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Short-term variation in fluxes of carbon dioxide, nitrous oxide and methane in cultivated and forested organic boreal soils

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Abstract

Short-term changes in fluxes of nitrous oxide and methane were measured with an automatic opaque chamber method in boreal organic soils growing barley, grass or birch and on bare agricultural organic soil. The diurnal variation in these gas fluxes were compared with that of CO_2 production which is known to be highly temperature-dependent. Here, the mean daytime (10:00–16:00) CO_2 production rates were 14–23% higher than the mean daily fluxes. The Q_{10} (air temperature range 15–25 °C) for the CO_2 production was 1.5 in the agricultural soils and 1.3 in the forest. The N_2O fluxes followed the changes in the temperature of the surface soil (depth of 3 cm) in the agricultural soils. The maximum emissions occurred in the afternoon, a few hours later than the maximum air temperature and CO_2 production. There was a clear diurnal variation in the N_2O fluxes in all sites. The mean daytime emissions of N_2O were up to 1.3-fold higher than the daily average fluxes. At maximum, the daytime emissions were as much as 5-fold higher than those measured during night. All the sites were net sinks for CH_4, and no clear diurnal fluctuation was seen. Higher net CH_4 uptake during the measuring period was measured in the forest than in the agricultural soils. The results showed that the short-term variation in the N_2O fluxes, especially during periods with wide variation in temperature or during periods of rainfall, can cause a 60% overestimation in the N_2O emission for boreal organic soils if the daytime fluxes only are measured, a common practice with the manual chamber techniques. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Natural boreal peatlands usually act as sinks for carbon dioxide and sources for methane. In general, they are small sinks for nitrous oxide. Drainage of these soils can lead to major changes in the gas fluxes. After drainage, decomposition of organic matter increases and the sites may turn into net sources of CO_2 even though there may be a decrease in CH_4 emissions. Cultivated peat soils are major sources of N_2O (Kasimir-Klemedtsson et al., 1997).

Present estimates for N_2O balances are mostly based on manual flux measurements carried out during daytime. Diurnal variation in N_2O emissions from agricultural and forest soils has been observed in temperate regions (Denmead et al., 1979; Blackmer et al., 1982; Christensen, 1983; Brumme and Beese, 1992; Skiba et al., 1996; Ball et al., 1999; Laville et al., 1999; Smith et al., 1998). However, no daily variation was seen in tropical agricultural soils with high N_2O fluxes and minor diurnal variations in temperature (Crill et al., 2000).

Organic agricultural soils are important sources of N_2O, even in northern soils with their low mean annual temperatures. In Finland about 25% of the total anthropogenic N_2O emissions has been estimated to be emitted from organic agricultural soils (Kasimir-Klemedtsson et al., 1997), although these soils represent less than 10% of all agricultural soils in Finland (Myllys, 1996). The possible diurnal variation in N_2O fluxes in the boreal region is a potential error source in estimates of annual N_2O flux.

Diurnal variation in CH_4 emissions has been measured for water-logged natural peat soils (Silvola et al., 1992; Kim et al., 1998), for landfills (Börjesson and Svensson, 1997) and for dairy slurry (Khan et al., 1997). However, no data concerning diurnal variation in CH_4 fluxes in drained boreal agricultural soils, with low water tables, have been reported.

To estimate accurately the N_2O and CH_4 balance for boreal agricultural soils, the short-term changes in the flux rates have to be known. We measured the short-term variation in the fluxes of N_2O and CH_4 in boreal organic soils with different cultivation practices (grass, barley or

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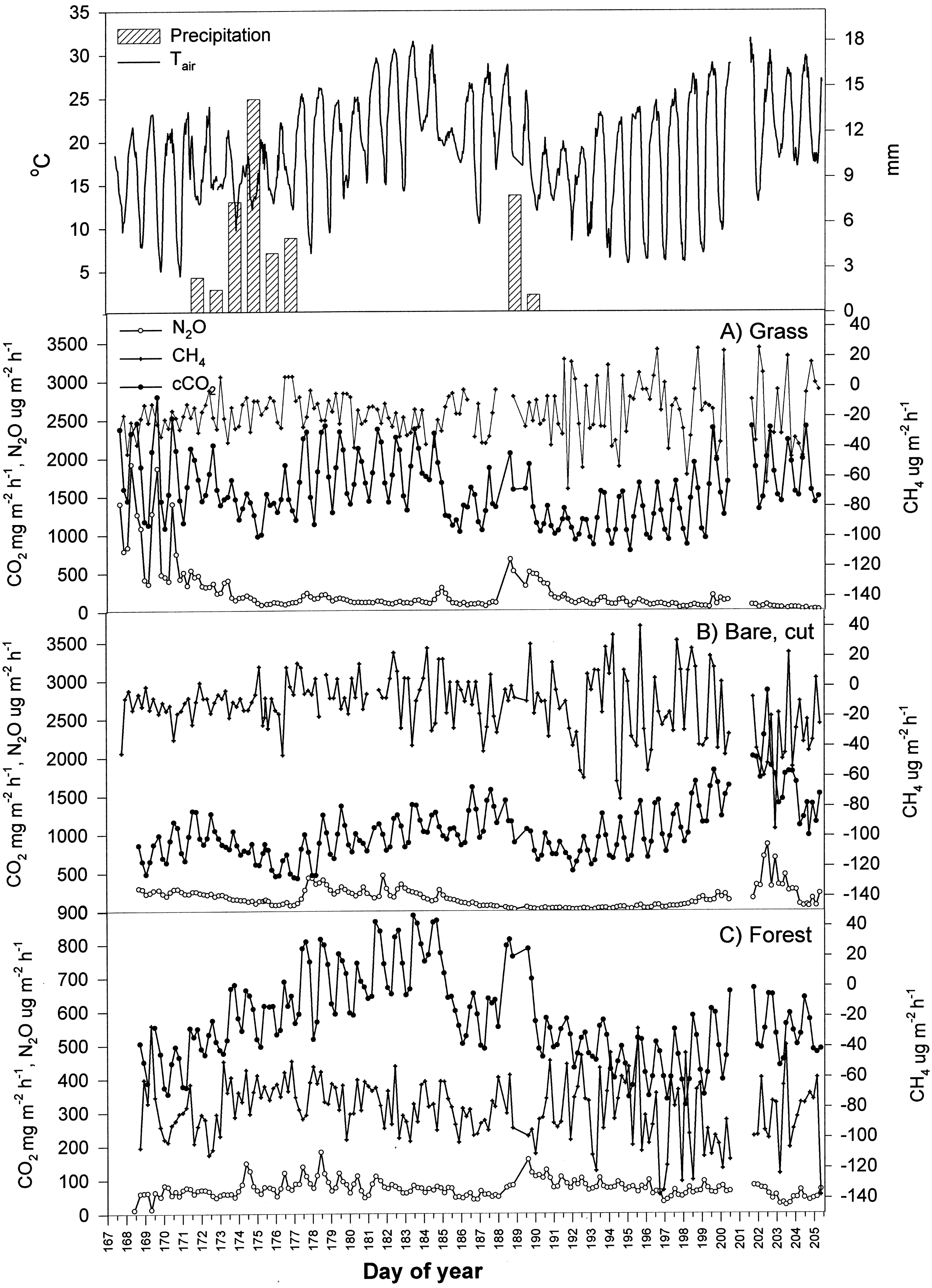

Fig. 1. Fluxes of N_2O (open circles), CH_4 (cross), and CO_2 production (filled circles), air temperature (solid line), and daily rainfall (bars) on grassland (A), bare tilled soil (B) and forest soil (C) measured five times daily during a period of 38 d (14 June–23 July, 1997).

forestry) using an automatic chamber system in situ. The diurnal variation in the fluxes of N_2O and CH_4 was compared to that of CO_2 production, which is known to be associated closely to the fluctuation in air temperature (e.g. Silvola et al., 1985; Benstead and Lloyd, 1996).

2. Materials and methods

2.1. Study site

The experimental site is an old shore and organic sediment of a pond, which is located in Eastern Finland (62°31′N, 29°23′E). The pond was drained in 1957 and planted with birch (*Betula pendula* Roth). Farming started in 1979 after felling a part of the birch forest. Grass (a mixture of *Phelum pratense* 60%, *Festuca pratensis* 25%, *Trifolium pratense* 10% and *Trifolium hybridium* 5%) was grown on the main field (area 0.8 ha) and barley was grown on two separate smaller plots (area 54 m^2). Some plots (area 50–100 m^2) on the cultivated soil were kept bare by regular tilling or cutting. On 5 June 1997 the barley plots were treated with 60 kg N ha^{-1}, 9 kg P ha^{-1} and 27 kg K ha^{-1}. The grassland was fertilized on 4 June 1997 with 100 kg N ha^{-1}, 15 kg P ha^{-1} and 45 kg K ha^{-1}.

The mean annual precipitation in the area is 612 mm of which 320 mm is snow. The annual average temperature is 2.2 °C. The topsoil is mostly frozen from December to May. During summer, the water table level in the cultivated soils varied from 0.8 to 1.6 m below the soil surface and from 1.0 to 1.5 m in the forest.

At present, the depth of the organic soil in the field is 20 cm and in the forest 50 cm. The soil (0–20 cm) total C content is 26% in the cultivated soils and 49% in the forest soil. The content of total N is 1.6% in the field and 2.4% in the forest soil. The mean amount of NO_3^- during the measuring period was 39 mg g^{-1} in the cultivated soils and 25 mg g^{-1} in the forest soil. The mean amount of NH_4^+ was 5 mg g^{-1} in the cultivated soils and 50 mg g^{-1} in the forest soil, respectively.

2.2. Flux measurements

An automatic gas chromatograph system (Silvola et al., 1992) was used when measuring the short-term changes in the gas fluxes. The controller of the system was a standard computer equipped with data acquisition cards. The gas fluxes were measured with six aluminium chambers (60×60 cm^2, height 24 cm, equipped with a fan), which were consecutively closed for the flux measurements. Two of the chambers were located on the grassland and one chamber on the barley field, bare tilled plot, bare cut plot and in the forest, respectively. The air was constantly circulated from the chamber to the magnetic valve board and back to the chamber by pumps when the chamber was closed. Air samples were led from that gas flow to the gas chromatograph (Shimadzu GC-14A) using loops in a 10-port valve. The gas chromatograph was equipped with FI-, TC- and EC-detectors to measure CH_4, CO_2 and N_2O, respectively. Five air samples were analysed from the closed chamber at time intervals of 5 min, after which the chamber was opened and two samples were measured from a calibration gas tank. The gas fluxes were calculated from the linear increase or decrease in the gas concentrations (Nykänen et al., 1995).

During the gas measurements, temperatures (CuKo thermocouple sensors) in the air chamber and peat at a depth of 3 cm were measured. The gas measurements of a chamber with calibration air gas took 45 min, which means, that the gas fluxes of each chamber were measured 4–5 times per day. Gas flux measurements were made during a period of about 40 d in June–August, 1997. During that period, precipitation and air temperature were also recorded in the field (Davis Weather Monitor I Instrument).

3. Results

3.1. CO_2 production

Carbon dioxide from aerobic and anaerobic decomposition processes, respiration of soil animals, dark respiration of plants, as well as CO_2 from root respiration, are included in the CO_2 fluxes measured with the opaque static chambers. This CO_2 flow is termed here as CO_2 production. The mean CO_2 production during the study period was 1400 mg m^{-2} h^{-1} in the grassland (average of two chambers), 1500 mg m^{-2} h^{-1} in the barley field, 1100 mg m^{-2} h^{-1} in the bare cut soil, 1100 mg m^{-2} h^{-1} in the bare tilled soil and 600 mg m^{-2} h^{-1} in the forest. The CO_2 production showed clear diurnal variation with the changing air temperature (Figs. 1–3). The CO_2 production rate was positively correlated with air temperature at all sites and regression models with air temperature as an independent variable explained 41–68% of the variation in CO_2 fluxes during the measuring period of 38 d (Table 1). The CO_2 production showed minimum in the night and maximum around mid-day (Figs. 2 and 3). The Q_{10} (temperature range 15–25 °C) values for the CO_2 production rates were 1.5 in the agricultural soils and 1.3 in the forest.

3.2. Nitrous oxide fluxes

There were diurnal variations in the N_2O fluxes in the agricultural and in the forest soils (Figs. 1–3). In the agricultural soils, the maximum emissions usually occurred in the afternoon whereas in the forest the maximum emission was found in the morning (Figs. 2 and 3). The N_2O emissions from the agricultural soils followed the changes in soil temperature at a depth of 3 cm (Fig. 2). The mean N_2O emissions during the study period were 160 μg m^{-2} h^{-1} from the grassland, 130 μg m^{-2} h^{-1} from the barley field, 170 μg m^{-2} h^{-1} from the bare cut soil, 60 μg m^{-2} h^{-1} from the bare tilled soil and 70 μg m^{-2} h^{-1} from the forest.

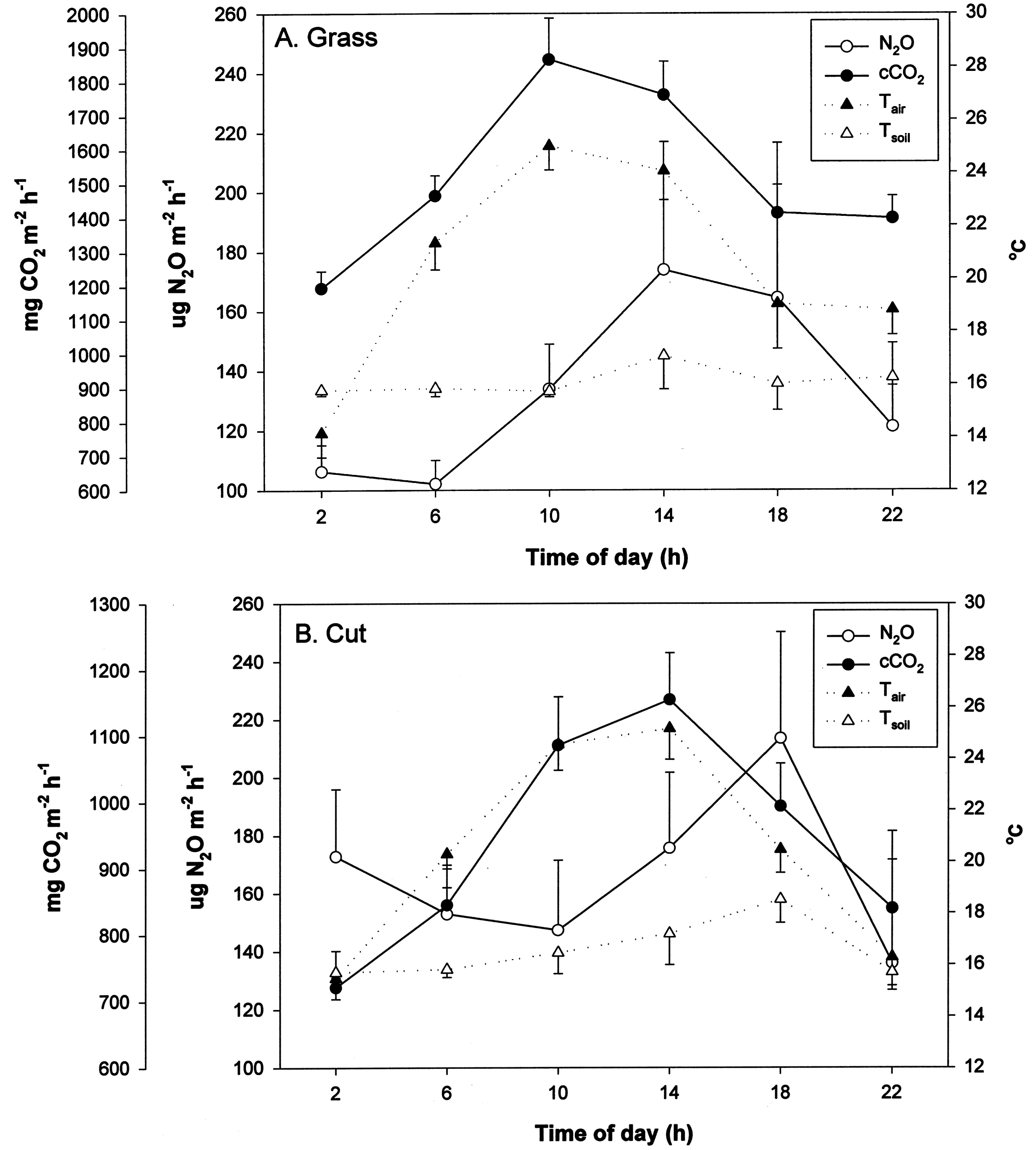

Fig. 2. Mean hourly N_2O fluxes (open circles) and CO_2 production (filled circles), and daily changes in air and soil (of 3 cm depth) temperatures (filled triangles and open triangles) for grassland (A), bare cut soil (B) and forest soil (C) during d 174–188 in 1997. Data points represent average fluxes for each 4 h period during the day. Standard errors are shown by error bars.

The highest diurnal variation in the N_2O fluxes in the grassland was associated with a major diurnal variation in temperature. There was a clear diurnal variation in the N_2O fluxes and in temperature in the early summer, d 167–172 in Fig. 1. During that period, the maximum daytime emission from the grassland (1900 $\mu g\ m^{-2}\ h^{-1}$) was more than 5-fold times higher than the emission recorded during the following night (360 $\mu g\ m^{-2}\ h^{-1}$) (Fig. 1).

Enhanced N_2O fluxes were also associated with rainfall (Fig. 1). In the forest soil, the highest diurnal variation in the emissions took place after the first rainfall in the measuring period, during d 174–182 (Fig. 1). The daytime maximum emission from the forest soil (180 $\mu g\ m^{-2}\ h^{-1}$) was about three times that (70 $\mu g\ m^{-2}\ h^{-1}$) during the following night. In the grassland, after the second rainy period in the measuring period (d 188–189), the N_2O emissions increased from 100 to 800 $\mu g\ m^{-2}\ h^{-1}$. On the bare cut soil, the first rainfall enhanced the N_2O fluxes 6 d after the rain period began (Fig. 1). The variation in soil temperatures after that rain period was higher than in the other soils, and also the diurnal variation in the N_2O fluxes was clearer (Figs. 1 and 2). However, no major peaks were seen after the second

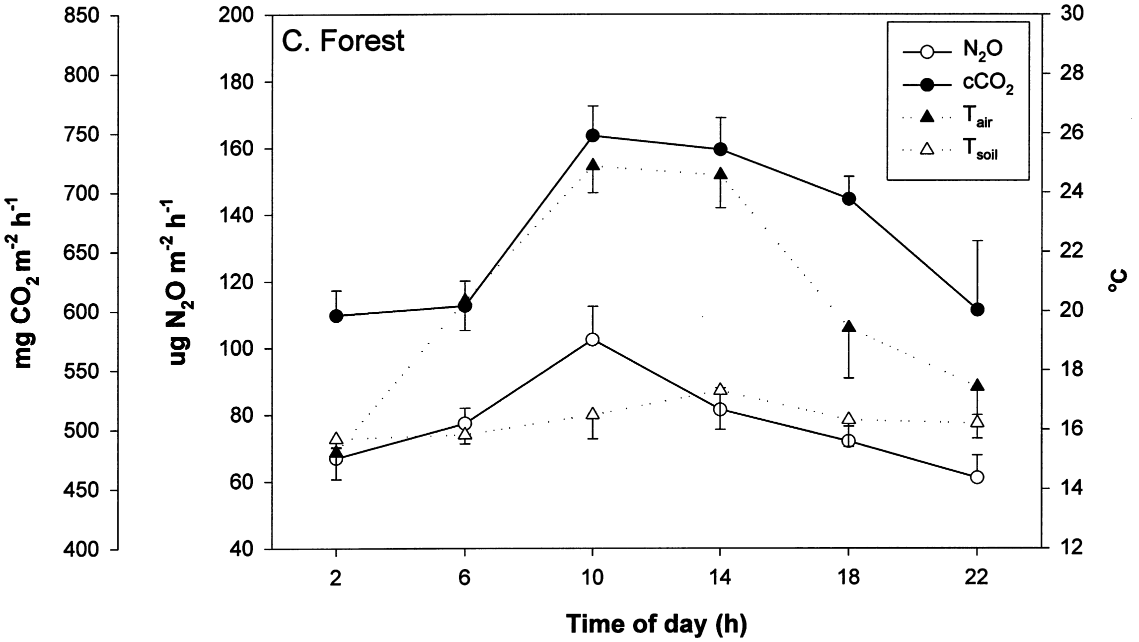

Fig. 2. (*continued*)

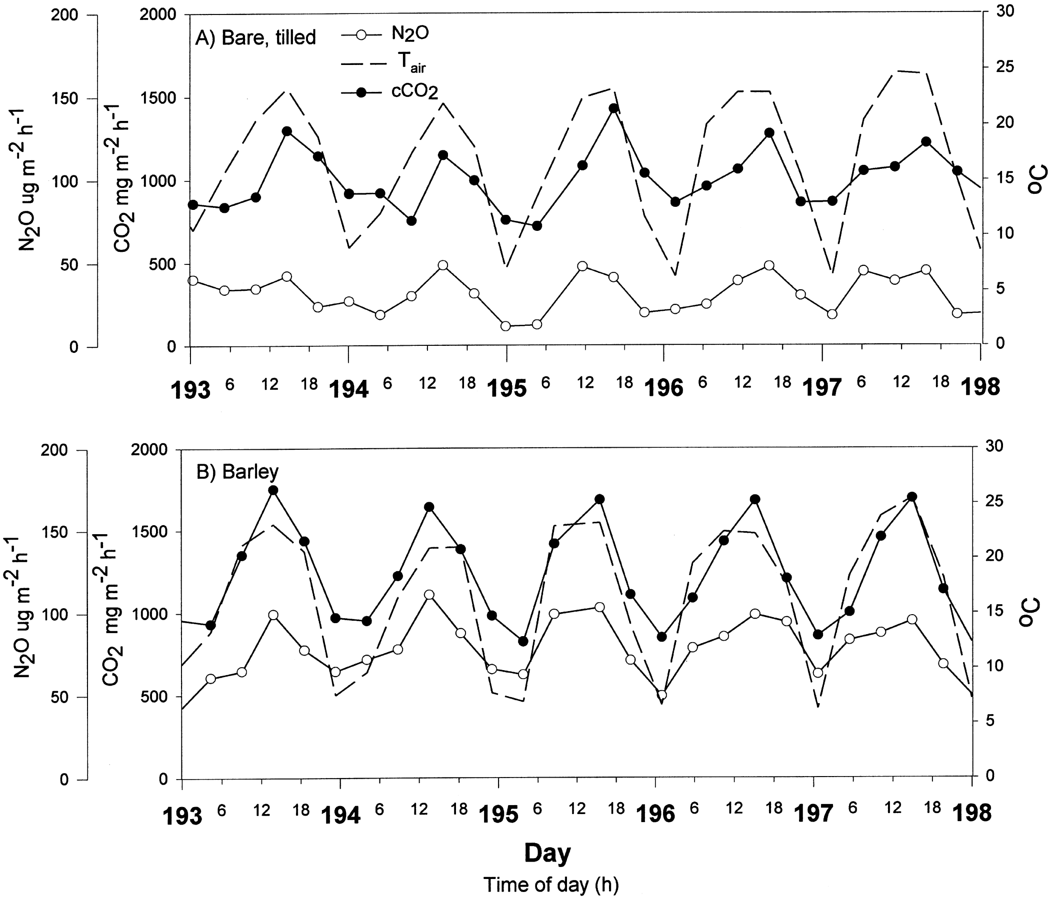

Fig. 3. An example of daily variations with low fluxes of N_2O (solid line, open circles) and CO_2 production (solid line, filled circles), and air temperature (dashed line) for barley soil and bare tilled soil during 5 d in July 1997.

Table 1
Linear regression models for CO_2 production with air temperature as the independent variable ($\ln CO_2 = b_0 + b_1 \times T_{air}$)

Soil	b_0	SE	b_1	SE	R^2	P
Grass	6.329	0.048	0.039	0.002	0.61	< 0.001
Barley	6.559	0.039	0.038	0.002	0.68	< 0.001
Bare, tilled	6.176	0.069	0.038	0.003	0.41	< 0.001
Bare, cut	6.410	0.040	0.032	0.002	0.60	< 0.001
Forest	5.852	0.044	0.024	0.002	0.43	< 0.001

rainfall in the measuring period (Fig. 1). On the barley field and on bare tilled soil, the N_2O emissions were lower than the fluxes on grassland or bare cut soil, and no major peaks in the N_2O fluxes were found after the rain periods. However, these soils with low N_2O fluxes also showed a clear diurnal variation after the second rainfall period with up to 3-fold higher emissions in the afternoon than during night (Fig. 3).

The mean emissions during daytime between 10:00 and 16:00 of N_2O in the 38 d measuring period were 2–30% higher than the daily mean emission. One exception was the barley field, where the daytime emissions were 5% lower than the mean daily emissions (Table 2). However, for a short period the N_2O emissions from the barley field also had a diurnal pattern with maximum emissions during the afternoons (Fig. 3).

3.3. Methane fluxes

During the study period, the soils were usually small sinks for CH_4 (Fig. 1, Table 2). Forest soil had higher net CH_4 uptake during the measuring period (80 $\mu g\ m^{-2}\ h^{-1}$) than the cultivated soils (20 $\mu g\ m^{-2}\ h^{-1}$). There were only minor differences in the CH_4 fluxes between the various agricultural soils. No clear diurnal fluctuation was seen in the CH_4 fluxes.

4. Discussion

4.1. Temperature and CO_2 production

The CO_2 production rate was closely associated with the air temperature, as is well known in general for soil ecosystems (e.g. Silvola et al., 1985, 1996). The highest CO_2 production took place in the daytime with minimum production during the night. The results indicated a lag of a few hours between fluctuation of air temperature and respiration, agreeing with the measurements of Silvola et al. (1985) from drained peatlands. This would have been seen more clearly, if more frequent measurements had been made in our study. During sunny days the maximum air temperature occurred in the morning around 10:00 probably because at that time the forest was not shading the field site. Also in the forest the temperature reached maximum in the morning. The forest chamber was located at the edge of the forest, close to the field site, and therefore the trees were not shading the chamber in the morning. These results show that the biological activities in the uppermost soil layers, where the soil temperature follows the air temperature, were responsible for most of the CO_2 production.

4.2. Diurnal N_2O fluctuation

There was also a strong diurnal variation in the N_2O fluxes both in the agricultural and forest soils during certain periods. The highest diurnal variation in the N_2O fluxes was measured in the early summer when there was a wide diurnal variation in temperature. The diurnal variation in the N_2O fluxes was also evident after rainfall, which induced high episodic flux rates. Rainfall is known to enhance the N_2O emissions (Sextone et al., 1985; Ball et al., 1999). This kind of diurnal variation in the N_2O fluxes has been reported for temperate agricultural soils (Denmead et al., 1979; Blackmer et al., 1982; Christensen, 1983; Ineson et al., 1998; Laville et al., 1999). In our study, the maximum

Table 2
Mean daily emissions of N_2O, CO_2 production and mean daily CH_4 uptake calculated from the measurements conducted during the whole day, and mean fluxes calculated using daytime (08:00–20:00 or 10:00–16:00) measurements only (The percentage difference in the flux rates calculated by these two ways is shown in parenthesis)

Time	Barley	Grass	Bare, cut	Bare, tilled	Forest
N_2O $\mu g\ m^{-2}\ h^{-1}$					
00:00–24:00	132	159	171	62	73
08:00–20:00	129 (−2%)	176 (+11%)	174 (+2%)	66 (+8%)	77 (+5%)
10:00–16:00	142 (+8%)	206 (+30%)	161 (−6%)	63 (+2%)	81 (+10%)
CO_2 mg $m^{-2}\ h^{-1}$					
00:00–24:00	1490	1400	1060	1140	569
08:00–20:00	1710 (+17%)	1590 (+13%)	1160 (+10%)	1270 (+11%)	623 (+10%)
10:00–16:00	1780 (+19%)	1720 (+23%)	1250 (+19%)	1310 (+14%)	662 (+16%)
CH_4 $\mu g\ m^{-2}\ h^{-1}$					
00:00–24:00	18.2	21.2	17.6	17.3	82.6
08:00–20:00	18.2 (0%)	20.6 (−3%)	18.3 (+4%)	18.1 (+5%)	81.3 (−2%)
10:00–16:00	17.0 (−7%)	20.0 (−6%)	17.2 (−2%)	19.1 (+10%)	81.2 (−2%)

N_2O emissions took place later than the maximum CO_2 production rates. The disparity between the peaks in the N_2O emission and the maximum air temperature was about 4 h. The soil temperature at the depth of 3 cm reached its maximum at the time of maximum N_2O emissions. These results suggest that the daily N_2O dynamics in the agricultural soils were associated with the N_2O production a few centimetres deeper than the air temperature-dependent CO_2 production. However, in forest soil, where the diurnal variation was lower than in the agricultural soil, the maximum N_2O emissions occurred in early morning, in agreement with Brumme and Beese (1992) who examined a temperate forest soil. The mechanism for this early maximum is not known.

The solubility of N_2O and CO_2 in water depends on temperature and this may explain some of the diurnal variations (Denmead et al., 1979; Blackmer et al., 1982). Also the diffusion rate of the gases increases with increasing surface soil temperature during the day. The change in the O_2 availability in soil could be one reason for the diurnal variation in the N_2O fluxes. The increase in temperature enhanced microbial activities as shown by the increase in the CO_2 production with increasing temperature. Denitrification activity follows the changes in soil respiration (Maag and Vinther, 1996, 1999). The increase in respiration enhances O_2 consumption in soil (Maag and Vinther, 1999) creating low-oxygen conditions for denitrification, which is the most important mechanism to produce N_2O in our study sites (Maljanen, M. pers. comm.). During rainy periods O_2 deficiency in the soil provides a good environment for denitrification, and allows the temperature-dependent diurnal variation in the N_2O production. High diurnal variations in the N_2O emissions have been found after fertilisation (Christensen, 1983; Smith et al., 1998), which enhanced N_2O fluxes for short periods (Christensen, 1983; Mosier et al., 1991). In our study, the measurements started 12 d after the fertilisation treatment and it is possible that the most intensive fluxes had already occurred. However, the grassland still had high N_2O flux rates at the beginning of the study, and showed the greatest variation in the diurnal N_2O flux rates at that time.

The diurnal variation in N_2O fluxes is not solely dependent on air or soil temperature. We found greater diurnal variation in the N_2O fluxes in the grassland and in the grassland where plants were cut than in the bare tilled soil, indicative of some regulatory mechanisms in the N_2O fluxes associated with plants. The mechanical transportation of gases through aerenchyma tissue is well known with wetland plants (Morrissey et al., 1993; Thomas et al., 1996; Yu et al., 1997; Yan et al., 2000). It has been found that upland plants like barley (*Hordeum vulgare* L.), canola (*Brassica napus* L.) (Chang et al., 1998) and rye grass (*Lolium perenne* L.) (Chen et al., 1999) can also transport N_2O dissolved in water, which the plants have taken up. Therefore, in the present work, plants may also have some importance in the transportation of N_2O from soil to atmosphere. Opening and closure of stomata regulates the transportation of gases by plants (Thomas et al., 1996). When there is enough water the stomata are open during the daytime and closed for nights. Therefore, during wet periods plants can participate in the diurnal variation of N_2O emissions showing daytime maximum.

Our study shows that the frequency of measurements is a critical factor for the accurate determination of N_2O emissions. Here, in the early summer, the N_2O fluxes measured during the daytime were as much as 1.6-fold higher than the mean daily flux calculated from the data covering both day and night time. If the N_2O fluxes are measured only during the daytime, the cumulative fluxes may be greatly overestimated in the boreal organic soils, especially during periods when there is a wide variation in diurnal temperature.

4.3. CH_4 fluxes

We found no clear diurnal variation in the CH_4 fluxes in our drained organic soils in contrast to the situation in natural wetlands, which have high CH_4 emission rates (Silvola et al., 1992; Alm et al., 1995; Mikkelä et al., 1995; Kim et al., 1998; Kettunen et al., 2000). The drained organic agricultural soils are usually net sinks for CH_4. The CH_4 oxidation in soils is generally less temperature-dependent than CH_4 production (Dunfield et al., 1993). Similar to our results, the CH_4 uptake in drained and forested peatland was only weakly correlated with temperature (Crill et al., 1994). The minor diurnal changes in the CH_4 fluxes in cultivated or forested peatland had no significant effect on the cumulative flux rates in contrast to the fluxes of N_2O and CO_2 production, which showed high diurnal variability.

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