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TELLUS

Methane consumption and soil respiration by a birch forest soil in West Siberia

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ABSTRACT

Methane and carbon dioxide fluxes were measured in a birch forest soil in West Siberia, in August 1999, June 2000 and September 2000. The study site had a very thick organic horizon that was subject to drought during the observation periods. The soils always took up CH_4, while CO_2 was released from the surface to the atmosphere. CH_4 consumption and CO_2 emission rates ranged from 0.092 to 0.28 mg C m^{-2} h^{-1} and from 110 to 400 mg C m^{-2} h^{-1} respectively. The CH_4 consumption rate and soil temperatures showed significant relationships for individual measurements. The soil respiration rate was weakly correlated with individual soil temperatures. This study examined the effect of current and lagged soil temperatures at a depth of 5 cm on CH_4 consumption and soil respiration. The variation in the correlation coefficient between CH_4 consumption and lagged soil temperature was greatest at a 4-h lag, whereas that for soil respiration showed a gentle peak at lags from several hours to half a day. This difference in the temperature-related lag effect between CH_4 consumption and soil respiration results from differences in the exchange processes. Neither flux showed any correlation with soil moisture. The limited variation in soil moisture during our observation period may account for the lack of correlation. However, the droughty soil conditions resulted in high gas diffusion and, consequently, high CH_4 consumption.

1. Introduction

Terrestrial ecosystems exchange carbon with the atmosphere. Upland boreal forest soils consume atmospheric methane (CH_4) by microbial oxidation and release large amounts of carbon dioxide (CO_2) by means of root respiration and microbial decomposition of soil organic matter. Therefore, boreal forest soils play a potentially important role in atmospheric CH_4 and CO_2 levels, which influence global climate change.

A number of studies have examined consumption of atmospheric CH_4 in boreal and temperate forests. Studies have taken place mainly in North America (Steudler et al., 1989; Crill, 1991; Castro et al., 1994, 1995; Savage et al., 1997; Gulledge and Schimel, 2000; McLain et al., 2002) and Europe (Born et al., 1990; Dörr et al., 1993; Koschorreck and Conrad, 1993; Priemé et al., 1996; Priemé and Christensen, 1997; Brumme and Borken, 1999; Borken et al., 2000). These studies reported consumption rates ranging from 0 to 0.25 mg C m^{-2} h^{-1}. Studies based on both laboratory and field measurements have also indicated that CH_4 consumption is controlled by soil temperature (Born et al., 1990; Crill, 1991; Whalen and Reeburgh, 1996; Priemé and Christensen, 1997; Savage et al., 1997; Borken et al., 2000), soil moisture (Crill, 1991; Koschorreck and Conrad, 1993; Castro et al., 1994; Czepiel et al., 1995; Whalen and Reeburgh, 1996; Borken et al., 2000; McLain et al., 2002), the amount of N in the soil (Steudler et al., 1989; Castro et al., 1995; Brumme and Borken, 1999) and the amount of soil organic matter (Czepiel et al. 1995; Savage et al., 1997; Brumme and Borken, 1999).

The evolution of CO_2 from soils is commonly called soil respiration. Temperature has a strong impact on rates of soil respiration (Dörr and Münnich, 1987; Lessard et al., 1994; Rayment and Jarvis, 1997; Savage et al., 1997; Boone et al., 1998; Davidson et al., 1998). Soil moisture also controls soil respiration. Extremely dry and wet soils reduce CO_2 production and diffusion, respectively (Dörr and Münnich, 1987; Grant and Rochette, 1994; Keith et al., 1997; Davidson et al., 1998, 2000).

This paper presents measurements of CH_4 and CO_2 fluxes between soils and the atmosphere in summer at a birch forest in West Siberia. The West Siberian Plain is an extremely paludinous area that is characterized by enormous carbon stocks due to peat accumulation (Yefremov and Yefremova, 2001). Our study site also has a thick organic soil layer derived from peat, although it is currently well-drained woodland. White birch forest is very common in the southern part of West Siberia, and the volume

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of growing stock in such forests has been estimated to represent about 40% of the total growing stock in southern West Siberian forests (Alexeyev et al., 1996). However, little up-to-date information exists on CH_4 oxidation and soil respiration in these forests. We aim to (1) evaluate rates of CH_4 consumption and soil respiration from the boreal forest study site in West Siberia and (2) investigate the environmental parameters affecting net CH_4 and CO_2 fluxes from the forest soil.

2. Sites and methods

The research site was located in a boreal forest (lat 56°52′N, long 83°17′E) near Plotnikovo, Tomsk Oblast, in the southern part of the West Siberian Plain. The forest consisted of white birch trees (*Betula pendula*) with occasional Scotch pines (*Pinus sylvestris*). The ground vegetation consisted of shrubs (*Ledum palustre*, *Chamaedaphne calyculata*, *Rubus chamaemorus*) and herbaceous plant communities. The area has an annual mean air temperature of −1.1°C, mean monthly temperatures varying between −18.6°C and 17.6°C throughout the year, and annual precipitation of approximately 530 mm (Lapshina et al., 2001).

A 3 cm thick layer of decomposing litter (L horizon) was underlain with a thick (about 90 cm), black, organic layer (H horizon) derived from bog peat, overlying a silty, mineral horizon (B horizon). Surface soil samples were collected and brought back to Japan in September 2000. The relative gas diffusion coefficient (D/D_0) was determined using Osozawa's (1987) diffusion chamber method with 100 cm^3 undisturbed soil cores. After autoclaving at 105°C, soil core porosity was measured with a volume meter (DIK-1000, Daiki Rika Kogyo Co.). The total carbon and nitrogen contents were determined by dry combustion using a CN analyser (Vario-EL, Elementar Analysensysteme GmbH) equipped with a thermal conductivity detector. The soil properties of the surface organic layer at our study site are summarized in Table 1. The values are the averages and standard deviations of three or four samples.

The CH_4 and CO_2 fluxes were measured using a closed-chamber method. The system comprised an acrylic plastic chamber 0.4 m in height, stainless steel collars, a portable CH_4/CO_2 analyser equipped with a semiconductor CH_4 detector and a solid electrolyte CO_2 detector, and a 12 V lead–acid battery. The chamber was equipped with sampling ports, a thermometer and a battery-operated fan. We also placed a Tedlar bag inside the chamber, which was connected to the outside of the chamber with a 0.25 inch tube, to compensate for pressure changes within the chamber. Two collars, which enclosed 0.152 m^2, were embedded in the soil to a depth of 10 cm before measurements commenced and remained in place throughout the study. The distance between the two collars was about 10 m. Neither collar included live plants, and surface and soil conditions within the collars were similar. The chamber was fitted into a water-filled groove in the collar for the measurements.

Table 1. Soil properties of the surface organic layer (H horizon) in the West Siberia birch forest

	Average	SD
Thickness (m)	0.89	0.056
Bulk density (Mg m^{-3})	0.19	0.017
Porosity (%)	90	2.4
D/D_0*	0.37	0.048
Total C (g g^{-1})	0.43	0.016
Total N (g g^{-1})	0.025	0.0021
C/N	17	1.8

*D/D_0 is the relative gas diffusion coefficient.

Sample air was continuously pumped at a rate of about 1 dm^3 min^{-1} from the chamber through a polyethylene tube to the CH_4/CO_2 analyser and back to the chamber. Signals from the CH_4/CO_2 detectors were outputted as voltage values and recorded at 5 s intervals by a datalogger (NR-1000, Keyence Co.). Inoue et al., (1998) has described the operation and accuracy principles of solid-state CH_4 and CO_2 detectors. To calibrate the detectors, air samples were also taken from the chamber with a syringe before and after flux measurements and placed in 10 ml vacuum vials for analysis. Analysis was conducted with a gas chromatograph equipped with a flame ionization detector for CH_4 and a thermal conductivity detector for CO_2 (GC-14BPTF, Shimadzu Co.). Flux estimates were based on changes in chamber CH_4 and CO_2 concentrations over time, which were measured for 10 min after the chamber enclosed the soil surface. Net fluxes were calculated from the rate constant of the exponential curve fit (Nakano et al., 2004). Observations were conducted over three 1-week periods in August 1999, June 2000 and September 2000. CH_4 and CO_2 fluxes were measured four times per day for each of the two collars: early morning (0300–0600 local time (LT)), morning (0900–1200 LT), afternoon (1500–1800 LT) and night (2100–2400 LT).

The mean differences in the flux values between the two collars and among the three periods were compared statistically using the Mann–Whitney and Kruskal–Wallis tests, respectively (Zar, 1999).

Environmental data were collected concurrently with flux measurements. Air temperature at 1.5 m above ground level and soil temperature at a depth of 5 cm were measured every 30 min using a datalogger with two thermistor probes (SK-L200T, Sato Keiryoki Manufacturing Co.). Soil moisture at the time of the flux measurements was determined using time-domain reflectometry (TDR) probes (0–12 cm depth; HydroSense, Campbell Scientific Inc.) positioned vertically from the surface into the soil. The TDR results were cross-checked using the gravimetric method with 100 cm^3 undisturbed soil cores. Soil temperatures (5 and 10 cm depths) at the time of the flux measurements were also measured using thermocouple thermometers (ST-920, Testoterm Co.).

Table 2. Summary of net CH_4 and CO_2 fluxes and environmental variables in the West Siberia birch forest

		Aug. 1999	Jun. 2000	Sep. 2000
CH_4 flux	*n*	5	14	24
(mg C m^{-2} h^{-1})	Mean	−0.12	−0.20	−0.15
	SE	0.013	0.011	0.006
	Range	−0.14 to −0.092	−0.28 to −0.15	−0.20 to −0.11
CO_2 flux	*n*		17	24
(mg C m^{-2} h^{-1})	Mean	ND	280	200
	SE	ND	15	9.4
	Range	ND	180 to 400	110 to 310
Air temp. (°C)	Mean	11.1	21.9	9.1
	Range	10.3 to 12.0	12.7 to 30.7	1.2 to 13.8
Soil temp. (°C)	Mean	10.4	15.6	12.5
at 5 cm depth	Range	9.4 to 11.5	13.5 to 18.3	8.6 to 14.6
Vol. water	Mean	11.1	10.7	11.5
content (%)	Range	8 to 20	7 to 15	8 to 14

SE, standard error; ND, not determined.

3. Results

During all gas samplings, CH_4 and CO_2 fluxes were consistently negative and positive respectively, indicating that atmospheric CH_4 was consumed by the soils and CO_2 was released from the surface to the atmosphere (Table 2). Since the flux values did not differ significantly between the subsites for either CH_4 or CO_2 (Mann–Whitney test, $p > 0.10$), the mean fluxes were computed from all the measurements made in each period. The mean values differed significantly among the measurement periods (Kruskal–Wallis test for CH_4 flux and Mann–Whitney test for CO_2 flux, $p < 0.01$). The mean CH_4 consumption rate ranged from 0.12 to 0.20 mg C m^{-2} h^{-1}, and individual values ranged from 0.092 to 0.28 mg C m^{-2} h^{-1}. The highest value was observed in June 2000, when air and soil temperatures were also highest. CO_2 fluxes were three orders of magnitude greater than CH_4 influx, and individual measurements ranged from 110 to 400 mg C m^{-2} h^{-1}. The mean value was also higher in June 2000 than in September 2000. Soil moisture (volumetric water content) was consistently low (about 10%) during the study periods, although soil temperature showed seasonal variation. Since bulk density was very low and the soil was droughty, the relative gas diffusion coefficient, D/D_0, was high (Table 1).

Individual CH_4 and CO_2 fluxes showed a negative relationship, indicating high soil respiration at times of high CH_4 consumption (Fig. 1). Savage et al. (1997) found a similar relationship for spatial distributions of CH_4 and CO_2 fluxes. Our results suggest that this negative relationship is appropriate for temporal variations in CH_4 and CO_2 fluxes, as well as for the spatial variation described by Savage et al. (1997).

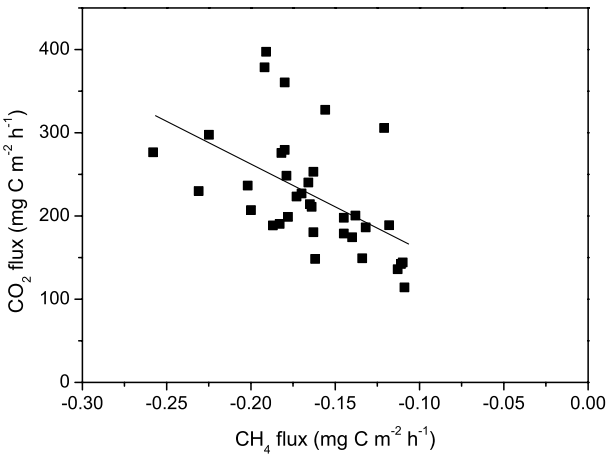

Fig 1. Relationship between individual CH_4 and CO_2 fluxes.

Significant rank correlations were found between individual CH_4 consumption rates and air and soil (5 cm depth) temperatures, while individual soil respiration rates correlated with the soil temperature at 5 cm depth (Table 3). Mean rates of CH_4 consumption and soil respiration for each measurement period also positively related to the mean soil temperature (Fig. 2).

4. Discussion

4.1. CH_4 consumption

Methane uptake rates in temperate and boreal forests have a large temporal and spatial variation. Researchers have found

Table 3. Spearman's rank correlation coefficient (r_s) for correlations between individual measurements of gas exchange rates and environmental variables

	CH_4 consumption	Soil respiration
Air temp.	0.40*	NS
Soil temp. (5 cm)	0.50**	0.38*
Soil temp. (10 cm)	NS	NS
Vol. water content	NS	NS

NS, not significant at $p = 0.05$.
*$p < 0.05$.
**$p < 0.01$.

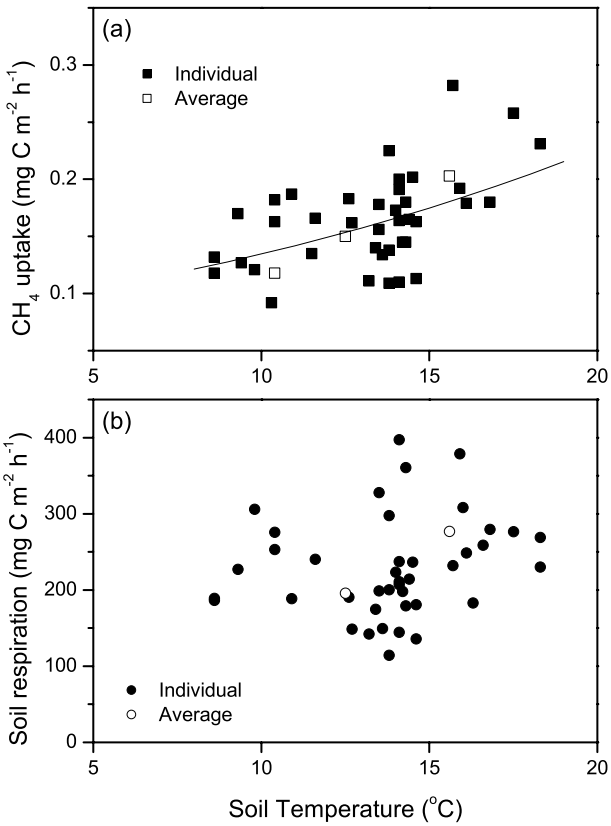

Fig 2. Relationships between soil temperature at 5 cm depth and (a) CH_4 consumption and (b) soil respiration for individual measurements and averages. The exponential regression line (solid line) is significant ($p < 0.01$).

summer-time (June to September) values of 0.084 to 0.11 mg C m^{-2} h^{-1} in a mixed deciduous-coniferous forest in New Hampshire (Crill, 1991), 0.08 to 0.056 mg C m^{-2} h^{-1} in several soils in Germany (Koschorreck and Conrad, 1993), 0.09 to 0.22 mg C m^{-2} h^{-1} in a red pine plantation and a mixed hardwood stand in central Massachusetts (Castro et al., 1995) and 0.01 to 0.04 mg C m^{-2} h^{-1} in an upland birch/aspen forest in interior Alaska (Gulledge and Schimel, 2000). Our results were relatively high compared with the ranges found in these previous studies.

Gas transport is generally considered a major factor affecting the CH_4 consumption rate (Potter et al., 1996), as gas transport capabilities regulate CH_4 diffusion from the atmosphere to the oxidizing sites. Accordingly, a number of studies have found that soil moisture (Koschorreck and Conrad, 1993; Castro et al., 1994; Lessard et al., 1994; Whalen and Reeburgh, 1996; Borken et al., 2000) and soil texture (Born et al., 1990; Dörr et al., 1993) are most important in controlling the CH_4 consumption rate, as these factors influence soil gas diffusivity. We found no significant relationship between measured soil moisture and CH_4 consumption, but the limited variation in soil moisture during the study periods may account for this finding. Throughout the study period, the site had a very low volumetric water content and high relative gas diffusivity (D/D_0). The high diffusivity probably caused high CH_4 consumption rates in our results.

Individual CH_4 fluxes are significantly correlated with soil temperature at 5 cm depth (Fig. 2a and Table 3). The mean fluxes for each measurement period also showed positive relationships with soil temperature. Previous studies have found relatively weak correlations between soil temperature and CH_4 consumption when Q_{10} values ranged from 1.2 to 2.0 (Crill, 1991; Lessard et al., 1994; Priemé and Christensen, 1997; Savage et al., 1997). In this study, the Q_{10} values, calculated by fitting the temperature function to an exponential formula (Davidson et al., 1998), equalled 1.7 for individual CH_4 consumption. This value was comparable with those reported in the studies mentioned above.

Most studies examining the effect of soil temperature on CH_4 consumption have used soil temperatures at the time of flux measurement or daily and monthly average temperatures. We, however, investigated the correlation between CH_4 consumption and time-lagged soil temperature (Fig. 3). Spearman's rank correlation coefficients (r_s) between CH_4 consumption and lagged soil temperature showed an obvious change with the time lag. The correlation coefficient was highest for the temperature 4 h

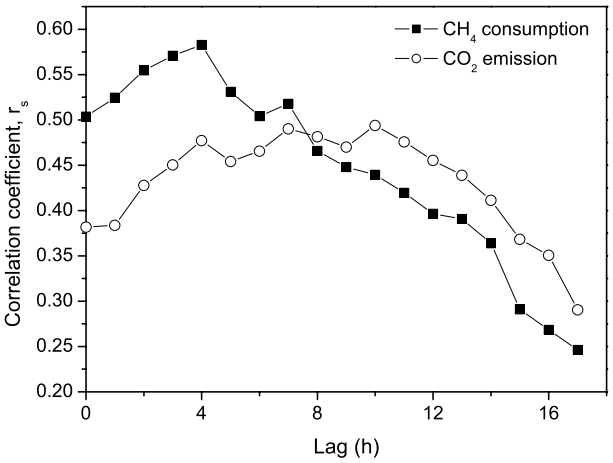

Fig 3. Spearman's rank correlation coefficient between gas exchange rates and lagged soil temperature at a depth of 5 cm.

before the flux measurement ($r_s = 0.58$, $p = 0.0002$) and declined steeply as the lag increased. This result indicates that time-lagged temperatures enabled a more sensitive regulation of CH_4 uptake than did simultaneous temperature measurements. Since CH_4 consumption was caused simply by microbial oxidation, this retardation in the temperature relationship can be interpreted as a lag in the heat transfer from the 5 cm level to the CH_4 oxidation zone. To examine this lagged response to temperature more closely, it is necessary to measure the methane concentration and temperature profiles in soils.

4.2. Soil respiration

Soil respiration is a combination of root respiration and microbial decomposition of soil organic matter. Root respiration represents 33 to 71% of total soil respiration (Nakane et al., 1983; Bowden et al., 1993; Eguchi et al., 1997; Striegl and Wickland, 1998). Although many environmental factors influence the biological and physical processes controlling soil respiration rates, previous studies have shown that respiration rates relate to soil temperature, moisture and/or organic characteristics (Dörr and Münnich, 1987; Skopp et al., 1990; Crill, 1991; Grant and Rochette, 1994; Lessard et al., 1994; Savage et al., 1997; Boone et al., 1998; Davidson et al., 1998, 2000).

Our soil respiration rates were at the high end of the range that has been reported in other studies of boreal and temperate regions. For example, other researchers found summer-time values of 100 to 200 mg C m^{-2} h^{-1}in a New Hampshire forest soil (Crill, 1991), 70 to 160 mg C m^{-2} h^{-1} in upland boreal forests in Manitoba (Savage et al., 1997), 170 to 320 mg C m^{-2} h^{-1} in a mixed-hardwood control-site stand in Massachusetts (Boone et al., 1998), 65 to 230 mg C m^{-2} h^{-1} in a mature jack pine stand in Saskatchewan (Striegl and Wickland, 1998) and 18 to 390 mg C m^{-2} h^{-1} in East Siberian larch forests (Sawamoto et al., 2000). We hypothesize that the greater availability of organic matter in soil and litter resulted in the higher soil respiration rates at our site.

We found only a weak relationship between individual soil respiration rates and soil temperature at 5 cm depth (Fig. 2b and Table 3), although many studies have reported that temperature has a strong impact soil respiration (e.g. Boone et al., 1998; Davidson et al., 1998). This study examined the effect of time-lagged soil temperature at 5 cm depth on soil respiration together with CH_4 consumption (Fig. 3). The rank correlation coefficient increased as the time lag increased from 0 to 4 h and remained high until 10 h. The variation in the relationship between soil respiration and the temperature obviously differed from that with methane uptake, which had a sharp peak at a lag of 4 h. Furthermore, the correlation coefficient for the soil respiration had a small range of variation compared with that of the CH_4 uptake. This suggests that the response to temperature differs between soil respiration and CH_4 oxidation, probably depending on the different gas exchange processes involved.

The process of CH_4 consumption is relatively simple, because it is regulated exclusively by microbial activity and gas diffusion from the atmosphere to the soil, whereas soil respiration is controlled by complicated systems such as plant physiology and phenology and availability of labile C, in addition to soil moisture and temperature controls. Post et al. (2003), suggested that labile soil organic matter significantly affected heterotrophic respiration at short time scales and that this obscures the sensitivity of the respiration to temperature. Eguchi et al. (1997), in diurnal observations of soil respiration in a deciduous broad-leaved forest in Hokkaido, Japan, found that diurnal variation patterns in soil CO_2 efflux differed from diurnal variation patterns in temperature. That is, soil respiration increased at night and decreased in the daytime. Eguchi et al. (1997) deduced that the discrepancy between diurnal variation patterns was caused by tree physiology affecting root respiration, which contributed approximately 70% of the CO_2 production in the H/A horizon at their study site. Generally, when plant roots absorb water, the rate of root respiration increases to replenish energy lost through temporary consumption. Based on measurements of stem circumference and xylem pressure potential presented by Hinckley and Bruckerhoff (1975), Eguchi et al. (1997) suggested that root water uptake by large trees occurred from dusk to night-time. Thus, a night-time increase in soil respiration accompanying high water uptake activity probably contributes to the night-time increase in soil respiration.

By contrast, Rayment and Jarvis (1997) and Davidson et al. (1998) found significant relationships between diurnal variation in soil respiration and soil temperature in an old black spruce forest in Saskatchewan and a mixed hardwood forest in Massachusetts, respectively. Unlike our result, these studies indicated that the soil respiration at their sites responded to soil temperature in phase. Therefore, the temperature sensitivity of soil respiration differs from site to site, and probably depends on the dominant tree species, stand age and soil type. Future research must evaluate the ratio of root respiration to total soil respiration and investigate the physiological conditions of the trees to better understand the factors controlling soil respiration.

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References

Alexeyev, V. A., Stakanov, V. D. and Korotkov, I. A. 1996. The forest resources of Russia. In: *Carbon Storage in Forests and Peatlands of*

Russia (eds V. A. Alexeyev and R. A. Birdsey), USDA Forest Service, Washington, DC, 3–11.

Boone, R. D., Nadelhoffer, K. J., Canary, J. D. and Kaye, J. P. 1998. Roots exert a strong influence on the temperature sensitivity of soil respiration. *Nature* **396**, 570–572.

Borken, W., Brumme, R. and Xu, Y.-J. 2000. Effects of prolonged soil drought on CH_4 oxidation in a temperate spruce forest. *J. Geophys. Res.* **105D**, 7079–7088.

Born, M., Dörr, H. and Levin, I. 1990. Methane consumption in aerated soils of the temperate zone. *Tellus* **42B**, 2–8.

Bowden, R. D., Nadelhoffer, K. J., Boone, R. D., Mellilo, J. M. and Barrison, J. B. 1993. Contributions of aboveground litter, belowground litter, and root respiration to total soil respiration in a temperate mixed hardwood forest. *Can. J. Forest Res.* **23**, 1402–1407.

Brumme, R. and Borken, W. 1999. Site variation in methane oxidation as affected by atmospheric deposition and type of temperate forest ecosystem. *Global Biogeochem. Cycles* **13**, 493–501.

Castro, M. S., Melillo, J. M., Steudler, P. A. and Chapman, J. W. 1994. Soil moisture as a predictor of methane uptake by temperate forest soils. *Can. J. Forest Res.* **24**, 1805–1810.

Castro, M. S., Steudler, P. A., Melillo, J. M., Aber, J. D. and Bowden, R. D. 1995. Factors controlling atmospheric methane consumption by temperate forest soils. *Global Biogeochem. Cycles* **9**, 1–10.

Crill, P. M. 1991. Seasonal patterns of methane uptake and carbon dioxide release by a temperate woodland soil. *Global Biogeochem. Cycles* **5**, 319–334.

Czepiel, P. M., Crill, P. M. and Harriss, R. C. 1995. Environmental factors influencing the variability of methane oxidation in temperate zone soils. *J. Geophys. Res.* **100D**, 9359–9364.

Davidson, E. A., Belk, E. and Boone, R. D. 1998. Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest. *Global Change Biol.* **4**, 217–227.

Davidson, E. A., Verchot, L. V., Cattânio, J. H., Ackerman, I. L. and Carvalho, J. E. M. 2000. Effects of soil water content on soil respiration in forests and cattle pastures of eastern Amazonia. *Biogeochemistry* **48**, 53–69.

Dörr, H. and Münnich, K. O. 1987. Annual variation in soil respiration in selected areas of the temperate zone. *Tellus* **39B**, 114–121.

Dörr, H., Katruff, L. and Levin, I. 1993. Soil texture parameterization of the methane uptake in aerated soils. *Chemosphere* **26**, 697–713.

Eguchi, S., Sakata, T., Hatano, R. and Sakuma, T. 1997. Daily changes of CO^2 efflux from the soil of a deciduous broad-leaved forest and its significance as a CO_2 source for vegetation. *Japan. J. Soil Sci. Plant Nutr.* **68**, 138–147 (in Japanese with English summary).

Grant, R. F. and Rochette, P. 1994. Soil microbial respiration at different water potentials and temperatures: theory and mathematical modeling. *Soil Sci. Soc. Am. J.* **58**, 1681–1690.

Gulledge, J. and Schimel, J. P. 2000. Controls on soil carbon dioxide and methane fluxes in a variety of taiga forest stands in interior Alaska. *Ecosystems* **3**, 269–282.

Hinckley, T. M. and Bruckerhoff, D. N. 1975. The effects of drought on water relations and stem shrinkage of *Quercus alba*. *Can. J. Bot.* **53**, 62–72.

Inoue, G., Ohnishi, H. and Matsui, M. 1998. Application of solid state gas-sensors of CH_4 and CO_2 to environment research. In: *Proc. 6th Symposium of Joint Siberian Permafrost Studies between Japan and Russia in 1997* (eds S. Mori, Y. Kanazawa, Y. Matsuura, G. Inoue). Forestry and Forest Products Research Institute, Tsukuba, 201–206.

Keith, H., Jacobsen, K. L. and Raison, R. J. 1997. Effects of soil phosphorus availability, temperature and moisture on soil respiration in *Eucalyptus pauciflora forest*. *Plant Soil* **190**, 127–141.

Koschorreck, M. and Conrad, R. 1993. Oxidation of atmospheric methane in soil: measurements in the field, in soil cores and in soil samples. *Global Biogeochem. Cycles* **7**, 109–121.

Lapshina, E. D., Mouldiyarov, E. Ya. and Vasiliev, S. V. 2001. Analyses of key area studies. In: *Carbon Storage and Atmospheric Exchange by West Siberian Peatlands* (eds W. Bleuten and E. D. Lapshina). Utrecht University, Utrecht, 23–42.

Lessard, R., Rochette, P., Topp, E., Pattey, E., Desjardins, R. L. and Beaumont G. 1994. Methane and carbon dioxide fluxes from poorly drained adjacent cultivated and forest soils. *Can. J. Soil Sci.* **74**, 139–146.

McLain, J. E. T., Kepler, T. B. and Ahmann, D. M. 2002. Belowground factors mediating changes in methane consumption in a forest soil under elevated CO_2. *Global Biogeochem. Cycles* **16**(3), 1050, doi:10.1029/2001GB001439.

Nakane, K., Yamamoto, M. and Tsubota, H. 1983. Estimation of root respiration rate in a mature forest ecosystem. *Japan. J. Ecol.* **33**, 397–408.

Nakano, T., Sawamoto, T., Morishia, T., Inoue, G. and Hatano, R. 2004. A comparison of regression method for estimating soil–atmosphere diffusion gas fluxes by a closed chamber technique. *Soil Biol. Biochem.* **36**, 107–113.

Osozawa, S. 1987. Measurement of soil-gas diffusion coefficient for soil diagnosis. *Soil Phys. Cond. Plant Growth Japan.* **58**, 528–535 (in Japanese with English summary).

Post, W. M., Gu, L. and King, A. W. 2003. Rapid decomposition of labile soil organic matter inputs obscures sensitivity of heterotrophic respiration to temperature: a model analysis. *Eos. Trans. AGU*, **84**(46) (Fall Meet. Suppl.), abstract B12E-05.

Potter, C. S., Davidson, E. A. and Verchot, L. V. 1996. Estimation of global biogeochemical controls and seasonality in soil methane consumption. *Chemosphere* **32**, 2219–2246.

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

Priemé, A., Christensen, S., Galle, B., Klemedtsson, L. and Griffith, D. W. T. 1996. Spatial variability of CH_4 uptake in a Danish forest soil and its relation to different measurement techniques. *Atmos. Environ.* **30**, 1375–1379.

Rayment, M. B. and Jarvis, P. G. 1997. An improved open chamber system for measuring soil CO_2 effluxes in the field. *J. Geophys. Res.* **102D**, 28779–28784.

Savage, K., Moore, T. R. and Crill, P. M. 1997. Methane and carbon dioxide exchanges between the atmosphere and northern boreal forest soils. *J. Geophys. Res.* **102D**, 29279–29288.

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

Skopp, J., Jawson, M. D. and Doran, J. W. 1990. Steady-state aerobic microbial activity as a function of soil water content. *Soil Sci. Soc. Am. J.* **54**, 1619–1625.

Steudler, P. A., Bowden, R. D., Melillo, J. M. and Aber, J. D. 1989. Influence if nitrogen fertilization on methane uptake in temperate forest soils. *Nature* **341**, 314–316.

Striegl, R. G. and Wickland, K. P. 1998. Effects of a clear-cut harvest on soil respiration in a jack pine–lichen woodland. *Can. J. Forest Res.* **357**, 145–147.

Yefremov, S. P. and Yefremova, T. T. 2001. Present stocks of peat and organic carbon in bog ecosystems of West Siberia. In: *Carbon Storage and Atmospheric Exchange by West Siberian Peatlands* (eds. W. Bleuten and E. D. Lapshina). Utrecht University, Utrecht, 73–78.

Whalen, S. C. and Reeburgh, W. S. 1996. Moisture and temperature sensitivity of CH_4 oxidation in boreal soils. *Soil Biol. Biochem.* **28**, 1271–1281.

Zar, J. H. 1999. *Biostatistical Analysis*, 4th edn, Prentice-Hall, Upper Saddle River, NJ.