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Short-term effects of thinning, clear-cutting and stump harvesting on methane exchange in a boreal forest

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Abstract

Forest management practices can alter soil conditions, affecting the consumption and production processes that control soil methane (CH_4) exchange. We studied the short-term effects of thinning, clear-cutting and stump harvesting on the CH_4 exchange between soil and atmosphere at a boreal forest site in central Sweden, using an undisturbed plot as the control. Chambers in combination with a high precision laser gas analyser were used for continuous measurements. Both the undisturbed plot and the thinned plot were net sinks of CH_4, whereas the clear-cut plot and the stump harvested plot were net CH_4 sources. The CH_4 uptake at the thinned plot was reduced in comparison to the undisturbed plot. The shift from sink to source at the clear-cut and stump harvested plots was probably due to a rise of the water table and an increase in soil moisture, leading to lower gas diffusivity and more reduced conditions which favour CH_4 production by archea. Reduced evapotranspiration after harvesting leads to wetter soils, decreased CH_4 consumption and increased CH_4 production, and should be accounted for in the CH_4 budget of managed forests.

1 Introduction

Methane (CH_4) is the second most important carbon greenhouse gas, with a radiative forcing at least 25 times higher than carbon dioxide from a 100 year perspective (Shindell et al., 2009). Consumption of CH_4 by methanotrophic bacteria in the aerobic part of the soil profile (Harriss et al., 1982) and production of CH_4 by archaeans in the anaerobic water-saturated part of the profile (Ehhalt, 1974) and at anaerobic micro-sites (von Fischer and Hedin, 2002; Kammann et al., 2009) often occur simultaneously (Le Mer and Roger, 2001; Megonigal and Guenther, 2008). Generally, well-aerated forest soil is a net sink of atmospheric CH_4 (Van Amstel, 2012). Consumption in soils is the second largest sink of CH_4 after tropospheric oxidation by hydroxyl radicals with a global sink capacity estimated recently at 28–32 Tg CH_4 year^{-1} (Kirschke et al., 2013). The

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soil sink capacity is higher in forest soils than in grasslands and arable land (Dutaur and Verchot, 2007), and therefore the global CH_4 budget is sensitive to disturbances in forests. Conversion of natural forests to arable land, increased N deposition from the atmosphere, and N-fertilization of agricultural lands are estimated to have reduced the global CH_4 soil sink by about 30 % between 1880 and 1980 (Ojima et al., 1993).

Disturbances, including forest management practices, can also have an impact on the soil CH_4 exchange by altering soil conditions such as soil moisture (Zerva and Menucuccini, 2005; Castro et al., 2000), water table depth (Zerva and Menucuccini, 2005) bulk density (Mojeremane et al., 2012), soil temperature (Zerva and Menucuccini, 2005; Thibodeau et al., 2000), nutrient content (Smolander et al., 1998) and pH (Smolander et al., 1998). CH_4 oxidation in soil has been observed to be controlled by diffusivity (Koschorreck and Conrad, 1993; Whalen and Reeburgh, 1996; Gulledge and Schimel, 1998). A well-drained coarse soil facilitates the exchange of oxygen and CH_4 between the atmosphere and the deeper soil levels where CH_4 is consumed (Verchot et al., 2000). By contrast, increased soil moisture and soil compaction reduce the diffusivity, and promotes anoxic environments in which CH_4 can be produced (Koschorreck and Conrad, 1993; Whalen and Reeburgh, 1996; Gulledge and Schimel, 1998). Changes in water table depth also influence the CH_4 exchange by altering the relative extent of anaerobic and aerobic zones in the soil (Whalen and Reeburgh, 1990). Temperature is also an important driver of CH_4 production, with higher temperatures leading to higher CH_4 production, while consumption by methanotrophs is less strongly enhanced (Dunfield et al., 1993). Increased nitrogen content in the soil has been shown to inhibit CH_4 consumption in several studies (Steudler et al., 1989; Hutsch et al., 1993; Wang and Ineson, 2003). This is due to competition by certain nitrifiers, which might occupy the same niche in the soil. These nitrifiers have an enzyme similar to methanotrophs and are also able to oxidize CH_4, though possibly at a lower rate (Hutsch et al., 1993).

Summarizing the effects of forest management practices on CH_4 exchange is difficult since relatively few studies have been made on this topic, and they have covered a range of management practices, soil types and forests. However, several studies reported that clear-cutting led to reduced CH_4 uptake, possibly due to increased soil moisture (Wu et al., 2011), increased nitrogen availability (Steudler et al., 1991; Bradford et al., 2000), changes in pH, (Bradford et al., 2000) and erosion (Kagotani et al., 2001). A shift from soil CH_4 sink to soil CH_4 source has been reported due to a rise in water table depth combined with increases in substrate availability (Zerva and Mencuccini, 2005) and due to increases in soil moisture (Castro et al., 2000). The same shift from sink towards emission has been seen following soil compaction by skid trails and machinery, as a part of clear-cutting (Teepe et al., 2004) and thinning (Keller et al., 2005). One study on a clear-cut drained peat soil showed no substantial changes in CH_4 exchange (Huttunen et al., 2003).

Site preparation by mounding at clear-cuts can have a negative impact on CH_4 exchange from a climate perspective. In one study, compaction of the soil by excavators during mounding increased CH_4 emissions (Mojeremane et al., 2012). CH_4 emissions from stagnant water in hollows created during mounding can sometimes exceed the consumption in the mineral soil on top of the mounds (Mojeremane et al., 2010). However, bedding after clear-cutting has resulted in reduced CH_4 emissions (Castro et al., 2000). Drainage can also reduce CH_4 emissions following clear-cutting, but its positive effect on CH_4 emissions was outweighed by increases in CO_2 emissions when drainage was conducted on saturated peaty soils (Mojeremane et al., 2012).

Stump harvesting for bioenergy production has recently been proposed as a way of substituting fossil fuel CO_2 emissions in Sweden. To our knowledge there are no publications on the effects of stump harvesting on CH_4 exchange, although it is likely to have a similar effect to other clear-cutting and site preparation actions. There are a few studies on the effect of thinning on CH_4 exchange in a forest. Reduced CH_4 uptake due to increased nitrogen availability has been reported (Thibodeau et al., 2000). A study at three thinned plots in a temperate beech forest reported slightly reduced emissions at one plot, whereas the other two were not significantly different from the control plots (Dannenmann et al., 2007). Another study in a temperate forest actually showed an increased CH_4 uptake after thinning, as opposed to a decrease at two adjacent clear-cut areas (Bradford et al., 2000). Some studies found no significant changes in CH_4 exchange after thinning (Wu et al., 2011; Sullivan et al., 2008).

The objective of this study was to quantify the short-term CH_4 exchange at four sites: an undisturbed forest plot, a thinned forest plot, a clear-cut plot with stumps remaining, and a clear-cut plot with stumps removed. The comparison between the different treatments is facilitated because all four sites are within a defined area and have a common soil type. We also wanted to investigate how soil moisture, soil temperature and water table depths influenced the soil CH_4 exchange.

2 Methods

2.1 Site description

The CH_4 exchange measurements took place in a forested area on the southern edge of the boreal zoon, at Norunda research station in central Sweden, 60°05′ N, 17°29′ E. Hourly automated chamber measurements were made using a system that was moved between 4 differently managed plots. One plot contained undisturbed 120 year-old mixed pine (*Pinus sylvestris*) and spruce (*Picea abies*) forest, which had not been thinned or fertilized in several decades. The other three plots were recently (2009–2010) impacted by either thinning, clear-cutting or stump harvesting. Thinning was done in order to stimulate continuous forestry cover, rather than to increase growth.

Measurements were made using four chambers at the thinned plot, and five chambers at each of the other plots. The chamber locations were named U_1–U_5 at the undisturbed plot, T_1–T_4 at the thinned plot, C_1–C_5 at the clear-cut plot and S_1–S_5 at the stump harvested plot. At the clear-cut and stump harvested plots half of the chamber frames were positioned on bare soil, where organic and mineral soil layers were mixed. The disturbance was caused either by stump harvesting, or by site preparation to facilitate the establishment and growth of new plants. The remaining frames were placed on soil surfaces with intact vegetation. The clear-cut and stump harvested plots had been fertilized in 1976, 1988 and 1998.

Ground vegetation was sparse and dominated by bilberry (*Vaccinium myrtillus*) and feather mosses (*Hylocomium splendens* and *Pleurozium schreberi).* There were more shrubs and grass at the clear-cut site, following the soil's disturbance. The soil was a glacial till (Lundin et al., 1999) with an organic layer of 3–10 cm depth. For the period 1980–2010, the mean air temperature was 6.5 °C, and the mean annual precipitation was 576 mm (measured 30 km south of Norunda).

2.2 Timing of measurements

Thinning took place in November 2008, the clear-cutting in February 2009 and stump harvesting in May 2010. Both the clear-cut plot and the stump harvested plot were mounded and planted in May 2010. The chamber frames were installed in 2005 at the undisturbed and thinned plots, and in June 2010 at the clear-cut and stump harvested plots, to allow time for soil and vegetation to recover from the disturbance.

Due to equipment limitations, measurements were conducted at one plot at a time. Measurements at the thinned plot were made from 1 August 2009 to 31 May 2010, at the undisturbed plot from 7 July 2010 to 4 October 2010, at the stump-harvested plot from 7 October 2010 to 20 October 2010 and at the clear-cut plot from 21 October to 9 November 2010. Winter data at the thinned plot from 1 December 2009 to 14 April 2010 were not used in the analyses due to uncertainties in the measurements caused by snow and frost.

2.3 Equipment

We used automated, transparent chambers of Polymethyl methacrylate in combination with a high precision off-axis integrated cavity output spectroscopy (ICOS) laser gas-analyser (DLT-100, Los Gatos Research (LGR)) for simultaneous concentration measurements of CH_4, CO_2 and H_2O. The chambers had a volume of 110 L and covered a surface-area of 0.2 m^2. Gas concentrations in the chambers were measured after closure by recirculating the air through the gas analyser for 6 min. The flow rate between chambers and manifolds was 8–10 L min^{-1}. This air stream was sub-sampled and passed through the analyser at a flow rate of 1.2 L min^{-1}. A fan was installed in each chamber, designed to ensure sufficient mixing of chamber headspace air without disturbing the laminar boundary layer at the ground. Soil moisture was measured in the chambers at 0–5 cm depth with a Ml-2x thetaProbe from DeltaT Devices. The soil temperature was measured at 5 cm depth inside the chambers using a type T thermocouple. Soil temperature measurements at the thinned plot did not work properly and so temperature data from the undisturbed plot, 125 m away, was used instead.

2.4 Water table

There were differences in height between the chamber frames relative to the ground water table. One pipe with continuous measurements of the ground water table was located 125 m from the thinned plot and 30 m from the undisturbed plot. The groundwater table at these plots was treated as horizontal. At the clear-cut and stump harvested plots, the ground water table was measured manually in seven pipes at each plot, on 8 and 20 October 2010 and 2 November 2010. An inverse distance-weighting model was used to calculate the height of the ground water table in relation to the ground surface for 40 m^2 areas surrounding the chamber frames. The ground water table was also measured continuously at one position on the clear-cut plot.

2.5 Soil sampling

Soil samples were taken in order to determine carbon (C) and nitrogen (N) content and pH in the top 20 cm of the soil including the humus layer, where the chambers had been positioned. The litter layer was not taken into account. Sampling was done in November 2010 at the clear-cut and stump harvested plots and in September 2012 at the undisturbed and thinned plots.

At the clear-cut and stump harvested plots, humus layer samples were taken, down to the border between organic and mineral soil layers, using a 10 cm × 10 cm quadratic frame. The mineral soil was sampled with a 15.9 cm^2 steel corer to a depth of 20 cm, but was subdivided in the field into 0–10 and 10–20 cm layers. Humus samples were treated individually, while the mineral soil samples were pooled plot-wise for each soil layer. The samples, folded in plastic bags, were transported in cooling boxes to the laboratory, where they were kept fresh at 4–5 °C during the preparation process before the final analyses.

Soil samples were passed through either a 5 mm (humus samples) or a 2 mm (mineral soil) mesh. Stones and gravel > 2 mm diameter not passing the mesh were always rejected, as were any roots. The sieved soil material from each sample was carefully mixed and divided into a number of sub-samples for determination of soil pH (H_2O), and total C and N content. Fresh weight/dry weight ratios were determined after drying the sub-samples at 105 °C for 24 h. Soil layer pH was determined with a glass electrode in the supernatant after shaking for 2 h on a rotary shaker, and sedimentation in an open flask for another 22 h. The proportion of fresh soil to distilled water was 1 : 1 by volume, compared to about 1 : 10 for dry matter to water for humus, and 1 : 2.5 for mineral soil). Total C and N content were determined, using vacuum-dried soil samples at 60 °C for 24 h, in a Carlo-Erba NA 1500 Analyser. Because soil pH was always below 6, we assumed that there was no carbonate C, and all C analysed was assumed to be organic C.

At the undisturbed and thinned plots a cylindrical metal corer with an 11 cm^2 opening was pressed horizontally into the humus layer, and also at 5 cm and 10 cm depth in the mineral layer. At some of the measurement locations (T_1, T_4, U_2, U_6) large stones, rocks and roots occupied a large volume of the mineral soil so that sampling at 10 cm depth in the mineral soil was not possible. The soil samples were kept below 5 °C until they were analysed.

The total amount of C and N in the soil samples was analysed with an element analyser (Elementar Analysensysteme GmbH, Germany). The pH value was measured after two hours equilibration with a 0.1 M barium chloride solution (Orion Research model Microprocessor ionalyzer/901). The extractions were made on fresh material. Before determining the bulk density, the samples were oven dried for 48 h at 100 °C and then sieved through a 2 mm mesh.

2.6 Data analyses

The rate of change of CH_4 concentration (dC_{CH_4}/dt) within the chamber was calculated using a linear fit to the first two minutes of concentration data measured by the gas analyser, beginning immediately after chamber closure. We calculated the r^2 values for the fits of five different slopes, which were lagged at 10 s intervals after chamber closure. The fit with the highest r^2 value was then selected. The CH_4 flux ($J_{CH_4 flux}$) was calculated as $J_{CH_4 flux} = \frac{dC}{dt}\frac{V}{A}$, where C is the molar density (µmol m^{-3}), V (m^3) is the chamber volume and A (m^2) is ground surface area. All fluxes with an r^2 value higher than 0.3 and a root mean square error less than 0.1 were kept for further analyses. This corresponded to 99 % of the data at the undisturbed plot, 97 % of the data at the thinned plot, 82 % of the data at the clear-cut plot and 73 % of the data at the stump harvested plot.

Correction of the measured CH_4 concentrations for dilution by water vapour was only possible at the undisturbed, clear-cut and stump harvested plots after water vapour measurements started in June 2010. This means that daytime data (global radiation > 20 W m^{-2}) from the thinned plot had to be excluded from the analyses. During night the dilution effect had very little impact.

The impact of the environmental variables on CH_4 exchange was analysed by Spearman linear correlations using the corr function, and by multilinear regression on standardized data using the function stepwisefit (both Matlab version R2009b). The significance of mean values at the measurement locations was calculated with the ttest function (also Matlab version R2009b).

3 Results

3.1 Environmental conditions

There were differences in soil moisture and soil temperatures among the plots. On average the undisturbed forest plot, with measurements exclusively from the summer season, July through September, had the driest and warmest records, and also the measurement locations were further above the ground water table than at other plots (Fig. 1, Table 1). The clear-cut plot, which was measured in October and November, showed the coldest and wettest conditions including the highest water table. Four of the five measurement locations at this plot were on average less than 15 cm above the ground water table (Fig. 1, Table 1). The thinned plot and the stump harvested plot had similar average moisture and temperature conditions, but the measurements at the thinned plot proceeded over a longer time period and thus the conditions varied more. The thinned plot also had a generally lower ground water table than the stump harvested plot (Fig. 1, Table 1).

Soil N and C content and pH were higher at the clear-cut and stump harvested plots than at the undisturbed and thinned plots (Table 1).

3.2 CH_4 exchange

The mean CH_4 exchange of all measurement locations within the plots were as follows: the undisturbed plot and the thinned plot were net CH_4 sinks of $-10\,\mu mol\,m^{-2}\,h^{-1}$ and $-5\,\mu mol\,m^{-2}\,h^{-1}$ respectively, while the clear-cut plot and at the stump harvested plot were net sources of $13.6\,\mu mol\,m^{-2}\,h^{-1}$ and $13.1\,\mu mol\,m^{-2}\,h^{-1}$, respectively (Fig. 1). However, the CH_4 exchange varied within the plots. At the clear-cut and stump harvested plots, both net sources and net sinks existed (Fig. 2). Plot T_3 and T_4 at the thinned plot shifted between net daily CH_4 sinks and net daily CH_4 sources on a few occasions (Fig. 3b). Fluxes ranged from -7.2 to $-11.4\,\mu mol\,m^{-2}\,h^{-1}$ at the undisturbed plot, from -0.3 to $-8.6\,\mu mol\,m^{-2}\,h^{-1}$ at the thinned plot, from -2.9 to $29.6\,\mu mol\,m^{-2}\,h^{-1}$

at the clear-cut plot and from −2.8 to 53.8 μmol m^{-2} h^{-1} at the stump harvested plot (Fig. 2).

The measurement locations at the managed plots showed a large variability in CH_4 exchange ranges and temporal behaviour (Fig. 3b–d). The measurement locations at the undisturbed plot were consistently CH_4 sinks throughout the measurement period (Fig. 3a).

3.3 Drivers of CH_4 exchange at the undisturbed and thinned plots

Linear regression analyses between CH_4 exchange and climatic variables showed that for most measurement locations at the undisturbed and thinned plots, consumption significantly ($p < 0.001$) increased with decreasing soil water content, decreasing water table depth and increasing temperatures. Exceptions to this were net CH_4 uptake at locations T_3 and T_4 which decreased with increasing temperatures, and net CH_4 uptake at locations T_2 and T_4, which decreased with decreasing soil moisture (Table 2). Figure 5 shows an example of the CH_4 exchange response to temperature and soil water conditions at plot U_2.

Monthly multilinear regression analyses (Table 3) added some temporal information to the CH_4 exchange at the undisturbed and thinned plots. At the undisturbed plot the water table depth affected CH_4 consumption in August. In September 2010 temperature was the most influential variable at all measurement locations. In July 2010 the result was less distinct, showing some measurement locations with a higher dependency on water table depth and soil moisture, and some measurement locations with a higher dependency on temperature. The clearest result at the thinned plot was a strong dependency on soil moisture at measurement locations T_1 and T_3 in August 2009 and at locations T_1 and T_2 in April 2010 (Table 3). Soils were wetter than average in August and April due to heavy rains in June and July 2009, and snowmelt in spring 2010.

3.4 Drivers of CH_4 exchange at the clear-cut and stump harvested plots

Generally at the clear-cut and stump harvested plots, the measurement locations with net emissions of CH_4 had either a relatively short distance to water table, or were disturbed by site preparation, or both, although there were exceptions. Plot S_4 and S_5 had the same water table depth and were not disturbed by preparation, but plot S_4 was a CH_4 sink while plot S_5 was a CH_4 source (Fig. 4).

At the majority of the measurement locations on the clear-cut and stump harvested plots, higher temperatures correlated significantly ($p < 0.05$) with lower CH_4 emissions, or in one case with a higher net uptake. Both negative and positive significant correlations between CH_4 exchange and soil moisture was found at a few measurement locations but the soil moisture range at those measurement locations was very small. At two measurement locations with net emissions at the clear-cut plot, there was a significant ($p < 0.05$) negative correlation between CH_4 exchange and water table depth, so that a lower water table depth gave higher CH_4 emissions (Table 2). The multilinear regression confirmed the significantly negative correlation between CH_4 exchange and temperature at 5 measurement locations.

4 Discussion

All measurement locations at the undisturbed forest plot were sinks of CH_4 throughout the measurement period, which is consistent with the generally drained, drier and warmer soil conditions at the plot (Fig. 1). The measurement locations at the thinned plot were also net sinks of CH_4, although reduced in comparison to the undisturbed plot. By contrast, the clear-cut and stump harvested plots were net sources of CH_4. Since the measurements at the different plots were conducted at different times of year, seasonality and annual variations can probably explain some of the differences in CH_4 exchange and soil conditions. However, it is not likely that differences in water table depth between the plots are due solely to seasonal variations. In the autumn of

2010 the water table was on average more than 1 m higher at the clear-cut and stump harvested plots than at the undisturbed plot. In addition to this, the mean CH_4 exchange for the autumn period October to November at the thinned site did not differ much from the mean CH_4 exchange for the whole measurement period, indicating that average seasonal variations are small (Fig. 1). Precipitation was on average higher during the measurement period at the thinned site than during measurements at the other plots, which did not cause a switch from CH_4 sink to CH_4 source.

Water table depth, soil moisture and soil temperature were all shown to be important drivers of CH_4 exchange, as demonstrated by the linear and multilinear regression analyses. However it appears that the rise of water table and increased soil moisture caused some of the measurement locations to shift to CH_4 sources. This is consistent with results by Zerva and Menucuccini (2005) and Castro et al. (2000). Temporal shifts to CH_4 emissions after snowmelt and summer precipitation, as were seen at measurement locations T_3 and T_4, were also reported by Wang and Bettany (1995).

A majority of net emitting measurement locations at the clear-cut and stump harvested plots (C_2, C_3, C_4, C_5, S_1) were positioned less than 21 cm above the water table, and had a volumetric soil moisture content above 40 % (Table 1). Also measurement location T_3, when it had temporarily shifted to a CH_4 source, had volumetric soil moisture content above 40 %. Net emissions were also measured at measurement location S_2 and S_5 with water table depths at 30–40 cm and volumetric soil moisture contents of 23–40 %. Fiedler and Sommer (2000) found a threshold value of water table depth at 15 cm, below which only minor annual emissions were measured. The three measurement locations at the clear-cut and stump harvested plots which showed net consumption of CH_4 were further than average above the water table for those plots (Fig. 4).

Temperature seemed to have a stronger impact on CH_4 exchange in drier conditions. Figure 5 illustrates a high correlation, $r^2 = 0.74$, between soil temperature and CH_4 exchange at measurement location U_2, when excluding data points with soil moisture above 22 % and a distance to the water table of less than 1.25 m. The threshold value of 22 % was selected after visual inspection of the data. If all the data from wetter conditions were included (volumetric soil moisture content > 22 % and water table < 1.25 m away), the corresponding r^2 equals 0.47. This is consistent with the results from the multilinear regression analyses showing that water table depth had a significant impact on the CH_4 exchange at all measurement locations in August 2010, when the water table depth varied strongly. In contrast, during September, there were no major precipitation events and soil temperature was the most influential variable. Soil moisture was rarely below 30 % at the thinned plot, thus the temperature dependence was less. In autumn, September to November 2009, all measurement locations at the thinned plot were stable sinks of CH_4, even though the soil temperature was at times below 5 °C.

At the clear-cut and stump harvested plots, where most measurement locations were net sources of CH_4, we would expect a positive correlation between soil temperature and CH_4 exchange, so that higher temperatures led to higher net emissions of CH_4. Methanogens generally respond better than methanotrophs to increased temperatures (Dunfield et al., 1993). However this was not the case: a majority of the measurement locations showed a significantly negative correlation between temperature and CH_4 exchange.

Higher N content in the soil at the clear-cut and stump harvested plots could also possibly contribute to reduced consumption and shifts to emission of CH_4 (Thibodeau et al., 2000; Bradford et al., 2000), although we did not measure the fraction of total N that was freely available. Overall the total N content was higher at the clear-cut and stump harvested plots than at the undisturbed and thinned plots (Table 1), which is possibly due to fertilization that took place in 1976, 1988 and 1998. However at measurement location S_2, which showed the highest emissions of CH_4, the N content was relatively low.

The highest CH_4 emissions were found at four of the five disturbed measurement locations: that is, sites of bare soil where organic and mineral soils were mixed. The soil at disturbed measurement locations seemed less compact than at measurement locations with intact vegetation, so the disturbance probably did not inhibit diffusion. Possibly the availability of fresh organic material was higher at disturbed measurement locations. Fresh, labile organic matter would promote heterotrophic uptake of O_2 and increase the soil's water retention, thereby promoting the activity of methanogenic archeans (Wachinger et al., 2000). The one disturbed measurement location, which showed net CH_4 consumption, S_3, was positioned on top of a mound with relatively large distance to the ground water table (Fig. 4).

Since this is a study of the short-term effects of forest management practices on CH_4 exchange, there are no data on how long-lived these effects are. Sudden shifts from sinks to sources and back again due to changes in soil water conditions are evident, as we have seen at the thinned plot (Fig. 3b). It might take from years (Tate et al., 2006) to several decades for a soil to regain its full sink capacity. The recovery time for the soil CH_4 sink strength of forests on abandoned agricultural land was more than 100 years (Prieme et al., 1997; Smith et al., 2000). Hiltbrunner et al. (2012) found that the soil CH_4 sink capacity of abandoned agricultural land increased with stand age up to 120 years, due to the increased transpiration of older forests and their ability to shield the forest floor from precipitation, which resulted in more favourable conditions for methanotrophic activity.

Uptake rates by upland forests might be overestimated (Grunwald et al., 2012; Fiedler et al., 2005). A study by Grunwald et al. (2012) found that wet forests were as important as wetlands for the CH_4 budget of European forests, and Fiedler et al. (2005) found that if 2.3 % of a forest area consisted of wet soil the forest could turn from a sink to a source of CH_4. As mentioned, after clear-cutting, water table depth decreased and soil moisture increased. Wetter soils and a higher ground water table are common consequences of clear-cutting, and it is therefore important to consider their impact on the CH_4 budget in managed forests, especially if the recovery time for the soil CH_4 sink is several decades. In this study the effects of thinning on the CH_4 exchange were not as pronounced as for clear-cutting, although the plot average consumption was reduced in comparison to the undisturbed plot. Any forest management practice that reduces disturbance and leaves a continuous forest cover might be a better alternative from a global warming perspective.

5 Conclusions

Our study on the short term effects of boreal forest management on CH_4 exchange shows that the undisturbed plot and the thinned plot remained net CH_4 sinks, while the clear-cut and stump harvested plots were net CH_4 sources. Linear regression analyses between CH_4 exchange and climatic variables showed that for most measurement locations at the undisturbed and thinned plots, net CH_4 uptake increased significantly with decreasing soil moisture, decreasing water table depth and increasing temperatures. A higher water table and increased soil moisture were likely to be responsible for the shift to CH_4 emissions at the clear-cut and stump harvested plots. At most of the measurement locations, which showed net emissions, the soil was almost saturated and the water table was within a few decimetres of the soil surface. Clear-cutting of the forest resulted in a raised ground water table and in increased soil moisture. These effects should be accounted for in the CH_4 budget of managed forests.

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Table 1. Information regarding vegetation, C and N pool, pH, soil moisture (5th and 95th percentiles) and depth to water table at the individual chamber locations. Chamber locations were named U_1–U_5 at the undisturbed plot, T_1–T_4 at the thinned plot, C_1–C_5 at the clear-cut plot and S_1–S_5 at the stump harvested plot.

ID	Time period	Vegetation/Bare soil	Carbon[a] (kg m^{-2})	Nitrogen[a] (kg m^{-2})	pH[b]	Soil moisture (%)	Depth to water table (cm)
T_1	1 Aug 2009–31 May 2010	Mosses, bilberry	6.7	0.22	3.1	28.8–45.8	54–154
T_2	1 Aug 2009–31 May 2010	Mosses, bilberry	5.0	0.17	3.1	25.0–40.0	44–144
T_3	1 Aug 2009–31 May 2010	Mosses, bilberry	5.5	0.24	3.5	33.5–55.6	15–116
T_4	11 Dec 2009–31 May 2010	Mosses, bilberry	3.3	0.10	3.0	19.2–36.3	29–129
U_1	7 Jul 2010–4 Oct 2010	Mosses, bilberry	2.6	0.17	3.3	6.0–27.3	120–173
U_2	7 Jul 2010–4 Oct 2010	Mosses, bilberry	6.1	0.29	3.2	10.0–33.4	107–160
U_3	7 Jul 2010–4 Oct 2010	Mosses, bilberry	no data	no data	no data	9.4–37.0	102–155
U_4	7 Jul 2010–4 Oct 2010	Mosses, bilberry	2.3	0.09	3.3	6.6–32.9	136–190
U_5	7 Jul 2010–4 Oct 2010	Mosses, bilberry	3.9	0.15	3.4	7.8–23.5	132–185
S_1	7 Oct 2010–20 Oct 2010	Mosses, bilberry	14.1	0.45	4.4	42.0–42.9	20–21
S_2	7 Oct 2010–20 Oct 2010	Bare soil, mixed organic and mineral soil layers	6.0	0.19	4.4	23.4–25.3	31–32
S_3	7 Oct 2010–20 Oct 2010	Bare soil, mixed organic and mineral soil layers	19.0	0.62	4.4	30.0–33.2	47–48
S_4	7 Oct 2010–20 Oct 2010	Some vegetation and thick litter layer	no data	no data	no data	35.9–39.4	35–36
S_5	7 Oct 2010–20 Oct 2010	No vegetation and thick litter layer	no data	no data	no data	33.7–36.1	37–38
C_1	21 Oct 2010–9 Nov 2010	Mosses, bilberry	4.7	0.16	4.2	41.5–46.2	44–50
C_2	21 Oct 2010–9 Nov 2010	Bare soil, mixed organic and mineral soil layers	13.1	0.41	4.2	44.2–50.3	6–12
C_3	21 Oct 2010–9 Nov 2010	Bare soil, mixed organic and mineral soil layers	11.9	0.35	4.2	no data	7–13
C_4	21 Oct 2010–9 Nov 2010	Mosses, bilberry	9.5	0.30	4.2	56.6–57.6	6–13
C_5	21 Oct 2010–9 Nov 2010	Bare soil, mixed organic and mineral soil layers	11.5	0.36	4.2	49.5–49.9	0–1

[a] C and N pool to a depth of 20 cm in the mineral soil (litter layer excluded).

[b] pH ($BaCl_2$) for the undisturbed and thinned plots and pH (H_2O) for the clear-cut and stump harvested plots were measured at 0–10 cm depth in the mineral soil.

Table 2. Correlation coefficients C and corresponding P values for the linear regressions between CH_4 exchange and soil temperature, soil moisture and water table depth.

	C Soil temperature	P Soil temperature	C Soil moisture	P Soil moisture	C Water table depth	P Water table depth
T_1	−0.09	[a]	0.57	[a]	0.12	[a]
T_2	−0.34	[a]	−0.23	[a]	0.46	[a]
T_3	0.34	[a]	0.72	[a]	0.45	[a]
T_4	0.28	[a]	−0.72	[a]	0.55	[a]
U_1	−0.61	[a]	0.48	[a]	0.51	[a]
U_2	−0.59	[a]	0.39	[a]	0.54	[a]
U_3	−0.56	[a]	0.43	[a]	0.54	[a]
U_4	−0.69	[a]	0.54	[a]	0.69	[a]
U_5	−0.82	[a]	0.53	[a]	0.68	[a]
S_1	−0.39	[a]	−0.14	[b]	[c]	[c]
S_2	−0.15	[b]	−0.05	0.50	[c]	[c]
S_3	−0.04	0.58	−0.11	0.11	[c]	[c]
S_4	−0.15	[b]	−0.03	0.72	[c]	[c]
S_5	−0.34	[a]	−0.42	[a]	[c]	[c]
C_1	−0.05	0.36	−0.12	[b]	0.04	0.47
C_2	−0.52	[a]	0.25	[a]	−0.09	0.07
C_3	−0.57	[a]	no data	no data	−0.42	[a]
C_4	−0.09	0.20	0.05	0.45	−0.03	0.74
C_5	−0.53	[a]	−0.04	0.44	−0.27	[a]

[a] significant, $p < 0.001$

[b] significant, $p < 0.05$

[c] At the time for measurements on the stump harvested plot, the water table depth was only measured manually on a few occasions and therefore no linear regression could be made for this period.

Table 3. Coefficients from multilinear regression analyses. A value is given only if the variable significantly contributes to explain the variation in the CH_4 exchange.

Thinned	T_1			T_2			T_3			T_4		
	Soil moist.	Soil temp.	Water table	Soil moist.	Soil temp.	Water table	Soil moist.	Soil temp.	Water table	Soil moist.	Soil temp.	Water table
Aug 2009	0.62	–	0.34	0.16	−0.15	0.38	0.66	0.33	–	No data	No data	No data
Sep 2009	0.31	–	–	–	−0.29	–	0.28	0.19	–	No data	No data	No data
Oct 2009	–	−0.16	−0.12	−0.13	−0.27	−0.11	−0.10	–	−0.15	No data	No data	No data
Nov 2009	0.40	−0.20	0.31	0.18	−0.29	0.25	–	−0.22	0.18	–	0.2	–
Apr 2010	0.54	0.39	0.34	0.65	−0.34	−0.60	–	−0.26	–	No data	No data	No data
May 2010	–	–	–	–	−0.30	–	−0.49	−0.28	–	–	0.72	–

Table 3. Continued.

Undisturbed	U_1			U_2			U_3			U_4			U_5		
	Soil moist.	Soil temp.	Water table	Soil moist.	Soil temp.	Water table	Soil moist.	Soil temp.	Water table	Soil moist.	Soil temp.	Water table	Soil moist.	Soil temp.	Water table
Jul 2010	0.42	–	−0.18	No data	–	0.18	0.60	−0.13	0.48	0.12	−0.28	–	0.20	−0.29	0.47
Aug 2010	–	−0.12	0.62	No data	−0.21	0.61	0.08	–	0.60	0.19	−0.18	0.78	0.15	−0.34	0.63
Sep 2010	0.1	−0.29	−0.10	No data	−0.53	–	0.12	−0.23	−0.10	0.46	−0.50	–	–	−0.52	−0.10

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Table 3. Continued.

Stump-harvested	S_1		S_2		S_3		S_4		S_5	
	Soil moist.	Soil temp.	Soil moist.	Soil temp.	Soil moist.	Soil temp.	Soil moist.	Soil temp.	Soil moist.	Soil temp.
Oct 2010	–	−0.28	−0.27	–	–	–	–	–	–	–

Table 3. Continued.

Clear-Cut	C_1			C_2			C_3			C_4			C_5		
	Soil-moist.	Soil temp.	Water table	Soil moist.	Soil temp.	Water table	Soil moist.	Soil temp.	Water table	Soil moist.	Soil temp.	Water table	Soil moist.	Soil temp.	Water table
Oct–Nov 10	–	−0.30	–	–	−0.47	−0.16	–	−0.53	–	–	–	–	−0.26	−0.61	−0.18

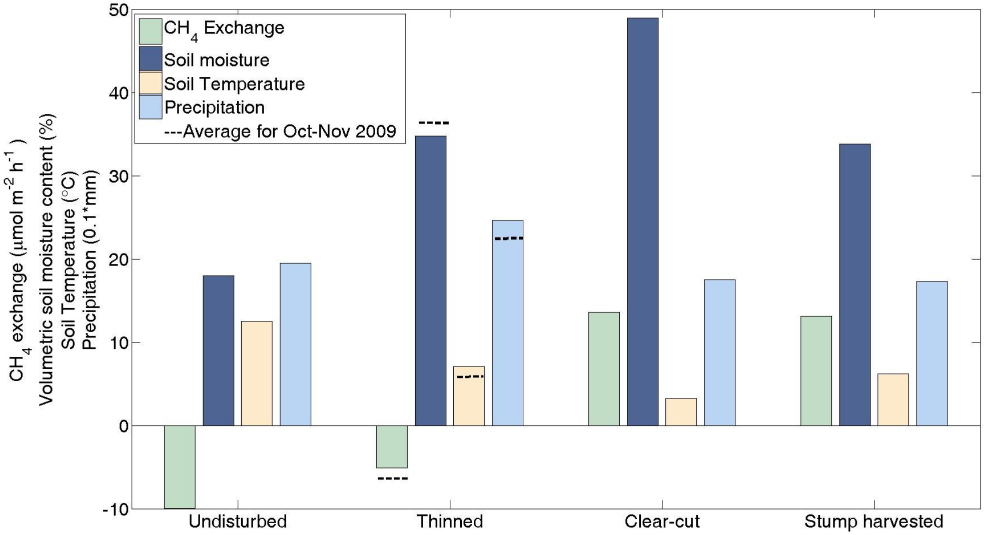

Fig. 1. Average CH_4 exchange rates, soil moisture and soil temperature at the four sampling plots. Data from the entire measurement period at each plot is included. The dashed line at the thinned plot represents average values for October and November, since measurements at the clear-cut and stump harvested plots were conducted during this part of the year.

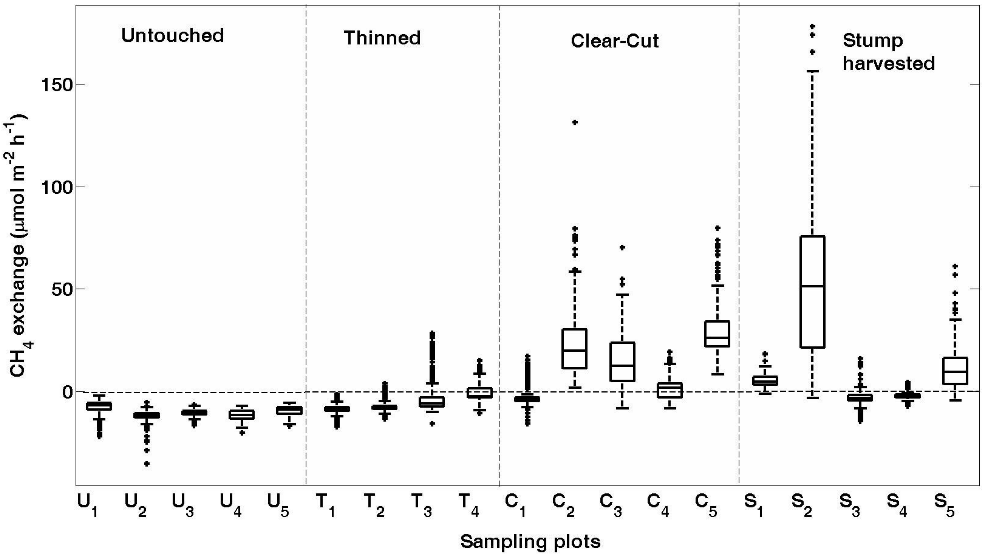

Fig. 2. Boxplots of CH_4 exchange (µmol m^{-2} h^{-1}) at all individual measurement locations. The middle line of the box and whisker plot represents the median of all recordings including night-time measurements. The edges of the box are the 25th and 75th percentiles, the whiskers, (black dotted lines) are the extreme values not considered outliers. Values larger than $q3 + w(q3 - q1)$ or smaller than $q1 - w(q3 - q1)$ are considered outliers, where $q1$ and $q3$ are the 25th and 75th percentiles, respectively, and $w = 1.5$ is the whisker length. The median values are all significantly different from zero at the 99 % significance level except for T_4, which is significant at the 95 % significance level.

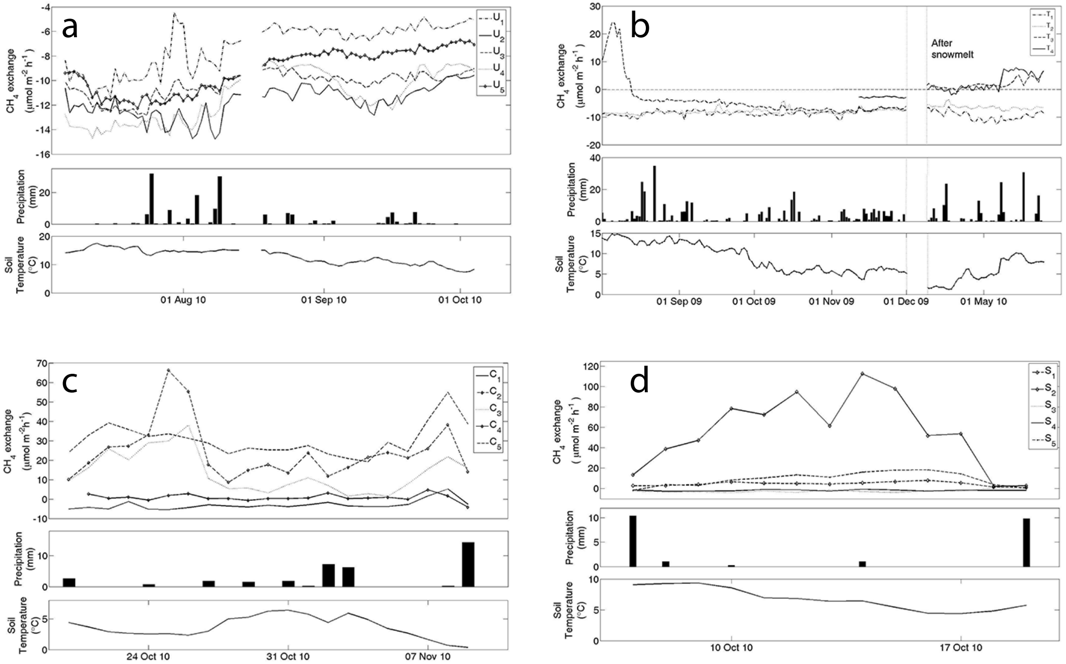

Fig. 3. Time series of daily mean CH_4 exchange, daily precipitation and daily mean soil temperature at the measurement locations. **(a)** Undisturbed plot, **(b)** Thinned plot, **(c)** Clear-cut plot, **(d)** stump harvested plot.

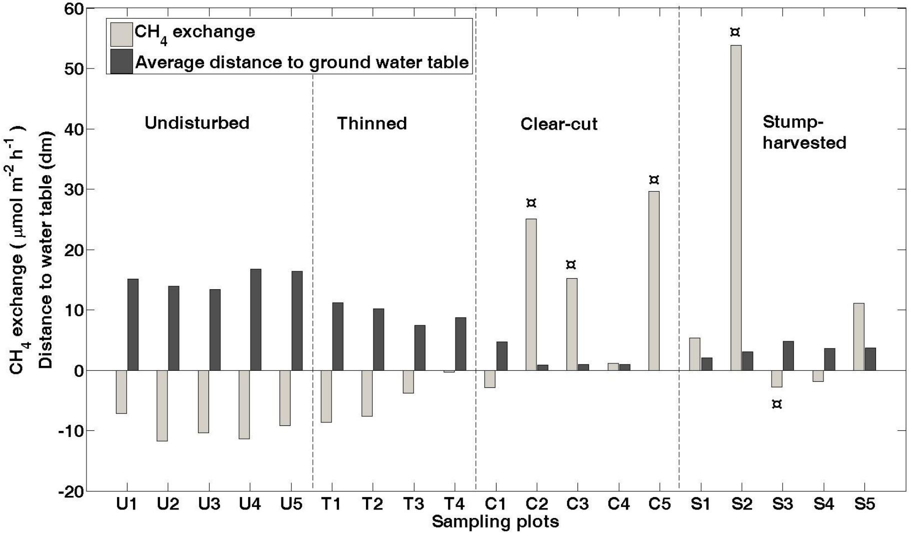

Fig. 4. CH_4 exchange ($\mu mol\,m^{-2}\,h^{-1}$) at all individual measurement locations with associated level of ground water table. The water table depth at plot C_5 is close to zero and that is why the bar is not visible in the diagram. ¤ Measurement locations where soil surface was disturbed during site preparation.

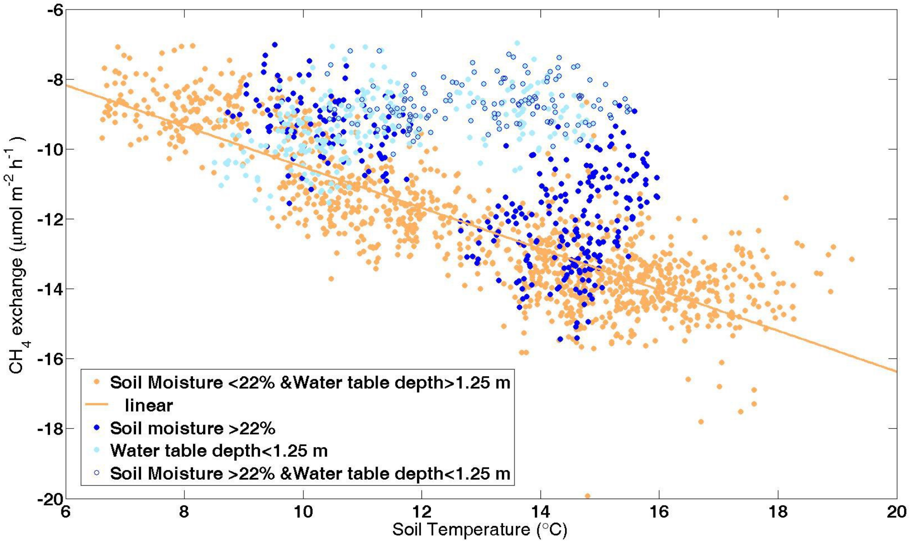

Fig. 5. Correlation between CH_4 exchange ($\mu mol\, m^{-2}\, h^{-1}$) and soil temperature (°C) at measurement location U_2. The different colours represent different soil moisture and water table depths.