Long-term effects of clear-cutting and selective cutting on soil methane fluxes in a temperate spruce forest in southern Germany

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ABSTRACT

Based on multi-year measurements of CH₄ exchange in sub-daily resolution we show that clear-cutting of a forest in Southern Germany increased soil temperature and moisture and decreased CH₄ uptake. CH₄ uptake in the first year after clear-cutting ($-4.5 \pm 0.2 \mu\text{g C m}^{-2} \text{ h}^{-1}$) was three times lower than during the pre-harvest period ($-14.2 \pm 1.3 \mu\text{g C m}^{-2} \text{ h}^{-1}$). In contrast, selective cutting did not significantly reduce CH₄ uptake. Annual mean uptake rates were $-1.18 \text{ kg C ha}^{-1} \text{ yr}^{-1}$ (spruce control), $-1.16 \text{ kg C ha}^{-1} \text{ yr}^{-1}$ (selective cut site) and $-0.44 \text{ kg C ha}^{-1} \text{ yr}^{-1}$ (clear-cut site), respectively. Substantial seasonal and inter-annual variations in CH₄ fluxes were observed as a result of significant variability of weather conditions, demonstrating the need for long-term measurements. Our findings imply that a stepwise selective cutting instead of clear-cutting may contribute to mitigating global warming by maintaining a high CH₄ uptake capacity of the soil.

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1. Introduction

Methane (CH₄) is known to be the third most important greenhouse gas after water vapor and CO₂ and currently contributes approximately 20% to global warming (IPCC, 2007). Its concentration in the atmosphere has more than doubled to ca. 1.8 ppmv during the past 200 years, mostly as a result of fossil fuel exploration, expansion of paddy rice cultivation, large-scale animal husbandry of ruminants, biomass burning and landfills (Crutzen, 1991; Le Mer and Roger, 2001). Aerated terrestrial soils act as a global sink for atmospheric CH₄ ($10\text{--}44 \text{ Tg yr}^{-1}$), accounting for up to 10% of the global atmospheric CH₄ sink (Dutaur and Verchot, 2007). Therefore, slight alterations of the soil CH₄ sink as a result of land management or environmental changes may significantly alter the global methane budget.

Temperate forest upland soils are generally net sinks of CH₄ (Butterbach-Bahl and Papen, 2002; Borken et al., 2003). Consumption of atmospheric CH₄ by soils is microbially mediated and consequently sensitive to various environmental factors and

disturbance by management (Ojima et al., 1993; Tate et al., 2007). In view of the huge spatial and temporal variability of environmental factors and the limited number and restricted temporal coverage of long-term field measurements, the annual CH₄ sink of temperate forest soils is still afflicted with a high degree of uncertainty, ranging from 0.01 to 0.64 g CH₄ m⁻² yr⁻¹ (Smith et al., 2000; Dutaur and Verchot, 2007).

Forest selective cutting and clear-cutting are the management practices most frequently used for silvicultural rotation and timber harvesting worldwide (Zerva and Mencuccini, 2005; Dannenmann et al., 2007). There is a growing number of studies pointing out that forest clear-cutting might cause a reduction in soil CH₄ consumption (Kagotani et al., 2001; Huttunen et al., 2003; Saari et al., 2004), or even switch of soils from being net CH₄ sinks to being net sources (Castro et al., 2000; Zerva and Mencuccini, 2005) by altering the biotic and abiotic factors (e.g. soil temperature, soil water content, root activity, soil nitrogen dynamics). However, very little is known about the effects of forest selective cutting on soil-atmospheric exchange of CH₄ and the existing results are not consistent. Sullivan et al. (2008) reported that methane uptake was not affected by selective cutting in ponderosa pine forest soils within one year of management. A study by Dannenmann et al. (2007) showed that forest selective logging led to a distinct

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reduction in CH₄ uptake in the first year after tree felling, but no significant effects of selective cutting on the magnitude of CH₄ exchange could be observed at another site 4–6 years after felling. However, an increased net CH₄ consumption after selective logging has also been reported by Bradford et al. (2000), who carried out a laboratory incubation study by collecting intact soil cores from Grizedale Forest, UK. Furthermore, most studies on the effect of forest management on soil CH₄ fluxes were performed over a relatively short period (≤ 2 years) or with low measurement frequencies (monthly or weekly), but the long-term effects on soil CH₄ consumption still remain unclear.

Therefore, the main objectives of this study were (1) to establish a long-term dataset (10 yrs) of continuous sub-daily soil CH₄ fluxes from a temperate forest, (2) to evaluate the long-term effects of clear-cutting and selective cutting on CH₄ exchange, (3) to assess the impact of environmental factors and soil parameters on CH₄ exchange at three sites with different management activities, and (4) to quantify annual CH₄ budgets.

2. Materials and methods

2.1. Site and soil descriptions

The study site, the "Höglwald", was an approximately 100-year-old Norway spruce (*Picea abies*) forest located in the hilly landscape of Southern Bavaria, Germany (11° 4' 30" E, 48° 17' 30" N) at an elevation of 540 m above sea level. The climate is sub-oceanic with a mean annual precipitation of 850 mm and a mean annual temperature of 7.6 °C (Rothe et al., 2002). The soil is a typical Hapludalf (FAO: dystric cambisol), strongly acidified in the top soil and N-saturated due to long-term heavy atmospheric N input of more than 35 kg N ha⁻¹ yr⁻¹ (Kreutzer and Weiss, 1998; Huber et al., 2004). The soil pH value (measured in CaCl₂) is 2.9–3.2 in the organic layer and 3.6–4.0 in the uppermost mineral soil layer (Kreutzer, 1995). In July 1999, soil CH₄ flux measurements were initiated at three sites with uniform stand and site conditions. Two of these sites (approx. 1.0 ha each) were either completely logged or partially logged at the end of February 2000. At the selective cutting site, 20% of the basal tree area was removed, creating gaps of about 20 m diameter but retaining the stability of the stand (Huber et al., 2004). The impact of soil compaction was avoided by choosing plots that were not affected by forest trails. Approximately two months after forest management, in April 2000, 3-year-old beech trees (*Fagus sylvatica* L.) were planted at the selective cutting site (SC) in the gaps underneath the remaining spruce stand and throughout the clear-cutting site (CC), while the third site was untreated control (UC). The SC site was situated in the middle between the other two sites, 250 m NE of UC, and 150 m SE of CC. The main soil characteristics at these sites are summarized in Table 1.

2.2. In-situ measurements of CH₄ fluxes

Complete annual cycles of CH₄ fluxes with high resolution were recorded since July 1999 at control and selective cutting sites, and since the beginning of September 1999 at clear-cutting site by fully automated measuring systems. Due to system failure, CH₄ flux measurements could not be performed at SC site from middle of

June 2003 to November 2004. Detailed descriptions of the automated measuring systems, including design of chambers, gas chromatographic conditions and calculation of CH₄ fluxes, can be found in Butterbach-Bahl et al. (1998) and Butterbach-Bahl and Papen (2002). In short, at each site, five chambers of the closed, static type were installed (dimensions: 0.5 m × 0.5 m × 0.15 m, length × width × height). The temporal resolution of CH₄ flux measurements was 2 h, i.e. 1 h closure time followed by 1 h with the chamber lids open, which made it possible to measure 12 CH₄ flux rates per day with each chamber at each site. CH₄ was determined using a gas chromatograph equipped with a flame ionization detector. Air samples from each closed chamber were taken automatically every 15 min for 3 min by a membrane pump at a rate of 200 ml min⁻¹. Depending on the value of the regression coefficient (*r*), CH₄ fluxes were either calculated by a linear or an exponential regression model based on the concentrations within chambers during closure. Average gas flux and standard error were calculated from five replicates for all observations.

Chamber positions in the pre-treatment phase (June 1999–February 2000) and following forest management (>February 2000) remained unchanged. This allowed to assess differences in the magnitude of CH₄ fluxes between treatment sites for the pre-treatment phase and to document treatment effects following the realization of the different forest management practices. Chambers were randomly distributed across the different treatment sites. It should be noted that such a design is not a full replication of treatments, which also would have been impossible with regard to the size of the forest and logistic constraints for automated gas flux measurements. For the selected cutting site the position of the individual chambers formed a transect including two gaps with one chamber each in the center and the edge of both gaps. The fifth chamber was in the middle of an undisturbed part of SC.

2.3. Measurements of environmental factors

Soil temperatures in the organic layer were monitored every minute by PT100 probes (IMKO GmbH, Ettlingen, Germany) in close vicinity to the chambers. Hourly soil moisture measurements were carried out by horizontally installed TDR probes (IMKO GmbH) at 10 cm soil depth from September 1999 to 2004 at UC, and from February 2000 to 2004 at SC and CC. *In situ* soil moisture values during 2005–2008 were not available at our sites due to instrumental failure or removal of the sensors. These gaps were filled by a machine-learning technique (support vector machine, SVM). The SVM method is based on a statistical learning algorithm and has been successfully applied to bioinformatics, flood forecasting and soil water prediction (Furey et al., 2000; Chen and Yu, 2007; Wu et al., 2010a). The required input data, creation of the training dataset and prediction of soil water content were described in detail by Wu et al. (2010a). Soil moisture values were converted to percent water-filled pore space (% WFPS) according to Wu et al. (2010a). Climatic data were obtained from the German Weather Service station Augsburg-Mühlhausen, which was about 20 km northwest from our study site.

2.4. Statistical analyses

The software packages SPSS 13.0 and SigmaPlot 2000 (SPSS Inc., Chicago, USA) were used for statistical analyses. Analyses of variance (ANOVAs) were performed using daily means to test the difference of soil temperature, soil moisture and CH₄ flux rates among different years and forest treatments. Linear and nonlinear regression models were used to examine relationships between CH₄ fluxes and the measured environmental parameters. Multivariate nonlinear regression analysis was done with SigmaPlot 2000 (SPSS Inc., Chicago, USA).

3. Results

3.1. Environmental and soil conditions

The annual means of air temperature, precipitation, soil temperature (organic layer) and WFPS at 10 cm depth from 2000 to 2008 at the three study sites are given in Fig. 1 and Table 2. Compared to the long-term annual mean air temperature (7.6 °C), the period of 2000–2008 was much warmer (8.8 ± 0.4 °C, mean $\pm$ SD), especially the years 2000 and 2007. The nine-year mean annual precipitation was 796.7 mm. However, precipitation in the relatively dry years (2003 and 2004) was much lower than in the relatively wet years (2000 and 2002). More than 60% of the annual precipitation occurred from April to September (Figs. 1 and 2).

The diurnal soil temperature amplitude was greatest at the clear-cut site, and still elevated at the selective logged site as compared to the control site (Fig. 1c). During most of the study period, selective

Table 1
Main characteristics of the three study sites.

	Untreated control (UC)	Selective cut (SC)	Clear-cut (CC)
Throughfall (mm) ^a	703 $\pm$ 89	774 $\pm$ 82	1151 $\pm$ 86
Bulk density (g cm ⁻³) ^b	0.82	0.72	0.64
Organic layer dry mass (kg m ⁻²) ^b	23.1 $\pm$ 4.6	19.0 $\pm$ 2.8	14.4 $\pm$ 2.8
Organic layer thickness (cm) ^b	15	12	9
NH ₄ ⁺ -N (mg kg ⁻¹ SDW) ^c			
Organic layer	52.8 $\pm$ 8.0	61.4 $\pm$ 16.0	37.4 $\pm$ 7.5
Mineral soil	5.5 $\pm$ 1.4	4.6 $\pm$ 0.7	5.1 $\pm$ 0.8
NO ₃ ⁻ -N (mg kg ⁻¹ SDW) ^c			
Organic layer	60.6 $\pm$ 3.2	42.8 $\pm$ 7.6	32.7 $\pm$ 7.8
Mineral soil	10.5 $\pm$ 2.6	6.9 $\pm$ 1.5	8.6 $\pm$ 2.8

^a Huber et al. (2004), means ($\pm$ SD) of 2000–2002.

^b Rosenkranz et al. (2010). Bulk density values are for 0–4 cm mineral soils.

^c Rosenkranz et al. (2010), means ($\pm$ SE) of 2003–2004.

Fig. 1. Daily mean air temperature, daily precipitation (a), WFPS at 10 cm soil depth (b), soil temperature at organic layer (c) and soil CH_4 fluxes (d) for the three study sites from 1999 to 2008. Each soil CH_4 flux data point represents the daily mean calculated from 60 individual fluxes (i.e. five replicate chambers at 12 time points each per day).

cutting and clear-cutting caused a significant increase in soil temperature of the organic layer in comparison with the control site ($P < 0.05$, Table 2), despite an absolute difference of only about 0.5–1.0 °C. Forest selective cutting and clear-cutting substantially increased soil moisture at 10 cm depth as compared to the control site. The relatively high (1054 mm) and low (527 mm) annual precipitation in 2002 and 2003 generated comparatively wet and dry conditions, respectively, which altered soil moisture at all three sites significantly (Table 2). Soil moisture averaged 51.9% WFPS at CC and 49.0% WFPS at SC, which were significantly higher ($P < 0.05$) than at the UC site (47.4% WFPS).

3.2. Seasonal and inter-annual variations in soil CH_4 fluxes

The soils were generally sinks for CH_4 , with some sporadic CH_4 emission events, especially during phases with high soil moisture content and soil freeze/thaw periods. Annual cycles of CH_4 fluxes at UC and SC sites showed distinct seasonal patterns (Fig. 1d), which were significantly positively correlated with monthly mean air and soil temperatures ($P < 0.01$). The lowest CH_4 uptake was generally observed in February or March and then increased gradually until November (Fig. 2), which implies that the changes of CH_4 flux may not only relate to temperature but also to differences between seasons.

Table 2

Annual means ($\pm$ SD) of air temperature, soil temperature (organic layer), WFPS (10 cm depth) and precipitation at the three study sites.

Year	Air Temperature (°C)	Precipitation (mm)	Soil Temperature (°C)			WFPS (%)		
			UC	SC	CC	UC	SC	CC
2000	9.3 $\pm$ 6.9	945.7	9.1 $\pm$ 4.7 ^a	9.4 $\pm$ 3.2 ^a	n.d.	48.8 $\pm$ 3.3 ^a	48.8 $\pm$ 1.9 ^a	52.3 $\pm$ 1.6 ^b
2001	8.6 $\pm$ 7.4	871.8	7.8 $\pm$ 5.5 ^a	8.7 $\pm$ 6.0 ^b	9.2 $\pm$ 8.3 ^c	48.3 $\pm$ 4.9 ^a	49.2 $\pm$ 2.3 ^b	52.8 $\pm$ 1.2 ^c
2002	9.1 $\pm$ 7.0	1054	8.5 $\pm$ 5.3 ^a	7.6 $\pm$ 6.7 ^b	n.d.	49.6 $\pm$ 3.2 ^a	50.0 $\pm$ 1.8 ^b	51.0 $\pm$ 2.5 ^c
2003	8.8 $\pm$ 9.0	527.1	8.4 $\pm$ 6.3 ^a	8.3 $\pm$ 8.6 ^a	9.4 $\pm$ 10.9 ^b	42.7 $\pm$ 7.3 ^a	45.8 $\pm$ 4.4 ^b	51.3 $\pm$ 3.1 ^c
2004	8.4 $\pm$ 7.6	628.5	8.4 $\pm$ 3.7 ^a	7.7 $\pm$ 6.1 ^b	8.6 $\pm$ 8.5 ^c	47.5 $\pm$ 5.6 ^a	50.3 $\pm$ 2.7 ^b	52.4 $\pm$ 1.2 ^c
2005	8.0 $\pm$ 8.3	889.5	8.5 $\pm$ 5.4 ^a	n.d.	8.7 $\pm$ 6.9 ^b	49.0 $\pm$ 3.7 ^a	49.8 $\pm$ 1.9 ^b	52.1 $\pm$ 1.6 ^c
2006	8.7 $\pm$ 8.3	756.6	7.1 $\pm$ 5.4 ^a	8.5 $\pm$ 5.8 ^b	10.3 $\pm$ 7.6 ^c	45.8 $\pm$ 6.2 ^a	48.1 $\pm$ 3.2 ^b	52.0 $\pm$ 1.8 ^c
2007	9.4 $\pm$ 6.9	821.4	8.1 $\pm$ 5.1 ^a	9.6 $\pm$ 4.7 ^b	9.7 $\pm$ 5.8 ^b	47.9 $\pm$ 4.0 ^a	49.1 $\pm$ 2.7 ^b	51.6 $\pm$ 1.5 ^c
2008	9.1 $\pm$ 7.1	675.6	7.6 $\pm$ 5.7 ^a	9.1 $\pm$ 5.1 ^b	8.2 $\pm$ 5.9 ^c	47.5 $\pm$ 3.7 ^a	49.4 $\pm$ 1.6 ^b	51.9 $\pm$ 1.8 ^c
Average	8.8 $\pm$ 7.6	796.7	8.2 $\pm$ 5.4 ^a	8.6 $\pm$ 6.6 ^b	9.1 $\pm$ 8.0 ^c	47.4 $\pm$ 5.2 ^a	49.0 $\pm$ 2.9 ^b	51.9 $\pm$ 2.0 ^c

Lowercase letters in the same row for each variable indicate significant differences ($P < 0.05$) among different treatments; n.d., not determined.

Fig. 2. Mean monthly air temperature, precipitation, soil temperature (organic layer) and CH_4 flux rates at the three study sites after cutting (2000–2008). SE of the means, shown by the error bars, is for sampling times (replicate measurements have first been averaged).

During the study period, the magnitude of soil CH_4 fluxes at the three sites varied significantly year by year (Table 3). Because the measurements started on July 23, 1999, the annual mean values of this year cannot be given. The mean annual CH_4 flux in 2002 at UC was $-7.8 \pm 0.2 \mu\text{g C m}^{-2} \text{ h}^{-1}$ ($-0.68 \text{ kg C ha}^{-1} \text{ yr}^{-1}$), i.e., lower by a factor of more than two ($P < 0.01$) as compared to 2004 ($-1.45 \text{ kg C ha}^{-1} \text{ yr}^{-1}$) and 2006 ($-1.37 \text{ kg C ha}^{-1} \text{ yr}^{-1}$), respectively. For the CC site, mean annual CH_4 flux in 2002 was only $-2.3 \pm 0.3 \mu\text{g C m}^{-2} \text{ h}^{-1}$ ($-0.20 \text{ kg C ha}^{-1} \text{ yr}^{-1}$), and therefore

approx. four times lower ($P < 0.001$) as compared to 2006 and 2008 ($-10.3 \pm 0.4 \mu\text{g C m}^{-2} \text{ h}^{-1}$ and $-8.4 \pm 0.4 \mu\text{g C m}^{-2} \text{ h}^{-1}$, respectively). The mean CH_4 fluxes at UC, SC and CC for the entire observation period after forest management (2000–2008) were -13.4 ± 0.1 , -13.2 ± 0.1 and $-5.0 \pm 0.1 \mu\text{g C m}^{-2} \text{ h}^{-1}$, respectively.

The annual coefficients of variation (CV), calculated as the ratio of the standard deviation to the mean value of CH_4 fluxes, at UC and SC were in general less than 50%, except for SC in 2003 and 2006 (Table 3). Owing to relatively large amplitudes of fluxes, the annual

Table 3
Mean ($\pm$ SE) annual fluxes ($\text{kg C ha}^{-1} \text{ yr}^{-1}$), maximum and minimum mean daily of CH_4 ($\mu\text{g C m}^{-2} \text{ h}^{-1}$) and coefficient of variation (%) at the three study sites from 1999 to 2008.

	1999 ^a	2000 ^b	2001	2002	2003	2004	2005	2006	2007	2008	Mean 2000–2008
Untreated control (UC)											
Annual mean	-12.2 ± 0.3	-12.1 ± 0.2	-13.2 ± 0.2	-7.8 ± 0.2	-14.9 ± 0.4	-16.5 ± 0.3	-12.6 ± 0.3	-15.6 ± 0.3	-14.1 ± 0.2	-14.1 ± 0.3	-13.4 ± 0.1
Maximum	-0.1	-5.2	-5.6	-4.1	8.5	-0.5	5.9	2.0	-1.3	-1.6	8.5
Minimum	-17.7	-24.6	-31.2	-16.6	-30.7	-30.8	-24.3	-30.8	-28.4	-30.7	-31.2
N	115	264	315	316	315	289	344	254	253	325	2675
CV (%)	24.5	28.5	28.0	41.9	42.8	27.5	42.2	34.1	27.4	33.4	39.1
$\text{kg C ha}^{-1} \text{ yr}^{-1}$	–	-1.06	-1.16	-0.68	-1.31	-1.45	-1.11	-1.37	-1.24	-1.24	-1.18
Selective cut (SC)											
Annual mean	-11.9 ± 0.4	-11.5 ± 0.2	-12.5 ± 0.2	-13.1 ± 0.2	-14.4 ± 0.6	-16.4 ± 0.7	-14.6 ± 0.4	-14.6 ± 0.4	-12.8 ± 0.2	-12.4 ± 0.2	-13.2 ± 0.1
Maximum	-3.5	-0.1	-4.2	-6.3	7.6	-12.3	7.6	4.2	2.2	-0.7	7.6
Minimum	-30.3	-28.7	-20.6	-22.9	-30.3	-24.2	-26.8	-27.9	-24.4	-26.6	-30.3
N	123	224	313	245	162	21	250	349	320	343	2227
CV (%)	38.7	31.9	30.1	21.5	56.5	18.7	40.8	50.9	28.2	32.4	39.5
$\text{kg C ha}^{-1} \text{ yr}^{-1}$	–	-1.01	-1.10	-1.15	-1.26	-1.44	-1.28	-1.28	-1.12	-1.09	-1.16
Clear-cut (CC)											
Annual mean	-14.2 ± 1.3	-4.5 ± 0.2	-3.0 ± 0.2	-2.3 ± 0.3	-3.8 ± 0.3	-4.6 ± 0.2	-3.3 ± 0.2	-10.3 ± 0.4	-5.3 ± 0.1	-8.4 ± 0.4	-5.0 ± 0.1
Maximum	2.3	3.7	7.1	12.8	19.9	5.4	9.6	4.0	0.8	-1.0	19.9
Minimum	-25.7	-14.3	-12.6	-9.6	-15.0	-24.3	-13.3	-24.9	-14.2	-29.5	-29.5
N	35	218	259	232	314	215	262	237	284	214	2235
CV (%)	52.1	57.4	94.2	211.6	135.8	74.3	87.0	63.3	42.7	61.8	97.6
$\text{kg C ha}^{-1} \text{ yr}^{-1}$	–	-0.40	-0.26	-0.20	-0.33	-0.41	-0.29	-0.90	-0.46	-0.74	-0.44

N, number of valid daily mean CH_4 fluxes; CV, coefficient of variation.

^a Measurements before clear cutting (from July 23, 1999 to February 29, 2000).

^b Data from March to December 2000 were used.

CV values for CC were usually greater than 50%, especially in the wet year 2002 and the dry year 2003. Throughout the entire observation period 2000–2008, the CC site showed the strongest inter-annual variation of all three experimental sites, with a CV of 97.6%.

3.3. Effect of forest management on soil CH_4 fluxes

Prior to forest management, the mean soil CH_4 fluxes at the three sites were of the same order of magnitude, although CH_4 uptake at CC was significantly higher ($P < 0.05$) than at the other two sites (Fig. 3 and Table 3). In contrast, there was no significant difference in CH_4 fluxes between UC and SC sites before selective cutting.

Following clear-cutting, CH_4 uptake rates at the CC site were significantly reduced ($P < 0.0001$) from $-14.2 \pm 1.3 \mu\text{g C m}^{-2} \text{h}^{-1}$ before cutting to $-4.5 \pm 0.2 \mu\text{g C m}^{-2} \text{h}^{-1}$ in 2000, the first year after cutting. Moreover, this reduction of CH_4 uptake was persistent throughout the entire observation period, i.e., CH_4 fluxes remained at this relatively low level during the first several years after cutting and began to increase gradually after more than 5 years after clear-cutting, though not reaching the original level (Fig. 3). At CC net CH_4 emission events were occasionally observed following heavy rains and during soil freeze/thaw periods. During the almost nine years of continuous measurements after clear-cutting, the average CH_4 flux at CC was significantly lower than at the other two sites ($P < 0.05$). In contrast to clear-cutting, selective cutting had no overall significant effect on CH_4 fluxes. There was a statistically significant difference between SC and UC sites in some years (Fig. 3), however the sign of the difference was not consistent.

3.4. Dependence of soil CH_4 fluxes on environmental factors

The relationships between CH_4 fluxes and soil temperature were generally weak and could be described best by quadratic functions (Fig. 4). Correlations between soil temperature and CH_4 fluxes were higher at SC and CC, with r^2 values of 0.18 and 0.11, respectively, than at UC with an r^2 value of 0.08. In order to quantify the sensitivity of CH_4 fluxes to temperature, Q_{10} values were calculated for

a temperature increase from 5°C to 15°C in the organic layer. The multi-year mean Q_{10} values ($\pm\text{SE}$) were 1.26 ± 0.13 , 1.38 ± 0.15 and 1.67 ± 0.32 for UC, SC and CC, respectively.

Correlations between CH_4 fluxes and WFPS in 10 cm soil depth were generally weak but significant ($P < 0.001$) at all three sites and could be described best by linear regressions (Fig. 5). The correlation analysis revealed similar basic dependency patterns of CH_4 fluxes on soil moisture at all sites, i.e. uptake of atmospheric CH_4 by the soils decreased linearly with increasing WFPS. The multivariate nonlinear regression analysis showing the conjunct effect of soil temperature and WFPS on CH_4 fluxes indicated that the dominant environmental factor affecting the magnitude of CH_4 fluxes at UC and SC was soil moisture rather than soil temperature. However, owing to a relatively narrow range of WFPS values at CC, the dependency of soil CH_4 fluxes on soil temperature was significant at a higher level as compared to soil moisture. Linear regression analysis showed that the annual mean CH_4 fluxes at all sites were positively correlated with annual cumulative precipitation (Fig. 6).

4. Discussion

4.1. Comparison with other studies

To our knowledge, this paper provides the longest time scale of continuous sub-daily measurements of soil-atmosphere exchange of CH_4 in a temperate forest. The results obtained in this study demonstrate distinct seasonal as well as inter-annual variations in CH_4 fluxes at control and managed Högwald sites. The seasonal variations in CH_4 fluxes generally followed the intra-annual changes in air and soil temperatures, with lowest uptake rates during winter and early spring, and highest CH_4 uptake during late summer and autumn. This is in good agreement with previous observations (e.g. Ambus and Christensen, 1995; Priemé and Christensen, 1997; Butterbach-Bahl and Papen, 2002; Teepe et al., 2004; Guckland et al., 2009). The annual mean CH_4 flux (-0.68 to $-1.45 \text{ kg C ha}^{-1} \text{ yr}^{-1}$) at the spruce control site of this study is consistent with earlier publications for this site (Butterbach-Bahl and Papen, 2002; Butterbach-Bahl et al., 2002) covering the period from 1994 to 1997. Moreover, our results fall within the range of annual mean CH_4

Fig. 3. Effect of clear-cutting and thinning on the annual means of CH_4 fluxes from forest soils. Lowercase letters indicate significant differences ($P < 0.05$) among the different treatments. SE of the means, shown by the error bars, is for sampling times (five replicate chambers have first been averaged).

Fig. 4. Relationship between daily mean CH_4 fluxes and soil temperature of the organic layer for UC (a), SC (b) and CC (c); n , number of valid CH_4 fluxes.

fluxes reported from several field measurements for temperate coniferous forests in Europe (Priemé and Christensen, 1997; Borken et al., 2000, 2003; Borken and Beese, 2006). However, consumption was lower than in some studies of temperate coniferous forests in North America (Yavitt et al., 1990; Castro et al., 1992; Gullledge et al., 2004). The underlying mechanism for this regional difference in CH_4 fluxes in temperate forest soils remains unclear, and its elucidation is impeded by the low number of available year-round

Fig. 5. Relationship between daily mean CH_4 fluxes and water-filled pore space at a depth of 10 cm for UC (a), SC (b) and CC (c); n , number of valid CH_4 fluxes.

Fig. 6. Relationship between annual mean CH_4 fluxes and precipitation for the three study sites. SE of the means, shown by the error bars, is for sampling times (five replicate chambers have first been averaged).

measurements of CH_4 fluxes in temperate forests. Poor drainage of clay rich-soils and low gas diffusivity (Brumme and Borken, 1999; Borken et al., 2006), relatively high N deposition (Bergström and Jansson, 2006) and differences in soil N availability (Brumme and Borken, 1999; Butterbach-Bahl et al., 1998) are some factors that have been shown to contribute to the lower CH_4 uptake capacity of temperate forest soils in Europe. However, in view of large spatial and inter-annual variations in CH_4 fluxes, the rates found in this study (approx. $0.8 \text{ kg C ha}^{-1} \text{ yr}^{-1}$ at UC) are in agreement with previous reports on the mean CH_4 sink strength of temperate coniferous forest soils ($1.0\text{--}2.0 \text{ kg C ha}^{-1} \text{ yr}^{-1}$, Borken et al., 2000; Butterbach-Bahl and Papen, 2002). This result indicates that more long-term continuous measurements over several years with high temporal resolution are needed to reliably estimate the mean CH_4 uptake potential of temperate forest soils.

4.2. Effect of forest management on environmental factors

Generally, clear-cutting and selective cutting are thought to alter the thermal properties and the energy balance at the soil surface due to the removal or reduction of the forest canopy. In the present study, clear-cutting and selective cutting not only induced a significant increase in soil temperature, but also caused greater ranges of soil temperature, which was in line with other findings (Castro et al., 2000; Zerva and Mencuccini, 2005). Although some studies have reported an increase in soil bulk density after logging (e.g. Yashiro et al., 2008), the bulk densities as well as the thickness and dry mass of the organic layer at our logged sites were lower as compared to the control site (Table 1). This may be ascribed to the fact that these values were determined about three years after logging. A significant increase in soil water content as a result of the reduction of evapotranspiration and hence water uptake by trees has been documented not only in clear-cutting studies (Castro et al., 2000; Zerva and Mencuccini, 2005), but also in a study on forest selective cutting (Dannenmann et al., 2007), which is consistent with our findings.

4.3. Effect of clear-cutting on soil CH_4 fluxes

The uptake of atmospheric CH_4 by soils is mainly controlled by the activity of methanotrophic bacteria, which can be strongly affected by soil disturbances, such as land-use change and agricultural practices (Ojima et al., 1993; Le Mer and Roger, 2001). Many publications have indicated that the inhibition of CH_4 oxidation due

to soil disturbance may persist for years to decades (Mosier et al., 1991; Ojima et al., 1993; Priemé et al., 1997). In the present study, the mean CH₄ uptake rate in the first year following clear-cutting ($-4.5 \pm 0.2 \mu\text{g C m}^{-2} \text{ h}^{-1}$) was approx. three times lower than during the pre-harvest period ($-14.2 \pm 1.3 \mu\text{g C m}^{-2} \text{ h}^{-1}$) and at the control site in the same year ($-12.1 \pm 0.2 \mu\text{g C m}^{-2} \text{ h}^{-1}$). Several previous investigations have shown that CH₄ consumption in forest soils could be significantly reduced by clear-cutting (Bradford et al., 2000; Kähkönen et al., 2002; Huttunen et al., 2003), albeit with different duration of the effect. Saari et al. (2004) reported for a Norway spruce forest in south-eastern Finland that the inhibition of CH₄ consumption by clear-cutting lasted only about one year, and the difference between clear-cut and control sites was no longer significant after 15–19 months. In two pine forest soils in Florida, Castro et al. (2000) found that the decrease of CH₄ oxidation activity after clear-cutting persisted until the end of the study (approx. two years after clear-cutting). In contrast, the results of our study clearly showed that the reduced CH₄ consumption due to clear-cutting could last for a decade or even longer (Fig. 3) and highlight the importance of long-term observations.

The decrease in CH₄ consumption is often attributed to the increase in soil mineral N contents after clear-cutting (Bradford et al., 2000; Yashiro et al., 2008), since both NH₄⁺ (Steinkamp et al., 2001) and NO₃⁻ (Kähkönen et al., 2002) could inhibit CH₄ oxidation. However, a study by Castro et al. (2000) showed that a 10-fold increase of soil NH₄⁺ concentration due to clear-cutting had no effect on CH₄ consumption. Moreover, in the present study both NH₄⁺ and NO₃⁻ concentrations in organic layer and mineral soil at CC were even lower than that at UC during 2003–2004 but elevated in the year 2000, i.e. the year of clear-cutting (Huber et al., 2004). This indicates that the increase in NH₄⁺ and NO₃⁻ concentrations may last only for a relatively short period due to the increased soil C and N turnover rates after forest disturbance (Saari et al., 2004; Dannenmann et al., 2006). This is followed by a decrease of C and N pools over time even below the initial values before clear-cutting as a result of increased C and N losses to the atmosphere and groundwater. The contrasting findings, however, point out that the impact of management on the mineral N content of the soil cannot be the key determinant of soil CH₄ fluxes in this study. Another possibility is that higher N turnover rates could inhibit soil CH₄ consumption, as pointed out by Mosier et al. (1991). This could be a relevant mechanism for the Högwald, as an earlier study at these sites demonstrated that the soil C and N turnover rates were significantly higher at the clear-cut site as compared to the control (Rosenkranz et al., 2010).

Much more evident than the potential role of N turnover in regulating soil CH₄ fluxes is the fact that the microbially mediated CH₄ consumption is substantially limited by the diffusivity of CH₄ and O₂ availability in the soil (Le Mer and Roger, 2001), which in turn are regulated by the soil water content (Borken et al., 2006; Guckland et al., 2009). In our study, the long time periods of significantly higher soil moisture values after clear-cutting may be the major factor leading to the drastic reduction of CH₄ fluxes at the clear-cutting site as compared to control site. Due to the relatively higher throughfall and significantly lower evapotranspiration, the soil water content remained at a higher level at CC throughout the years 2001–2008, i.e. WFPS was never less than 40% (Fig. 1b). High soil water contents were generally found to inhibit CH₄ oxidation, as well as to increase CH₄ production in soils (Le Mer and Roger, 2001; Butterbach-Bahl and Papen, 2002; Tate et al., 2007; Wu et al., 2010b). Several studies have demonstrated that the anaerobic condition caused by increased soil water contents after forest management was one of the main reasons for the decreasing soil CH₄ uptake or increasing emission (Castro et al., 2000; Dannenmann et al., 2006), which was further supported by our

results. Moreover, occasional CH₄ emissions were observed after some rainfall events in our study, especially at the CC site. Castro et al. (2000) also reported CH₄ emissions after major rainfall events three to eight times higher than before clear-cutting despite similar soil moisture levels, indicating that clear-cutting could not only increase soil moisture, but may promote production of CH₄ in deeper soil layers and in the organic layer. This is in agreement with results of earlier studies at our spruce control site (Butterbach-Bahl and Papen, 2002), where specifically for the organic layer and soil layers deeper than 20 cm soil depth a continuing CH₄ production activity could be demonstrated, though the soil in principle acted as a net CH₄ sink.

4.4. Effect of selective cutting on soil CH₄ fluxes

In contrast to clear-cutting, selective cutting did not significantly reduce CH₄ fluxes throughout our long-term experiment. Published studies on the effect of forest selective cutting on soil CH₄ flux were rather scarce, especially for long-term data, and sometimes contradictory. Dannenmann et al. (2007) reported a distinct decrease in soil CH₄ uptake in the first year after thinning of a beech forest, but no significant changes of CH₄ fluxes at another nearby site 4–6 years after selective cutting. One laboratory study done by Bradford et al. (2000) showed a significantly higher CH₄ uptake in soil cores from a selectively logged oak forest site than that from an undisturbed site. However, the reason for the stimulation of CH₄ uptake at the selectively logged site remained unclear. Based on one year of field measurements, Sullivan et al. (2008) found that selective logging had no significant short-term effect on soil CH₄ uptake because the forest floor density was not substantially reduced during logging and, thus, CH₄ diffusion into the soil was not affected. In our study, organic layer thickness and dry mass were slightly decreased due to the lower supply of litter by cutting 20% of the basal trees. However, planting 3-year-old beech seedlings in the gaps two months after selective cutting led to an increase in understory plant biomass. Though the multi-year mean soil water content at SC (49.0% WFPS) was significantly higher ($P < 0.05$) than at UC (47.4% WFPS), this change might not have been enough to affect gas diffusion into the soil. Overall, the results of our long-term continuous measurements suggest that forest selective cutting with suitable cutting intensity seems to contribute to mitigating global warming by maintaining a relatively high CH₄ uptake capacity of the soil as compared to clear-cutting.

4.5. Dependence of soil CH₄ fluxes on environmental factors

Soil temperature is widely reported to be positively correlated with CH₄ uptake (e.g. Castro et al., 1995; Dannenmann et al., 2007). In this study, generally low but statistically highly significant ($P < 0.001$) correlations were found between soil temperature and CH₄ fluxes, which was in accordance with the findings of other authors (Borken et al., 2000; Zerva and Mencuccini, 2005). Castro et al. (1995) reported that soil temperature was an important controller of CH₄ consumption at low temperatures, but had no significant effect of CH₄ uptake at temperatures between 10 and 20 °C, indicating that CH₄ diffusivity might become the limiting factor of CH₄ uptake rates above a certain temperature threshold. This is confirmed by a study by Steinkamp et al. (2001), who also showed a strong temperature sensitivity of CH₄ fluxes in forest soils at temperatures < 10 °C, which diminished at higher temperatures. The multi-year mean Q_{10} values found for UC (1.26 ± 0.13), SC (1.38 ± 0.15) and CC (1.67 ± 0.32) are in good agreement with the values (1.0–2.0) reported by others (Borken et al., 2000; Steinkamp et al., 2001; Butterbach-Bahl and Papen, 2002).

Soil water content is usually considered to be an important regulator of CH₄ fluxes in soils (Castro et al., 2000; Borken et al., 2006; Guckland et al., 2009). Weak but significant linear regressions between CH₄ fluxes and soil moisture, expressed as WFPS, were observed in the present study, which was in accordance with previous studies (Butterbach-Bahl and Papen, 2002; Borken et al., 2003). In general, soil moisture at both extremely low and high levels have been found to have a strong inhibitory effect on CH₄ uptake by soils (Castro et al., 1995; Borken et al., 2006; Wu et al., 2010b), pointing towards an inhibition of methanotrophic activity by drought stress in the former case, and to an inhibition of gas diffusion in the latter. In addition to low gas diffusivity into the soil caused by high soil moisture, the methanogenic activity might also be stimulated, leading to increased methane production offsetting overall soil methane uptake. However, there was no evidence of drought stress in our study, since soil moisture of our study sites never reached such low values. The negative correlation between soil moisture and CH₄ flux was less pronounced at CC than at UC and SC, most likely due to the significantly higher but narrower range of soil water content at CC.

Changes in annual precipitation amount and distribution have been found to affect seasonal and inter-annual variation in CH₄ exchange (Priemé and Christensen, 1997; Guckland et al., 2009). Our results showed a distinct decrease in CH₄ uptake with increasing annual precipitation (Fig. 6). The obvious reduction of precipitation from 1054 mm in 2002 to 527.1 mm in 2003 correlated with an increase in CH₄ uptake by 10–95% at our sites. Similar results were also reported by Borken et al. (2006), who found a significant increase of CH₄ uptake during artificial summer droughts by exclusion of throughfall. It is noteworthy that we also observed weak but significant CH₄ emission peaks during soil freeze/thaw periods in some winters (especially in 2003 and 2005). Although snow cover and the formation of ice during winter can reduce CH₄ uptake activity by acting as a gas diffusion barrier (Borken et al., 2006; Guckland et al., 2009), short-term CH₄ emissions have also been reported at low temperatures or during thawing (Butterbach-Bahl and Papen, 2002; Heyer et al., 2002; Wu et al., 2010b). Our results suggest that CH₄ fluxes during winter periods should be considered for better estimates of the regional or global CH₄ budget, since there is a globally increasing likelihood of extreme climate events (e.g. severe snow events, prolonged freezing periods) with global climate change.

5. Conclusions

To the best of our knowledge, this study provides for the first time almost ten years of data of long-term continuous measurements of CH₄ soil-atmosphere exchange in a temperate forest, including different forest management practices (clear-cutting and selective cutting). On the basis of these long-term observations, we documented the annual budgets of CH₄ fluxes at three differently managed forest sites with a high degree of accuracy. All sites were net sinks for atmospheric CH₄, though the sink strength varied markedly on seasonal as well as inter-annual scales. CH₄ fluxes at our three sites were weakly but significantly correlated with soil temperature and soil moisture, indicating that other factors may exert a strong effect on CH₄ fluxes.

Forest clear-cutting and selective cutting strongly changed the microclimate by increasing soil temperature and soil moisture. Clear-cutting significantly reduced the soil CH₄ uptake by about 60% as compared to the control site, which was most likely due to the more anaerobic conditions resulting from the higher soil water content. Moreover, our results also showed that clear-cutting will reduce the sink strength of forest soils for atmospheric CH₄ for several years. In contrast to clear-cutting, forest selective cutting

did not significantly reduce CH₄ uptake throughout our long-term measurement. Thus, selective cutting and replacing rotation forests by forests with continuous cover, instead of periodic clear-cutting, may be a more sustainable way of forest harvesting with regard to climate protection due to the avoidance of negative effects on the CH₄ uptake capacity of upland temperate forest soils.

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