitrogen Oxides, and Halomethanes*, Ed. JE Rogers and WB Whitman, pp. 91–110, American Society for Microbiology, Washington.
- Daulat WE, Clymo RS 1998: Effects of temperature and water table on the efflux of methane from peatland surface cores. *Atmos. Environ.*, **32**, 3207–3218.
- Desyatkin RV 1993: Syngenetic soil salinization during thermokarst alas formation. *Eurasian Soil Sci.*, **25**, 38–46.
- Dise NB, Gorham E, Verry ES 1993: Environmental factors controlling methane emissions from peatlands in northern Minnesota. *J. Geophys. Res.*, **98**, 10 583–10 594.
- Dixon RK, Krankina ON 1993: Forest fires in Russia: carbon dioxide emissions to the atmosphere. *Can. J. For. Res.*, **23**, 700–705.
- Fiedler S, Sommer M 1999: Methane emissions, groundwater levels and redox potentials of common wetland soils in a temperate-humid climate. *Global Biogeochem. Cycles*, **14**, 1081–1093.
- French NHF, Kasischke ES, Stocks BJ, Mudd JP, Martell DL, Lee BS. 2000: Carbon release from fires in the North American boreal forest. In *Fire, Climate Change, and Carbon Cycling in the Boreal Forest*. Ed. ES Kasischke and BJ Stocks, pp. 377–388, Springer-Verlag, New York.
- Garcia-Haro FJ, Gilabert MA, Melia J 2001: Monitoring fire-affected areas using Thematic Mapper data. *Int. J. Remote Sen.*, **22**, 533–549.
- Goodrum G, Kidwell KB, Winston W 1999: NOAA KLM User's Guide. NOAA, Washington, D.C.

- Heikkinen JEP, Elsakov V, Martikainen PJ 2002: Carbon dioxide and methane dynamics and annual carbon balance in tundra wetland in NE Europe, Russia. *Global Biogeochem. Cycles* **16**, 1115, doi:10.1029/2002GB001930.
- Isaev AS, Korovin GN, Bartalev SA *et al.* 2002: Using remote sensing to assess Russian forest fire carbon emissions. *Clim. Change*, **55**, 235–249.
- Juutinen S, Alm J, Martikainen P, Silvola J 2001: Effects of spring flood and water level draw-down on methane dynamics in the littoral zone of boreal lakes. *Freshwater Biology*, **46**, 855–869.
- Kalnay E, Kanamitsu M, Kistler R *et al.* 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.*, **77**, 437–471.
- Kasischke ES 2000: Boreal ecosystems in the global carbon cycle. In *Fire, Climate Change, and Carbon Cycling in the Boreal Forest*. Ed. ES Kasischke and BJ Stocks, pp. 377–388, Springer-Verlag, New York.
- Kasischke ES, Bruhwiler LP 2003: Emissions of carbon dioxide, carbon monoxide, and methane from boreal forest fires in 1998. *J. Geophys. Res.*, **108D**, 8146, doi:10.1029/2001JD000461.
- Kasischke ES, French NHF, Bourgeau-Chavez LL, Christensen NL 1995: Jr Estimating release of carbon from 1990 and 1991 forest fires in Alaska. *J. Geophys. Res.*, **100D**, 2941–2951.
- Kelley CA, Martens CS, Ussler W 1995: III. Methane dynamics across a tidally flooded riverbank margin. *Limnol. Oceanogr.*, **40**, 1112–1129.
- Kiene RP 1991: Production and consumption of methane in aquatic systems. In *Microbial Production and Consumption of Greenhouse Gases: Methane, Nitrogen Oxides, and Halomethanes*, Ed. JE Rogers and WB Whitman, pp. 111–146, American Society for Microbiology, Washington.
- Kim Y, Tanaka N 2003: Effect of forest fire on the fluxes of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O in boreal forest soils, interior Alaska. *J. Geophys. Res.*, **108D**, 8154, doi:10.1029/2001JD000663, 2003.
- Lapshina ED, Mouldiyarov EY, Vasiliev SV 2001: Analyses of key area studies. In *Carbon Storage and Atmospheric Exchange by West Siberian Peatlands*. Ed. W. Bleuten and ED Lapshina, pp. 23–42, Utrecht University, Utrecht.
- Levine JS, Cofer WR III, Sebacher DI *et al.* 1990: The effects of fire on biogenic emissions of methane and nitric oxide from wetlands. *J. Geophys. Res.*, **95D**, 1853–1864.
- Liblik LK, Moore TR, Bubier JL, Robinson SD 1997: Methane emissions from wetlands in the zone of discontinuous permafrost: Fort Simpson, Northwest Territories, Canada. *Global Biogeochem. Cycles*, **11**, 485–494.
- Lucarotti CJ 1980: The effect of fire and forest regeneration on mesofauna populations and microfungus species in lichen woodland soils. *McGill Subarctic Research Paper*, **32**, 7–26.
- MacDonald JA, Fowler D, Hargreaves KJ, Skiba U, Leith ID, Murray MB 1998: Methane emission rates from a northern wetland: response to temperature, water table and transport. *Atmos. Environ.*, **32**, 3219–3227.
- Moore T, Roulet N, Knowles R 1990: Spatial and temporal variations of methane flux subarctic/northern boreal fens. *Global Biogeochem. Cycles*, **4**, 29–46.
- Morishita T, Hatano R, Desyatkin RV 2003: CH<sub>4</sub> flux in an alas ecosystem formed by forest disturbance near Yakutsk, Eastern Siberia, Russia. *Soil Sci. Plant Nutr.*, **49**, 369–377.
- Nakano T, Kuniyoshi S, Fukuda M 2000: Temporal variation in methane emission from tundra wetlands in a permafrost area, northeastern Siberia. *Atmos. Environ.*, **34**, 1205–1213.
- Nakano T, Inoue G, Fukuda M. 2004: Methane consumption and soil respiration by a birch forest in West Siberia. *Tellus* **56B**: 223–229.
- Nykänen H, Alm J, Silvola J, Tolonen K, Martikainen PJ 1998: Methane fluxes on boreal peatlands of different fertility and the effect of long-term experimental lowering of the water table on flux rates. *Global Biogeochem. Cycles*, **12**, 53–69.
- Nykänen H, Heikkinen JEP, Pirinen L, Tiilikainen K, Martikainen PJ 2003: Annual CO<sub>2</sub> exchange and CH<sub>4</sub> fluxes on a subarctic tundra mire during climatically different years. *Global Biogeochem. Cycles*, **17**, 1018, doi:10.1029/2002GB001861.
- Oleson KW, Sarlin S, Garrison J, Smith S, Privette JL, Emery WJ 1995: Unmixing multiple land-cover type reflectances from coarse spatial resolution satellite data. *Remote Sens. Environ.*, **54**, 98–112.
- O'Neill KP, Kasischke ES, Richter DD 2003: Seasonal and decadal patterns of soil carbon uptake and emission along an age sequence of burned black spruce stands in interior Alaska. *J. Geophys. Res.*, **108D**, 8155, doi:10.1029/2001JD000443.
- Osozawa S 1987: Measurement of soil-gas diffusion coefficient for soil diagnosis. *Soil Phys. Cond. Plant Growth Jpn.*, **58**, 528–535 (in Japanese with English summary).
- Otter LB, Scholes MC 2000: Methane sources and sinks in a periodically flooded South African savanna. *Global Biogeochem. Cycles*, **14**, 97–111.
- Pitkänen A, Turunen J, Tolonen K 1999: The role of fire in the carbon dynamics of a mire, eastern Finland. *Holocene*, **9**, 453–462.
- Priemé A, Christensen S 1997: Seasonal and spatial variation of methane oxidation in a Danish spruce forest. *Soil Biol. Biochem.*, **29**, 1165–1172.
- Sebacher DI, Harriss RC, Bartlett KB, Sebacher SM, Grice SS 1986: Atmospheric methane sources: Alaskan tundra bogs, an alpine fen, and a subarctic boreal marsh. *Tellus*, **38B**, 1–10.
- Shimoda H, Fukue K, Cho K *et al.* 1998: Development of a software package for ADEOS and NOAA data analysis. Proc. of the International Geosciences and Remote Sensing, Seattle, July 6–10., **2**, 674–676.
- Smith KA, Dobbie KE, Ball BC *et al.* 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.
- Svensson BH, Sundh I 1992: Factors affecting methane production in peat soils. *Suo*, **43**, 183–190.
- Takeuchi W, Nakano T, Ochi S, Yasuoka Y. Monitoring of fire-affected areas in western Siberia using spectral mixture

- analysis. Proceedings of International Society for Photogrammetry and Remote Sensing, Technical Commission VII, Hyderabad December 3–6 International Symposium on Resource and Environmental Monitoring 2002; 382–387.
- Takeuchi W, Tamura M, Yasuoka Y 2003: Estimation of methane emission from west Siberian wetland by scaling technique between NOAA AVHRR and SPOT HRV. *Remote Sens. Environ.*, **85**, 21–29.
- Turetsky MR, Weider RK 2001: A direct approach to quantifying organic matter lost as a result of peatland wildfire. *Can. J. For. Res.*, **31**, 363–366.
- Weyhenmeyer CE 1999: Methane emissions from beaver ponds: rates, patterns, and transport mechanisms. *Global Biogeochem. Cycles*, **13**, 1079–1090.
- Whalen SC, Reeburgh WS 1992: Interannual variations in tundra methane emission: a 4-year time series at fixed sites. *Global Biogeochem. Cycles*, **5**, 261–273.
- Whiting GJ, Chanton JP 1992: Plant-dependent CH<sub>4</sub> emission in a subarctic Canadian fen. *Global Biogeochem. Cycles*, **6**, 225–231.
- Yamagata Y, Sugita M, Yasuoka Y 1997: Development of Vegetation–Soil–Water Index algorithms and application. *J. Remote. Sens. Soc. Jpn.*, **17**, 54–64 (in Japanese with English summary).
- Yefremov SP, Yefremova TT 2001: Present stocks of peat and organic carbon in bog ecosystems of west Siberia. In *Carbon Storage and Atmospheric Exchange by West Siberian Peatlands*. Ed. W Bleuten and ED Lapshina, pp. 73–78, Utrecht University, Utrecht.
- Zhuang Q, McGuire AD, O'Neill KP, Harden JW, Romanovsky VE, Yarie J 2003: Modeling soil thermal and carbon dynamics of a fire chronosequence in interior Alaska. *J. Geophys. Res.*, **108D**, 8147, doi:10.1029/2001JD001244.
- Zoltai SC, Morrissy LA, Livingston GP, de Groot WJ 1998: Effects of fires on carbon cycling in North American boreal peatlands. *Environ. Rev.*, **6**, 13–24.