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

E. Sundqvist [1], P. Vestin[1], P. Crill[2], T. Persson[3], A. Lindroth[1]

[1] Department of Physical geography and Ecosystem Science, Lund University
[2] Department of Geological Sciences, Stockholm University
[3] Department of Ecology, Swedish University of Agricultural Sciences

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 y^{-1} (Kirschke et al., 2013). The 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 (Fig.1). One plot contained undisturbed 120-yearold 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 simulate continuous cover forestry, 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 U1-U5 at the undisturbed plot, T1-T4 at the thinned plot, C1-C5 at the clear-cut plot and S1-S5 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 07 July 2010 to 04 October 2010, at the stump-harvested plot from 07 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 01 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 litres 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. This air stream was sub-sampled and passed through the analyser at a flow rate of 1.2 l/min. 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 meters 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 meters from the undisturbed plot (Fig. 1). 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 the 8th and 20th of October 2010 and 2nd of November 2010. Some of these pipes are shown in Fig.1. 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 organic 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 x 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 (T1, T4, U2, U6) 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 at the undisturbed and thinned plots were 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 hours 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 seconds intervals after chamber closure. The fit with the highest r^2 value was then selected. The CH_4 flux ($J_{CH4\,flux}$) was calculated as $J_{CH4\,flux} = \frac{dC}{dt}\frac{V}{A}$, where C is the molar density (µmol m^{-3}), V (m^3) is the chamber volume and A (m^2) is ground surface area. Fluxes with an r^2 value higher than 0.3 were generally kept for further analyses. An r^2 of 0.3 was the limit when the fluxes were significantly different from zero. A few outliers that passed the r^2 limit were visually sorted out based on normalized root mean square error. Data kept for further analyses corresponded to 98 % of the data at the undisturbed plot, 97 % of the data at the thinned plot, 84 % of the data at the clear-cut plot and 77 % of the data at the stump harvested plot.

Minimum flux detection limit (MDF) was calculated as $MDF = \frac{\sigma}{t}$, where t is the measurement time for one specific measurement and σ is the standard deviation for the concentration measurement. For a chamber the size as used in this study, the MDF for a single measurement was 2.8 μmol m^{-2} h^{-1}. For daily average values of hourly measurements this value is reduced to < 1 μmol $m^{-2}h^{-1}$ since the MDF value should be divided by the square root of the number of measurements. It is important to note that while fluxes below the MDF cannot be securely detected, they must still be considered. For example, consider time series where fluxes decrease smoothly from an emission peak to an uptake. In the transition phase from net emissions to net uptake, fluxes will be close to zero. Removing fluxes <MDF could possible bias the result towards a stronger sink or source than what times series from the individual chambers give support for. Therefore also the fluxes within the MDF interval will be kept in the analyses. Removing fluxes within the MDF interval for a single measurement (± 2.8 μmol m^{-2} h^{-1}) would lead to a decrease in the number of flux measurements by 0%, 16%, 13% and 30 % for the undisturbed, thinned, clear-cut and stump harvested plots respectively and not change the mean exchange of CH_4 at any of the plots by more than 0.6 μmol m^{-2} h^{-1}.

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 soil temperature, soil moisture, and water table depth on CH_4 exchange was analysed separately by Spearman linear correlations using the corr function, and by multiple linear regression on standardized data using the function stepwisefit (both Matlab version R2009b). The stepwise regression analyses were performed by bi-directional elimination. P-values were used in the selection process. The analysis was made on standardized data to adjust for the disparity in variable sizes, which makes the outcome of the analyses, the coefficients, comparable. The coefficients would be useful in modelling of CH_4 exchange. A variable with a larger coefficient has a higher impact on the CH_4 exchange. Standardization for a data point x_i was made by $x_i = \frac{x_i - \overline{x}}{\sigma}$ where $\overline{x}$ is the average of all data points and σ is the standard deviation of all data. An R^2 value for the overall model was also calculated showing how much of the variance in CH_4 exchange that is not explained by the environmental variables included in the analyses.

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.2, 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.2, 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 deeper ground water table than the stump harvested plot (Fig.2, 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 μmol m^{-2} h^{-1} and -5 μmol m^{-2} h^{-1} respectively, while the clear-cut plot and at the stump harvested plot were net sources of 13.6 μmol m^{-2} h^{-1} and 17 μmol m^{-2} h^{-1}, respectively (Fig.2). 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.3). 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 -11.6 μmol m^{-2} h^{-1} at the undisturbed plot, from -0.3 to -8.6 μmol m^{-2} h^{-1}at the thinned plot, from –3.0 to 32.5 μmol m^{-2} h^{-1} at the clear-cut plot and from -2.9 to 74.0 μmol m^{-2} h^{-1} at the stump harvested plot (Fig.3).

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_4.

Monthly multiple linear 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 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. However, according to the r^2 value of the overall model there are lot of unexplained variance in the CH_4 exchange at all measurement locations.

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 site 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 deeper water table depth gave higher CH_4 emissions (Table 2). The multiple linear regression confirmed the significantly negative correlation between CH_4 exchange and temperature at 6 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.2). 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 the 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.2). 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. The clear-cut and stump harvested plots are located on a plateau which is uphill from the thinned and undisturbed plots and hence topography should not be responsible for the higher water table at the clear-cut and stump harvested plots (Fig.1).

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 multiple linear regression analyses. However it appears that the rise of the 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 $U_{4,}$ 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 multiple linear 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. The result is difficult to explain since CH_4 production and oxidation are not measured separately. Soil temperature profiles at the clear-cut and stump harvested plots (data not shown) show that during the measurement period, changes in surface temperature, associated with periods of cloudy conditions and precipitation, at 5 cm depth are larger than at 20 and 40 cm depth. Methanotrophs are expected to be located closer to the soil surface than methanogens and the larger temperature increase at the surface might compensate their lower response to temperature, which could explain why net CH_4 exchange is negatively correlated to soil temperature during this period.

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 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). Increasing CH_4 uptake with time after afforestation can be an effect of an increase in the population of CH_4 oxidizing bacteria with time (Barcena et al., 2014) or better soil diffusivity and soil aeration with time (Christiansen & Gundersen, 2011; Peichl et al., 2010). A better soil aeration with time could be due to an increase in root biomass, which means that the roots over time loosen the soil and absorb more water (Peichl et al., 2010). 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 forest landscapes 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.

Acknowledgement

Support for this work was provided by Formas and by the Linnaeus Centre LUCCI (http://www.lucci.lu.se/index.html) funded by the Swedish Research Council. Airborne LiDAR for the Norunda site, the basis for the digital elevation model, was acquired with support from the British Natural Environment Research Council (NERC/ARSF/FSF grant EU10-01 and NERC/GEF grant 933). We thank Anders Båth and Tomas Karlsson for field assistance.

References

Bárcena, T.G., D’Imperio, L., Gundersen, P., Vesterdal, L., Priemé, A., and Christiansen, J.R., Conversion of cropland to forest increases soil CH4 oxidation and abundance of CH4 oxidizing bacteria with stand age: APPL SOIL ECOL, 79, 49-58, 2014

Bradford, M.A., Ineson, P., Wookey, P.A., and Lappin-Scott, H.M., Soil CH4 oxidation: response to forest clearcutting and thinning. SOIL BIOL BIOCHEM 32(7), 1035-1038, 2000

Castro, M.S., Gholz, H.L., Clark, K.K and Steudler, P.A., Effects of forest harvesting on soil methane fluxes in Florida slash pine plantations. CAN J FOREST RES, 30(10), 1534-1542, 2000

Christiansen, J.R., and Gundersen, P., Stand age and tree species affect N2O and CH4 exchange from afforested soils. BIOGEOSCIENCES, 8, 2535-2546, 2011

Dannenmann, M., Gasche, R., Ledebuhr, A., Holst, T,. Mayer, H and Papen, H., The effect of forest management on trace gas exchange at the pedosphere-atmosphere interface in beech (Fagus sylvatica L.) forests stocking on calcareous soils. EUR J FOREST RES, 126(2), 331-346, 2007

Dunfield, P., Knowles, R., Dumont, R and Moore, T.R., Methane production and consumption in temperature and sub-arctic pear soils-response to temperature and pH. SOIL BIOL BIOCHEM, 25(3), 321-326, 1993

Dutaur, L. and Verchot, L.V., A global inventory of the soil CH(4) sink. GLOBAL BIOGEOCHEM CY, 21(4), 2007

Ehhalt, D.H., Atmospheric cycle of methane. TELLUS, **26**(1-2), 58-70, 1974

Von Fischer, J.C. and Hedin, L.O., Separating methane production and consumption with a field-based isotope pool dilution technique. GLOBAL BIOGEOCHEM CY, 16(3), 8/1-8/13, 2002

Fiedler, S. and Sommer, M., Methane emissions, groundwater levels and redox potentials of common wetland soils in a temperate-humid climate. GLOBAL BIOGEOCHEM CY, 14(4), 1081-1093, 2000

Fiedler, S., Holl, B.S. and Jungkunst, H.F., Methane budget of a Black Forest spruce ecosystem considering soil pattern. BIOGEOCHEMISTRY, **76**(1), 1-20, 2005

Grunwald, D., Fender, A. C., Erasmi, S., and Jungkunst, H. F., Towards improved bottom-up inventories of methane from the European land surface, ATMOS ENVIRON, 51, 203-211, 2012

Gulledge, J. and Schimel, J.P., Moisture control over atmospheric CH4 consumption and CO2 production in diverse Alaskan soils. SOIL BIOL BIOCHEM, 30(8-9), 1127-1132, 1998

Harriss, R. C., Sebacher, D. I., and Day, F. P., Methane flux in the great dismal swamp, NATURE, *297*, 673-674, 1982

Hiltbrunner, D., Zimmermann, S., Karbin, S., Hagedorn, F., and Niklaus, P. A., Increasing soil methane sink along a 120-year afforestation chronosequence is driven by soil moisture, GLOBAL CHANGE BIOL, 18, 3664-3671, 2012

Hutsch, B.W., C.P. Webster, and Powlson D.S., Long term effects of nitrogen-fertilization on methane oxidation in soil of the broadbalk wheat experiment. SOIL BIOL BIOCHEM, 25(10), 1307-1315, 1993

Huttunen, J. T., Nykanen, H., Martikainen, P. J., and Nieminen, M., Fluxes of nitrous oxide and methane from drained peatlands following forest clear-felling in southern Finland, PLANT SOIL, 255, 457-462, 2003

Kagotani, Y., Hamabata, E., and Nakajima, T., Seasonal and spatial variations and the effects of clear-cutting in the methane absorption rates of a temperate forest soil. NUTR CYCL AGROECOSYS, 59(2)169-175, 2001

Kammann, C., Hepp, S., Lenhart, K., and Muller, C., Stimulation of methane consumption by endogenous CH4 production in aerobic grassland soil, SOIL BIOL BIOCHEM, 41, 622-629, 2009

Keller, M., Varner, R., Dias, J. D., Silva, H., Crill, P., and de Oliveira, R. C., Soil-atmosphere exchange of nitrous oxide, nitric oxide, methane, and carbon dioxide in logged and undisturbed forest in the Tapajos National Forest, Brazil, EARTH INTERACT. 9, 1-28, 2005

Kirschke, S., Bousquet, P., Ciais, P. Saunois, M., Canadell, J.G., Dlugokencky, E.J., Bergamaschi, P., Bergmann, D., Blake, D.R., Bruhwiler, L., Cameron-Smith, P., Castaldi, S., Chevallier, F., Feng, L., Fraser, A., Heimann, M., Hodson, E.L., Houweling, S., Josse, B., Fraser, P.J., Krummel1, P.B., Lamarque, J-F., Langenfelds, R.L., Quéré, C.L., Naik, V., O'Doherty, S., Palmer, P.I., Pison, I., Plummer, D., Poulter, B., Prinn, R.G., Rigby, M., Ringeval1, B., Santini, M., Schmidt, M., Shindell, D.T., Simpson, I.J., Spahni, R., Steele, L.P., Strode, S.A., Sudo, S., Szopa, S., van der Werf, G.R., Voulgarakis, A., van Weele, M., Weiss, R.F., Williams, J.E., and Zeng, G., Three decades of global methane sources and sinks. NAT GEOSCI, 6, 813-823, 2013

Koschorreck, M. and Conrad, R., Oxidation of atmospheric methane in soil-measurements in the field, in soil cores and in soil samples. GLOBAL BIOGEOCHEM CY, 7(1), 109-121. 1993

Le Mer, J. and Roger, P., Production, oxidation, emission and consumption of methane by soils: A review. EUR J SOIL BIOL, 37(1), 25-50, 2001

Lundin, L. C., Halldin, S., Lindroth, A., Cienciala, E., Grelle, A., Hjelm, P., Kellner, E., Lundberg, A., Molder, M., Moren, A. S., Nord, T., Seibert, J., and Stahli, M., Continuous long-term measurements of soil-plant-atmosphere variables at a forest site, AGR FOREST METEOROL, 98-9, 53-73, 1999

Megonigal, J.P. and Guenther, A.B., Methane emissions from upland forest soils and vegetation. TREE PHYSIOL, 28(4), 491-498, 2008

Mojeremane, W., Rees, R.M and Mencuccini, M., Effects of site preparation for afforestation on methane fluxes at Harwood Forest, NE England. BIOGEOCHEMISTRY, 97(1), 89-107, 2010

Mojeremane, W., Rees, R.M and Mencuccini, M., The effects of site preparation practices on carbon dioxide, methane and nitrous oxide fluxes from a peaty gley soil. FORESTRY, 85(1), 1-15, 2012

Ojima, D. S., Valentine, D. W., Mosier, A. R., Parton, W. J., and Schimel, D. S., Effect of land-use change on methane oxidation in temperate forest and grassland soils, CHEMOSPHERE, 26, 675-685, 1993

Peichl, M., Arain, M.A., Ullah, S., and Moore, T.R., Carbon dioxide, methane, and nitrous oxide exchanges in an age-sequence of temperate pine forests, GLOB CHANGE BIOL, 16 (8), 2198-2212, 2010

Prieme, A., Christensen, S., Dobbie, K. E., and Smith, K. A., Slow increase in rate of methane oxidation in soils with time following land use change from arable agriculture to woodland, SOIL BIOL BIOCHEM, 29, 1269-1273, 1997

Shindell, D. T., Faluvegi, G., Koch, D. M., Schmidt, G. A., Unger, N., and Bauer, S. E., Improved Attribution of Climate Forcing to Emissions, SCIENCE, 326, 716-718, 2009

Smith, K. A., Dobbie, K. E., Ball, B. C., Bakken, L. R., Sitaula, B. K., Hansen, S., Brumme, R., Borken, W., Christensen, S., Prieme, A., Fowler, D., Macdonald, J. A., Skiba, U., Klemedtsson, L., Kasimir-Klemedtsson, A., Degorska, A., and Orlanski, P., Oxidation of atmospheric methane in Northern European soils, comparison with other ecosystems, and uncertainties in the global terrestrial sink, GLOBAL CHANGE BIOL, 6, 791-803, 2000

Smolander, A., Priha, O., Paavolainen, L., Steer, J., and Malkonen, E., Nitrogen and carbon transformations before and after clear-cutting in repeatedly N-fertilized and limed forest soil, SOIL BIOL BIOCHEM, 30, 477-490, 1998

Steudler, P. A., Bowden, R. D., Melillo, J. M., and Aber, J. D., Influence of nitrogen-fertilization on methane uptake in temperate forest soils, NATURE, 341, 314-316, 1989

Steudler, P. A., Melillo, J. M., Bowden, R. D., Castro, M. S., and Lugo, A. E., The effects of natural and human disturbances on soil-nitrogen dynamics and trace gas fluxes in a Puerto-Rican wet forest. BIOTROPICA, 23, 356-363 1991

Sullivan, B., Kolb, T. E., Hart, S. C., Kaye, J. P., Dore, S., and Montes-Helu, M., Thinning reduces soil carbon dioxide but not methane flux from southwestern USA ponderosa pine forests, FOR ECOL MANAG, 255, 4047-4055, 2008

Tate, K. R., Ross, D. J., Scott, N. A., Rodda, N. J., Townsend, J. A., and Arnold, G. C. Post-harvest patterns of carbon dioxide production, methane uptake and nitrous oxide production in a Pinus radiata D. Don plantation, FOR ECOL MANAG, 228, 40-50, 2006

Teepe, R., Brumme, R., Beese, F., and Ludwig, B., Nitrous oxide emission and methane consumption following compaction of forest soils, SOIL SCI SOC AM J,68, 605-611, 2004

Thibodeau, L., Raymond, P., Camire, C., and Munson, A. D., Impact of precommercial thinning in balsam fir stands on soil nitrogen dynamics, microbial biomass, decomposition, and foliar nutrition, CAN J FOREST RES 30, 229-238, 2000

Van Amstel, A. Methane. A review, J INTEGR ENVIRON SCI, *9,* 5-30, 2012

Verchot, L. V., Davidson, E. A., Cattanio, J. H., and Ackerman, I.L., Land-use change and biogeochemical controls of methane fluxes in soils of eastern Amazonia, ECOSYSTEMS, 3, 41-56, 2000

Wachinger, G., Fiedler, S., Zepp, K., Gattinger, A., Sommer, M., and Roth, K., Variability of soil methane production on the micro-scale: spatial association with hot spots of organic material and Archaeal populations, SOIL BIOL BIOCHEM 32, 1121-1130, 2000

Wang, F.L. and Bettany, J.R., Methane emissions from a usually well-drained prairie soil after snowmelt and precipitation. CAN J SOIL SCI, 75(2), 239-241, 1995

Wang, Z.P. and Ineson, P., Methane oxidation in a temperate coniferous forest soil: effects of inorganic N. SOIL BIOL BIOCHEM, 35(3) 427-433, 2003

Whalen, S.C. and Reeburgh, W.S., Consumption of atmospheric methane by tundra soils. NATURE, 346(6280), 160-162, 1990

Whalen, S.C. and Reeburgh, W.S., Moisture and temperature sensitivity of CH4 oxidation in boreal soils. SOIL BIOL BIOCHEM, 28(10-11), 1271-1281, 1996

Wu, X., Bruggemann, N., Gasche, R., Papen, H., Willibald, G., and Butterbach-Bahl, K., Long-term effects of clear-cutting and selective cutting on soil methane fluxes in a temperate spruce forest in southern Germany, ENVIRON POLLUT, 159, 2467-2475, 2011

Zerva, A. and Mencuccini.M., Short-term effects of clearfelling on soil CO2, CH4, and N2O fluxes in a Sitka spruce plantation. SOIL BIOL BIOCHEM, **37**(11), 2025-2036, 2005

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 U1-U5 at the undisturbed plot, T1-T4 at the thinned plot, C1-C5 at the clear-cut plot and S1-S5 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	01 August 2009-31 May 2010	Mosses, bilberry	6.7	0.22	3.1	28.8-45.8	54-154
T_2	01 August 2009-31 May 2010	Mosses, bilberry	5.0	0.17	3.1	25.0-40.0	44-144
T_3	01 August 2009-31 May 2010	Mosses, bilberry	5.5	0.24	3.5	33.5-55.6	15-116
T_4	11 December 2009-31 May 2010	Mosses, bilberry	3.3	0.10	3.0	19.2-36.3	29-129
U_1	07 July 2010-04 October 2010	Mosses, bilberry	2.6	0.17	3.3	6.0-27.3	120-173
U_2	07 July 2010-04 October 2010	Mosses, bilberry	6.1	0.29	3.2	10.0-33.4	107-160
U_3	07 July 2010-04 October 2010	Mosses, bilberry	no data	no data	no data	9.4-37.0	102-155
U_4	07 July 2010-04 October 2010	Mosses, bilberry	2.3	0.09	3.3	6.6-32.9	136-190
U_5	07 July 2010-04 October 2010	Mosses, bilberry	3.9	0.15	3.4	7.8-23.5	132-185
S_1	07 October 2010-20 October 2010	Mosses, bilberry	14.1	0.45	4.4	42.0-42.9	20-21
S_2	07 October 2010-20 October 2010	Bare soil, mixed organic and mineral soil layers	6.0	0.19	4.4	23.4-25.3	31-32
S_3	07 October 2010-20 October 2010	Bare soil, mixed organic and mineral soil layers	19.0	0.62	4.4	30.0-33.2	47-48
S_4	07 October 2010-20 October 2010	Some vegetation and thick litter layer	no data	no data	no data	35.9-39.4	35-36
S_5	07 October 2010-20 October 2010	No vegetation and thick litter layer	no data	no data	no data	33.7-36.1	37-38
C_1	21 October 2010-09 November 2010	Mosses, bilberry	4.7	0.16	4.2	41.5-46.2	44-50
C_2	21 October 2010-09 November 2010	Bare soil, mixed organic and mineral soil layers	13.1	0.41	4.2	44.2-50.3	6-12
C_3	21 October 2010-09 November 2010	Bare soil, mixed organic and mineral soil layers	11.9	0.35	4.2	no data	7-13
C_4	21 October 2010-09 November 2010	Mosses, bilberry	9.5	0.30	4.2	56.6-57.6	6-13
C_5	21 October 2010-09 November 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 (BaCl2) for the undisturbed and thinned plots and pH (H2O) 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. The r^2 shows how well the combined variables explain the variance in the CH4 exchange. The correlation analyses are based on data from the entire measurement period.

	C *Soil temperature*	*P* *Soil temperature*	*C* *Soil moisture*	*P* *Soil moisture*	*C* *Water table depth*	*P* *Water table depth*	r^2
T_1	-0.09	**	0.57	**	0.12	**	0.27
T_2	-0.34	**	-0.23	**	0.46	**	0.26
T_3	0.34	**	0.72	**	0.45	**	0.61
T_4	0.28	**	-0.72	**	0.54	**	0.68
U_1	-0.61	**	0.48	**	0.51	**	0.47
U_2	-0.63	**	0.39	**	0.54	**	0.47
U_3	-0.57	**	0.44	**	0.55	**	0.53
U_4	-0.69	**	0.54	**	0.70	**	0.78
U_5	-0.82	**	0.54	**	0.69	**	0.81
S_1	-0.35	**	-0.18	*	*a*	*a*	*0.09*
S_2	-0.16	*	-0.10	0.09	*a*	*a*	*0.07*
S_3	-0.02	0.82	-0.09	0.21	*a*	*a*	*0.002*
S_4	-0.16	*	-0.009	0.9	*a*	*a*	*0.05*
S_5	-0.34	**	-0.46	*	*a*	*a*	*0.09*
C_1	-0.06	0.29	-0.13	*	0.03	0.54	0.14
C_2	-0.52	**	0.25	**	-0.07	0.13	0.22
C_3	-0.57	**	no data	no data	-0.47	**	0.46
C_4	-0.04	0.57	0.04	0.57	-0.01	0.91	0.01
C_5	-0.54	**	-0.03	0.54	-0.20	**	0.21

** significant, $p < 0.001$

* significant, $p < 0.05$

a, 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 multiple linear regression analyses. A value is given only if the variable significantly contributes to explain the variation in the CH_4 exchange. The r^2 shows how well the combined variables explain the variance in the CH4 exchange. S.m represents soil moisture, S.t, soil temperature and W.t, water table depth.

	T_1				T_2				T_3				T_4			
	r^2	**S.m.**	**S.t.**	**W.t.**	**r^2**	**S.m.**	**S.t.**	**W.t.**	**r^2**	**S.m.**	**S.t.**	**W.t.**	**r^2**	**S.m.**	**S.t.**	**W.t.**
Aug 09	0.58	0.61	-	0.43	0.24	0.14	-0.18	0.44	0.76	0.66	0.33	-	n.d	n.d	n.d	n.d
Sep 09	0.10	0.31	-	-	0.10	-	-0.28	-	0.28	0.52	-	-	n.d	n.d	n.d	n.d
Oct 09	0.18	0.27	-0.14	0.22	0.16	-0.28	-0.28	-0.20	0.10	-0.15	0.13	-0.21	n.d	n.d	n.d	n.d
Nov 09	0.31	0.44	-0.16	0.33	0.23	0.33	-0.44	0.43	0.33	-	0.13	0.50	0.04	-	0.20	-
Apr 10	0.31	0.54	0.39	0.34	0.27	0.65	-0.34	-0.59	0.10	-	-0.26	-	n.d	n.d	n.d	n.d
May 10	0.22	0.43	-	-0.18	0.10	-	-0.29	-	0.38	-0.49	-	0.46	0.62	n.d	0.79	n.d

	U_1				U_2				U_3				U_4				U_5			
	r^2	**S.m.**	**S.t.**	**W.t.**	**r^2**	**S.m.**	**S. t.**	**W.t.**	**r^2**	**S.m.**	**S.t.**	**W.t.**	**r^2**	**S.m.**	**S.t.**	**W.t.**	**r^2**	**S.m.**	**S.t.**	**W.t.**
Jul 10	0.22	0.42	-	-0.18	0.10	n.d	-0.24	0.22	0.42	0.60	-0.14	0.48	0.12	0.12	-0.28	-	0.49	0.20	-0.27	0.48
Aug 10	0.47	-	-0.12	0.62	0.56	n.d	-0.23	0.61	0.37	0.08	-	0.60	0.80	0.19	-0.18	0.79	0.78	0.15	-0.34	0.63
Sep 10	0.12	0.10	-0.29	-0.10	0.37	n.d	-0.60	-	0.10	0.11	-0.23	-0.10	0.63	0.46	-0.50	-	0.28	-	-0.51	-0.10

	S_1			S_2			S_3			S_4			S_5		
	r^2	**S.m.**	**S.t.**	**r^2**	**S.m.**	**S.t.**	**r^2**	**S.m.**	**S.t.**	**r^2**	**S.m.**	**S.t.**	**r^2**	**S.m.**	**S.t.**
Oct 10	0.09	-	-0.29	0.07	-0.27	-	0.002	-	-	0.05	0.10	0.10	0.09	-	-0.28

	C_1				C_2				C_3				C_4				C_5			
	r^2	**S.m.**	**S.t.**	**W.t.**	**r^2**	**S.m.**	**S.t.**	**W.t.**	**r^2**	**S.m.**	**S.t.**	**W.t.**	**r^2**	**S.m.**	**S.t.**	**W.t.**	**r^2**	**S.m.**	**S.t.**	**W.t.**
Oct -Nov 10	0.14	-	-0.32	-	0.22	0.29	-0.34	-0.38	0.46	n.d	-0.44	-0.44	0.01	-	-	-	0.21	-0.28	-0.59	0.12

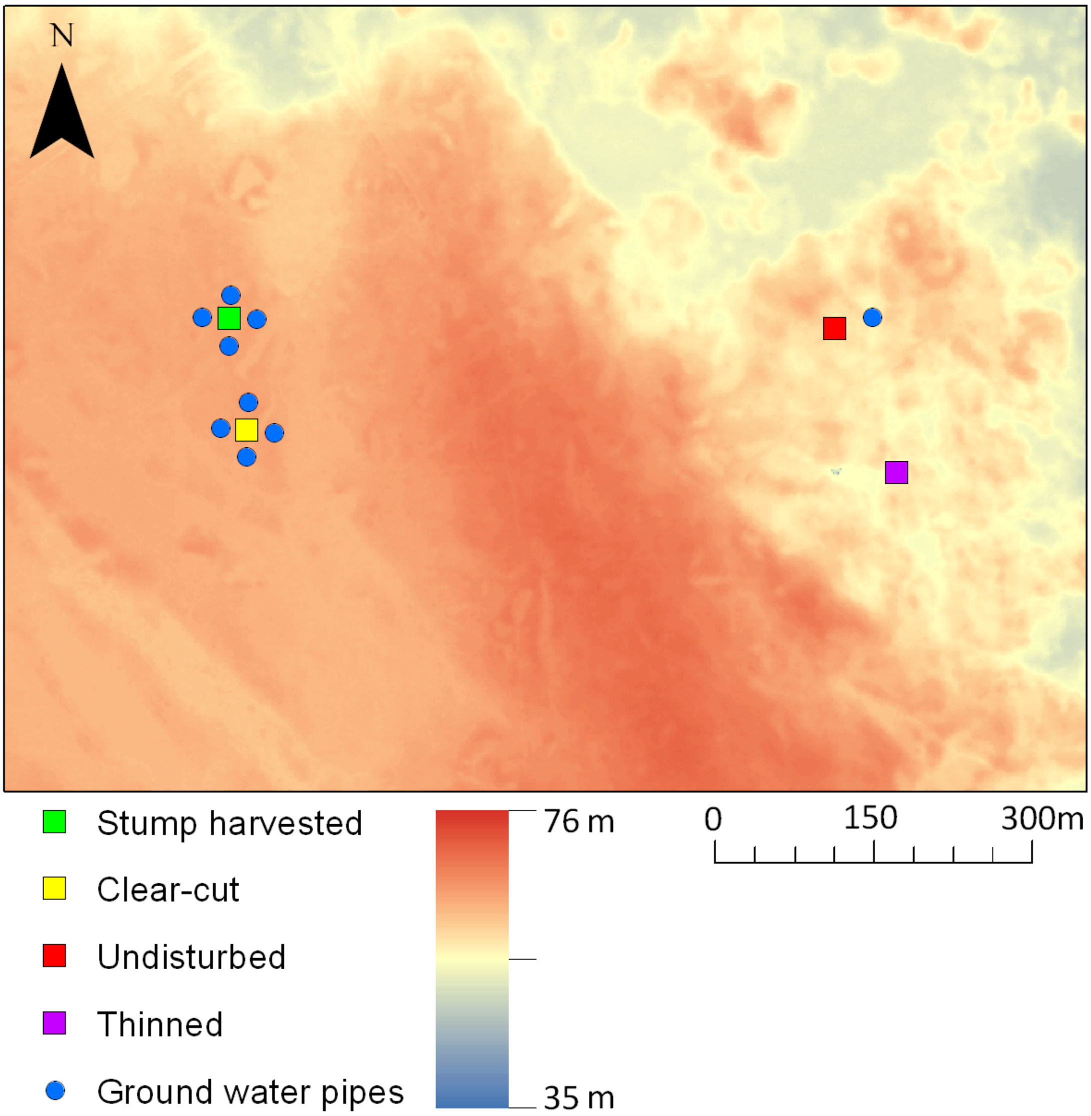

Fig.1. Schematic picture of the different plots and some of the ground water pipes. Three more pipes are located within the clear-cut and at the stump-harvested plots, but are covered by the plot symbol. The background consists of a digital elevation model showing the height above sea level for each square meter (DEM data kindly provided by N. Kljun et al.).

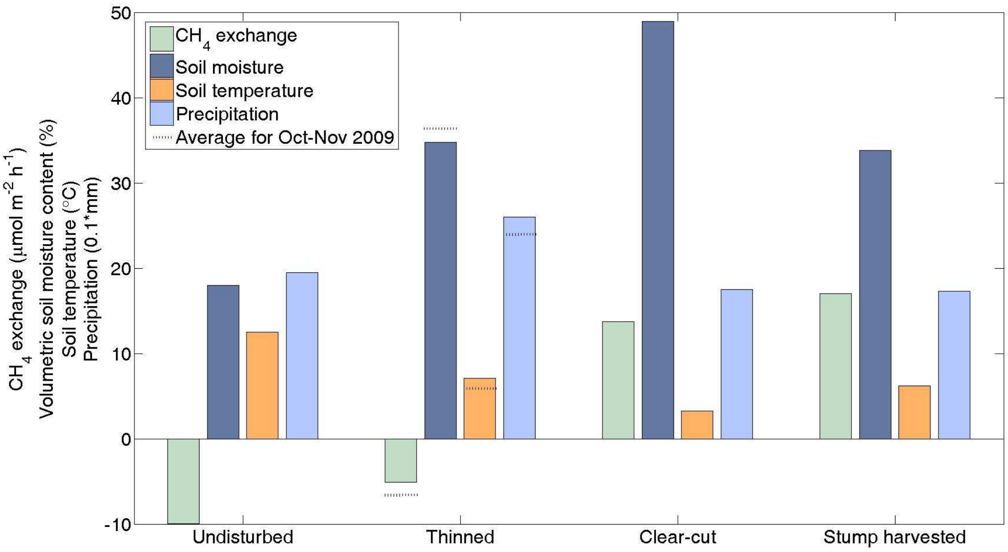

Fig.2. Average CH$_4$ exchange rates, soil moisture and soil temperature at the four sampling plots. Data from the entire measurement period at each plot is included. The dashed line at the thinned plot represents average values for October and November, since measurements at the clear-cut and stump harvested plots were conducted during this part of the year.

Fig.3a

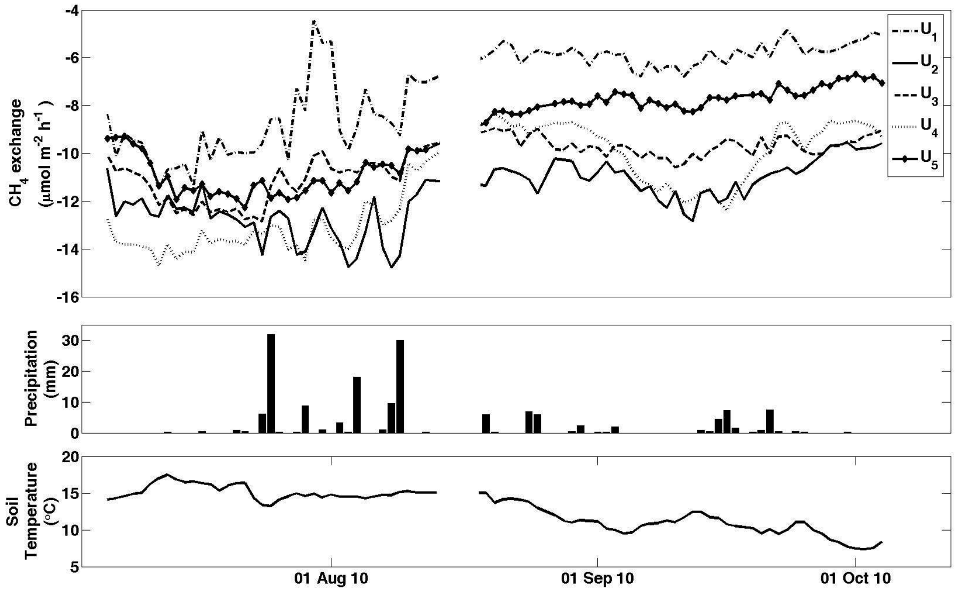
CH$_4$ exchange
(μmol m^{-2} h^{-1})
-4
-6
-8
-10
-12
-14
-16
U$_1$
U$_2$
U$_3$
U$_4$
U$_5$
Precipitation
(mm)
0
10
20
30
Soil
Temperature
(°C)
5
10
15
20
01 Aug 10
01 Sep 10
01 Oct 10

Fig.3b

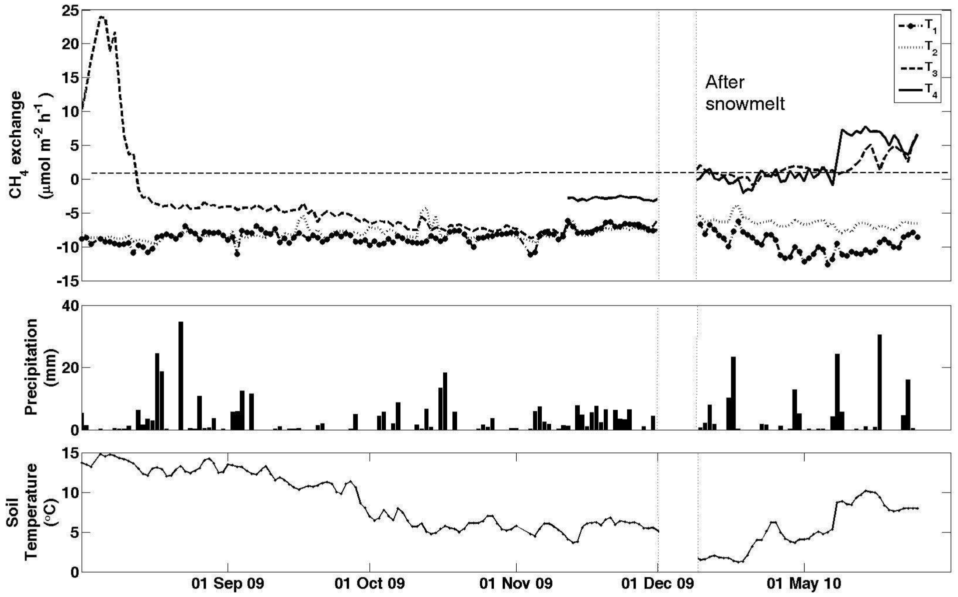
CH$_4$ exchange
(μmol m^{-2} h^{-1})
25
20
15
10
5
0
-5
-10
-15
T$_1$
T$_2$
T$_3$
T$_4$
After
snowmelt
Precipitation
(mm)
0
20
40
Soil
Temperature
(°C)
0
5
10
15
01 Sep 09
01 Oct 09
01 Nov 09
01 Dec 09
01 May 10

Fig.3c)

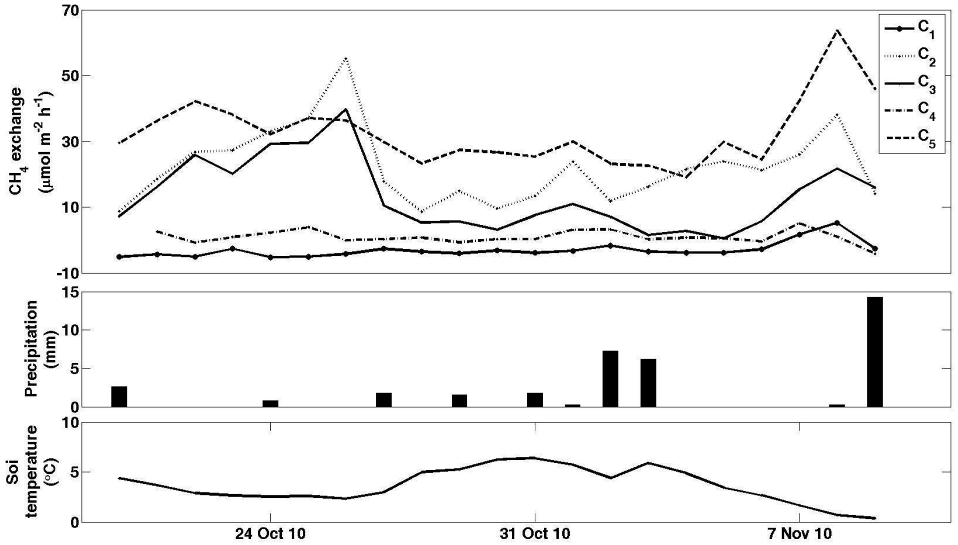

Fig.3d)

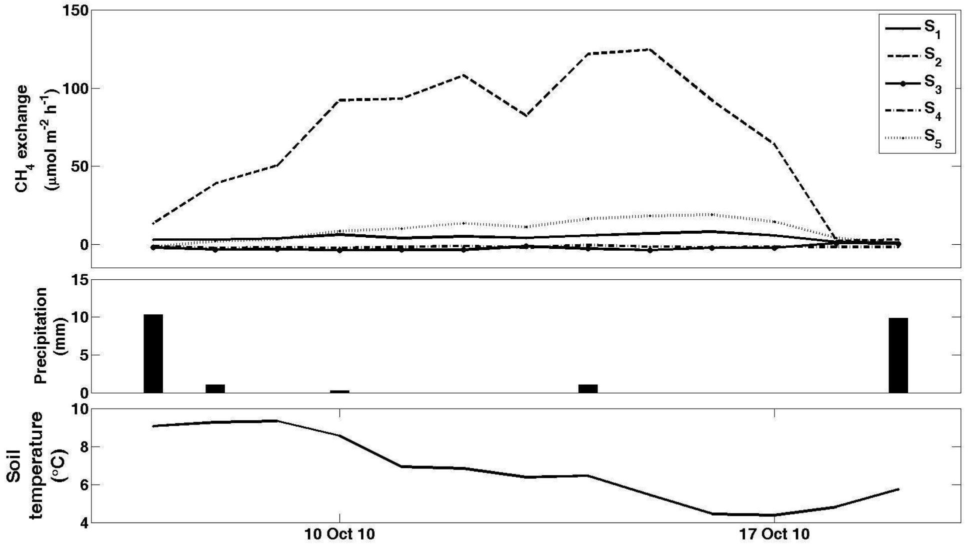

Fig.3. Time series of daily mean CH_4 exchange, daily precipitation and daily mean soil temperature at the measurement locations. Fig.3a) Undisturbed plot, Fig.3b) Thinned plot, Fig.3c) Clear-cut plot, Fig.3d) Stump harvested plot.

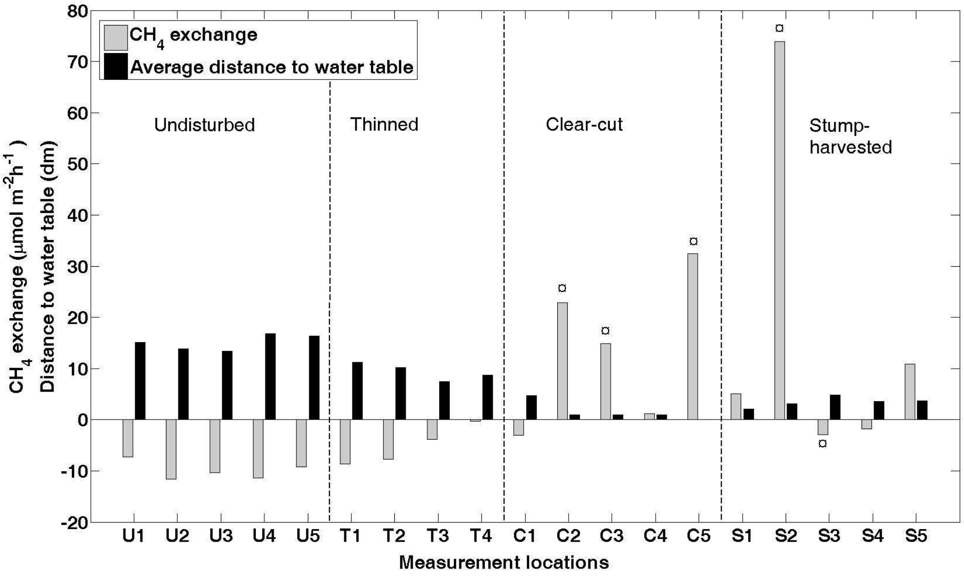

Fig.4. CH_4 exchange (µmol m^{-2} h^{-1}) at all individual measurement locations with associated level of ground water table. The water table depth at plot C_5 is close to zero and that is why the bar is not visible in the diagram.

¤ Measurement locations where soil surface was disturbed during site preparation.

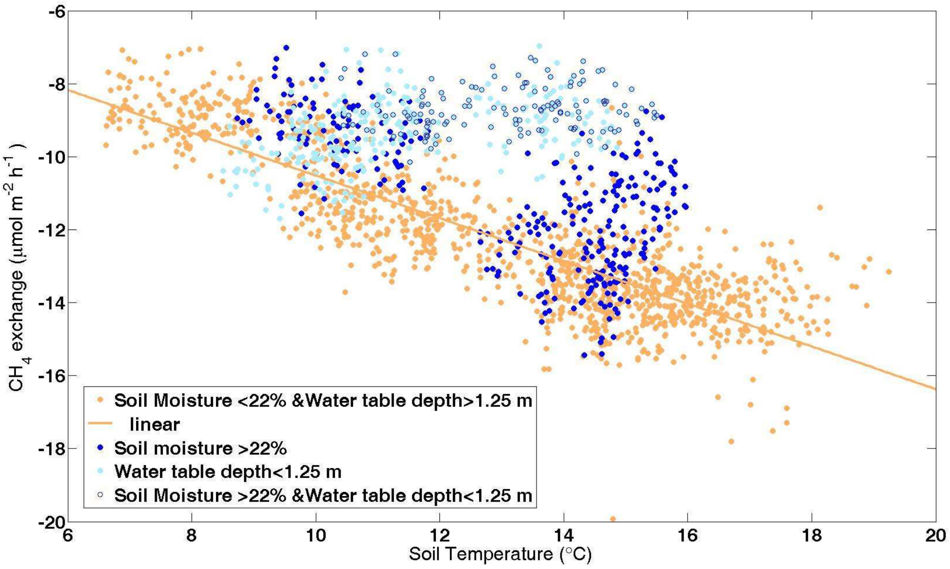

Fig.5. Correlation between CH_4 exchange (μmol m^{-2} h^{-1}) and soil temperature (˚C) at measurement location U_4. The different colours represent different soil moisture and water table depths.