Changes in surface methane flux after a forest fire in West Siberia

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1. INTRODUCTION

Methane (CH_4) is a strong greenhouse gas that is currently the second largest contributor to the anthropogenic greenhouse effect. Given that soils are major global sources and sinks of CH_4, they play an important role in regulating atmospheric CH_4 concentrations. Natural wetlands are significant sources of CH_4 emission to the atmosphere (e.g., Christensen et al. 1995; Nakano et al. 2000; Nykänen et al. 2003), whereas aerobic environments such as upland forest soils consume CH_4 via microbial oxidation (e.g., Priemé and Christensen 1997; Borken et al. 2000; Smith et al. 2000). The direction and rate of the net CH_4 exchange between soils and the atmosphere are usually 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 and nitrogen availability). Among these factors, soil moisture is the major determinant of whether soils are net CH_4 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). Associated with important consequences for carbon storage in boreal forests and pulses of trace gases to the atmosphere through combustion, fire also causes long-term surface disturbances and affects gas exchange between soil and the atmosphere. Carbon emissions during burning and the post-fire release of CO_2 have been investigated using satellite imagery, historical statistics, modeling, and field soil surveys (Auclair and Carter 1993; Dixon and Krankina 1993; Cahoon et al. 1994; Zoltai et al. 1998; Pitkänen et al. 1999; Turetsky and Wieder 2001; Conard et al. 2002; Kasischke and Bruhwiler 2003). In addition, changes in the surface CH_4 flux before and after controlled fires (Levine et al. 1990; Kim and Tanaka 2003) have been investigated using chronosequences (Burke et al. 1997). However, few studies have examined the continuous variation in soil-atmosphere CH_4 exchange over several years at a particular burned site.

Our study area, located in a boreal forest on the West Siberian Plain, burned 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 varied temporally in the years following the fire. The purpose of this study was to measure the temporal variations in CH_4 exchange between the soil and the atmosphere following a fire disturbance and to quantify the relationships between CH_4 flux and the controlling environmental factors.

2. MATERIALS AND METHODS

2.1 Study sites

The study area was located in a boreal forest (56°52' N, 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 as a result of peat accumulation (Yefremov and

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Yefremova 2001). The study area was covered with a thick organic soil layer derived from peat. The annual mean air temperature was −1.1°C, mean monthly temperatures ranged between −18.6°C and 17.6°C, and annual precipitation was approximately 530 mm (Lapshina et al. 2001). Measurements were made in an unburned forest and in an adjacent area burned in August 1998.

In the unburned area, the forest consisted of white birch (*Betula pendula*) with occasional Scots pine (*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) overlay a thick (approximately 90 cm), black, organic layer (H horizon), which overlay 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 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 with approximately 50-cm high undulations and was entirely covered with fallen trees. The burned area was covered with snow until the beginning of May. Following snowmelt, the surface was flooded but gradually dried up during the summer through evaporation. Although most plants were consumed by the fire in August 1998, the ground surface was gradually recolonized in the summers of the following years, first by liverwort (*Marchantia* spp.) and successively by other herbaceous plants (mainly *Epilobium angustifolium*). The soil had no litter layer, but the black, organic H horizon was about 30 cm thick and overlay a silty mineral B horizon. Some charcoal fragments were included in the upper part of the H horizon. The surface environment in the burned area was classified into one of three categories: open water, unvegetated bare soil, and plant-covered soil; the distribution and areal coverage of each component varied by season and year.

2.2 Field observations

Measurements of net CH_4 flux were conducted using a closed-chamber method at the following sites: unburned forest (site U) and, in the burned area, open water (site W), bare soil (site S), and vegetation (site V) sites. The closed-chamber system comprised a 0.4-m-tall transparent chamber, stainless-steel collars with an enclosure of 0.152 m^2, a portable CH_4/CO_2 analyzer equipped with a semiconductor CH_4 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. The flux measurements were performed during 1-week periods in August 1999, June 2000, and September 2000. Before the initiation of measurements, two collars were embedded in the soil at site U to a depth of 10 cm, and they remained there 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 were left there only for the duration of the study period, because the surface environment at the burned sites changed over time. For the measurements, the chamber was closed for 10 min by fitting it into a water-filled groove in the collar. Sample air was continuously pumped from the chamber through a polyethylene tube to the CH_4 analyzer and back to the chamber at a rate of about 1 dm^3 min^{-1}. CH_4 concentration in the chamber was recorded at 5-s intervals with a data logger (NR-1000, Keyence Co., Osaka, Japan). CH_4 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, while the flux was calculated by linear regression of the concentration changes over the first 3 min at the wetter burned site, which was more prone to ebullition and disturbances. The minimum r^2 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^{-2} d^{-1}. A positive CH_4 flux represented a CH_4 transfer from the soil surface to the atmosphere and a negative flux indicated CH_4 uptake by the soil.

At site U, the flux was measured four times per day for each of two collars for a study on temporal variation in CH_4 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 only measured in September 2000, because herbaceous plants invaded the observation area after the June 2000 measurement.

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, Utah, USA) positioned vertically from the surface into the soil. At site W, the depth of standing water was measured at the time of the flux measurements. The soil temperature, soil moisture, and water depth measurements were performed at five points around each collar immediately following the flux measurements and were 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 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.

3. RESULTS AND DISCUSSION

3.1 Field measurements

Results of the CH_4 flux measurements are presented in Fig. 1. Soil-atmosphere exchanges of CH_4 were always negative at site U, indicating that the forest soil was a net consumer of CH_4 before the fire. Average CH_4 fluxes for each observation period ranged from −2.8 to −4.7 mg C m^{-2} d^{-1}. The maximum uptake rate was observed in June 2000. CH_4 fluxes in the burned area varied greatly with surface environment and observation period. The mean CH_4 flux at the open water site (W) varied between 6.2 and 14.9 mg C m^{-2} d^{-1} and was lowest in June 2000. In contrast, the CH_4 flux from the bare soil (site S) was greatest (9.3 mg C m^{-2} d^{-1}) in June 2000. The CH_4 exchange between soil and the atmosphere was close to zero at site S and V in August 1999 and September 2000.

Fig. 2 shows the results of the transect measurements of pool water depth and VWC of bare and plant-covered soils in the burned area and VWC in the unburned forest. The VWC of the unburned forest soil remained very low throughout the entire study period (approximately 10%). The soil moisture in the burned area was greater than that in the unburned area for every period and at every site. Standing water depth was greatest in June 2000, immediately after snowmelt. Soil moisture in the bare soil was also highest in June 2000. The soil gradually dried out during the summer, and herbaceous plants started to invade the measurement lines in the summer of 2000. The VWC of the plant-covered

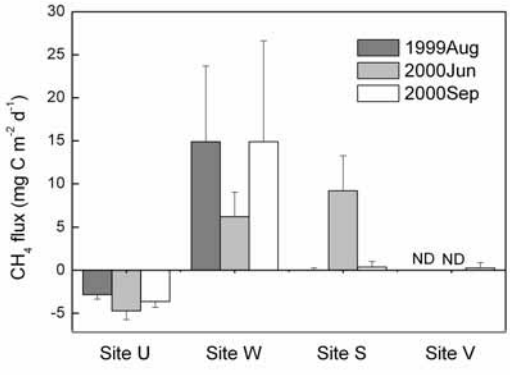

Fig. 1. Average CH_4 fluxes in the unburned area and at the three sites in the burned area. ND means "not determined". Error bars indicate standard deviation.

soils was about 25% in both September 2000 and August 2001.

Our results indicated that soil moisture increased dramatically after the fire disturbance. Desyatkin (1993) reported that in Eastern Siberia, thermokarsts (or "alas") are formed by subsidence associated with the thawing of permafrost following severe forest fires. The center of each alas is very wet with ponds of 10–100 m in diameter, because water is supplied from the thawed permafrost. In contrast, a model simulation for black spruce forests in Alaska suggested that the soil moisture of burned stands would be much lower than that of unburned stands for approximately the first 50-year period following a fire because of higher evaporation, given that more radiation would reach the soil surface with a reduced canopy, and greater drainage associated with a thicker active layer after the fire (Zhuang et al. 2003). Lucarotti (1980) indicated that soil moisture is unaffected by fire in the *Picea* woodlands of eastern Canada. Our study area became wet after the fire even though 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 killed trees, resulting in decreased transpiration by trees; hence, the soil surface became wet.

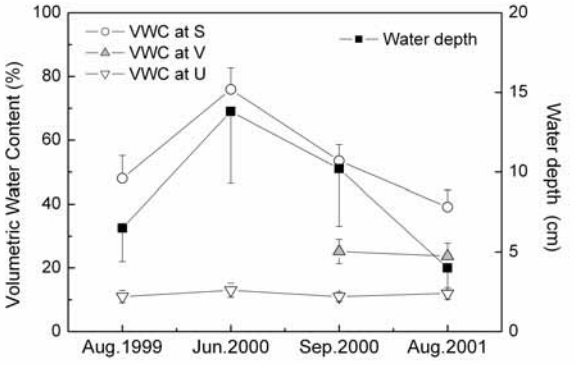

Fig. 2. Mean values for each observation period of the water depth at site W and the volumetric water content at site S, V and U. Error bars indicate standard deviations.

Air temperature recorded at 30-min intervals differed significantly between the burned and the unburned areas for all study periods (paired *t* test, $p < 0.0001$; Table 1). Mean temperatures for each period in the burned area were 0.3–0.8°C higher than those in the unburned area. Temperature variation was also significantly different between the areas; the range of temperature variation was greater in the burned area than in the unburned area.

Table 1. Summary of air temperature data (°C) recorded automatically at 30-min intervals at the burned area and unburned area

	Aug. 1999		June 2000		Sep. 2000	
Site	Burned	Unburned	Burned	Unburned	Burned	Unburned
Mean	10.7	10.3	18.0	17.2	11.5	11.2
Max.	21.3	21.0	32.1	30.8	26.5	26.1
Min.	−1.0	−0.4	2.0	3.1	−0.4	0.3

It has been noted in several studies that soil temperatures at burned sites exceed those at unburned sites throughout the growing season, and that it may take several years for the effects of fire to influence 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 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 at the burned site than at the unburned site. The higher and more variable temperature at

the burned site was attributed to the loss of plant canopy shading. A decrease in latent heat led to decreased transpiration due to plant losses and also resulted in a higher air temperature in the burned area.

3.2 Relationships between CH_4 flux and environmental factors

Spearman's rank correlation coefficients (r_s) for the relationships between individual measurements of CH_4 flux and environmental variables are given in Table 2. At site W, CH_4 flux was negatively correlated with water depth. The flux was positively correlated with air and soil temperatures and VWC at site S. We found no significant correlations at site V. The relationships among CH_4 flux, water depth, and VWC are presented in Fig. 3. The CH_4 fluxes after logarithmic transformation were approximated by linear functions of the water depth and VWC. CH_4 flux in the unburned forest was negatively correlated with air temperature (Table 2), indicating that soil CH_4 oxidation increased as temperature increased. The relationship between mean daily CH_4 oxidation and mean daily air temperature is shown in Fig. 4. The oxidation rate was approximated by a linear function of the air temperature.

Studies to date have indicated that the factors controlling CH_4 emission from aquatic environments include soil moisture, soil temperature (e.g., Bubier et al. 1995; Bellisario et al. 1999; Christensen et al. 2003), substrate type (Crill et al. 1991; Svensson and Sundh 1992), and vegetation (Whiting and Chanton 1992). Soil moisture is the most important of these factors, because it affects the degree of anaerobicity in the soil profile. In many studies, the relationship between CH_4 flux and water table position has been reported based on field measurements (e.g., Nykänen et al. 1998; Fiedler and Sommer 1999; Heikkinen et al. 2002) and laboratory experiments (Daulat and Clymo 1998; MacDonald et al. 1998). A correlation between CH_4 flux and soil VWC has also been reported (Christensen et al. 1995; Morishita et al. 2003). These studies have shown that a higher water table and higher water content lead to higher CH_4 emission; our results (Fig. 3b) agreed with these previous findings.

When the water table was above the soil surface, however, the higher water level was associated with a lower CH_4 flux (Fig. 3a). Similar results have been reported previously (Kelley et al. 1995; Weyhenmeyer 1999; Otter and Scholes 2000; Juutinen et al. 2001). In general, a large fraction of methane formed in methanogenic habitats is consumed by methane-oxidizing bacteria before reaching the atmosphere (Kiene 1991). The CH_4 oxidation potential is likely to be increased by the longer water column pathway, resulting in lower diffusive CH_4 fluxes across the sediment-water interface.

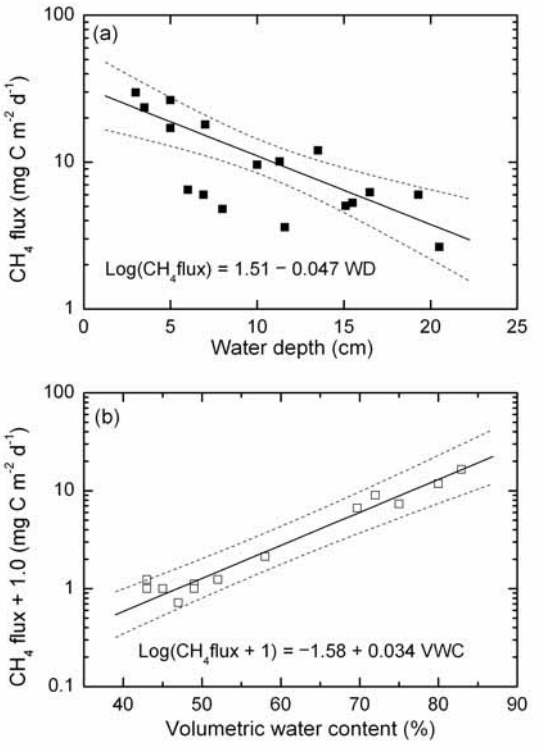

Fig. 3. Relationships between CH_4 flux and (a) water depth at site W, and (b) volumetric water content (VWC) at site S. Lines indicate linear regression (solid line) and the 95% confidence bands (broken lines) for the regression.

Table 2. Spearman's rank correlation coefficients (r_s) for the relationships between CH_4 flux and environmental variables for the burned sites and unburned site

	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.

At the plant-invaded site in the burned area, the CH_4 flux was almost zero, and no relationship was found between the flux and environmental variables. Soil moisture at this site was relatively low (about 25%) and consistent over time. This low moisture level suppressed CH_4 emission from the soil to the atmosphere. The limited variation in soil moisture and soil temperature during the study periods may account for the lack of a correlation.

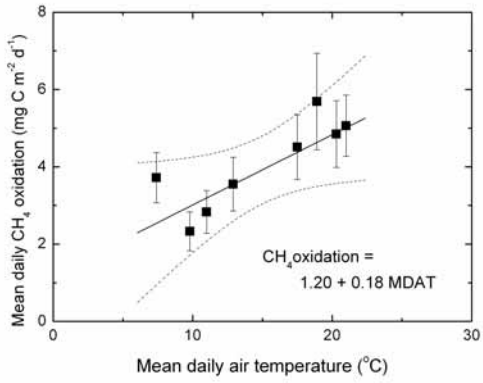

Fig. 4. Relationship between mean daily CH_4 oxidation rate and mean daily air temperature in the unburned birch forest (site U). Error bars indicate standard deviations. Lines indicate linear regression (solid line) and the 95% confidence bands (broken lines) for the regression.

While no published studies have evaluated temporal changes in CH_4 flux following fires, a few studies have examined the changes in CH_4 exchange between soils and the atmosphere before and after forest fires (Burke et al. 1997; Kim and Tanaka 2003). Burke et al. (1997) performed CH_4 and CO_2 flux measurements at several sites with different fire histories (fires had occurred 0–7 years before the measurements) in black spruce stands and jack pine stands in Canada. All sites were net sinks of atmospheric CH_4, and the burned sites tended to be slightly stronger CH_4 sinks than the unburned controls after several years of recovery. A net CH_4 emission was observed a few weeks after a fire and may have been of pyrogenic origin. Kim and Tanaka (2003) measured the fluxes of CO_2, CH_4, and N_2O before and after a prescribed fire in the boreal forest of interior Alaska. They reported that most CH_4 after the fire was oxidized by soil, but that some was emitted to the atmosphere. In addition, the CH_4 flux from soil increased from 7 to 142% after the fire, presumably because thawing of the frozen soil was accelerated by fire, and CH_4 may have been released from permafrost. In contrast, our results indicated that the surface soil changed from a net CH_4 oxidizer to an emitter after the fire.

4. CONCLUSION

In this study, the CH_4 exchanges between soil and the atmosphere after the forest fire were measured in the West Siberian Plain. The unburned forest soils were consistently very dry, and

CH_4 oxidation dominated for the entire study period. In contrast, CH_4 fluxes in the burned area were highly variable. The surface of the burned area was classified into one of three categories: bare soil, open water, or recolonized by herbaceous plants; the fractional coverage of these elements has changed seasonally and annually since the fire. At the open water site, CH_4 was emitted from the surface to the atmosphere and the emission rate was negatively correlated with the depth of standing water. CH_4 flux at the bare soil site showed the positive relationship with the soil volumetric water content. CH_4 exchange was close to zero at the plant-covered site due to low soil moisture. In conclusion, soil moisture was a key parameter in surface CH_4 exchange both before and after fire. Since the soil moisture in the burned area varied temporally and with site, depending on soil type, microrelief, and vegetation cover, monitoring surface moisture conditions over broad areas using a remotely sensed data such as satellite images would be appropriate for estimation of temporal changes in CH_4 fluxes following the fire.

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