

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

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9

10    **Abstract**

11    Forest management practices can alter soil conditions, affecting the consumption and  
12    production processes that control soil methane ( $\text{CH}_4$ ) exchange. We studied the short-  
13    term effects of thinning, clear-cutting and stump harvesting on the  $\text{CH}_4$  exchange  
14    between soil and atmosphere at a boreal forest site in central Sweden, using an  
15    undisturbed plot as the control. Chambers in combination with a high precision laser gas  
16    analyser were used for continuous measurements. Both the undisturbed plot and the  
17    thinned plot were net sinks of  $\text{CH}_4$ , whereas the clear-cut plot and the stump harvested  
18    plot were net  $\text{CH}_4$  sources. The  $\text{CH}_4$  uptake at the thinned plot was reduced in comparison  
19    to the undisturbed plot. The shift from sink to source at the clear-cut and stump harvested  
20    plots was probably due to a rise of the water table and an increase in soil moisture,  
21    leading to lower gas diffusivity and more reduced conditions which favour  $\text{CH}_4$   
22    production by archaea. Reduced evapotranspiration after harvesting leads to wetter soils,

23 decreased CH<sub>4</sub> consumption and increased CH<sub>4</sub> production, and should be accounted for  
24 in the CH<sub>4</sub> budget of managed forests.

25

26 **1. Introduction**

27 Methane (CH<sub>4</sub>) is the second most important carbon greenhouse gas, with a radiative  
28 forcing at least 25 times higher than carbon dioxide from a 100-year perspective  
29 (Shindell, et al., 2009). Consumption of CH<sub>4</sub> by methanotrophic bacteria in the aerobic  
30 part of the soil profile (Harriss et al., 1982) and production of CH<sub>4</sub> by archaeans in the  
31 anaerobic water-saturated part of the profile (Ehhalt, 1974) and at anaerobic micro-sites  
32 (von Fischer and Hedin, 2002; Kammann et al., 2009) often occur simultaneously (Le  
33 Mer and Roger, 2001; Megonigal and Guenther, 2008). Generally, well-aerated forest  
34 soil is a net sink of atmospheric CH<sub>4</sub> (Van Amstel 2012). Consumption in soils is the  
35 second largest sink of CH<sub>4</sub> after tropospheric oxidation by hydroxyl radicals with a global  
36 sink capacity estimated recently at 28-32 Tg CH<sub>4</sub> y<sup>-1</sup> (Kirschke et al., 2013). The soil sink  
37 capacity is higher in forest soils than in grasslands and arable land (Dutaur and Verchot,  
38 2007), and therefore the global CH<sub>4</sub> budget is sensitive to disturbances in forests.

39 Conversion of natural forests to arable land, increased N deposition from the atmosphere,  
40 and N-fertilization of agricultural lands are estimated to have reduced the global CH<sub>4</sub> soil  
41 sink by about 30 % between 1880 and 1980 (Ojima et al., 1993).

42

43 Disturbances, including forest management practices, can also have an impact on the soil  
44 CH<sub>4</sub> exchange by altering soil conditions such as soil moisture (Zerva and Menuccini,  
45 2005; Castro et al., 2000), water table depth (Zerva and Menuccini, 2005) bulk density

46 (Mojeremane et al., 2012), soil temperature (Zerva and Menuccini, 2005; Thibodeau et  
47 al., 2000), nutrient content (Smolander et al., 1998) and pH (Smolander et al., 1998). CH<sub>4</sub>  
48 oxidation in soil has been observed to be controlled by diffusivity (Koschorreck and  
49 Conrad, 1993; Whalen and Reeburgh, 1996; Gulledge and Schimel, 1998). A well-  
50 drained coarse soil facilitates the exchange of oxygen and CH<sub>4</sub> between the atmosphere  
51 and the deeper soil levels where CH<sub>4</sub> is consumed (Verchot et al., 2000). By contrast,  
52 increased soil moisture and soil compaction reduce the diffusivity, and promotes anoxic  
53 environments in which CH<sub>4</sub> can be produced (Koschorreck and Conrad, 1993; Whalen  
54 and Reeburgh, 1996; Gulledge and Schimel, 1998). Changes in water table depth also  
55 influence the CH<sub>4</sub> exchange by altering the relative extent of anaerobic and aerobic zones  
56 in the soil (Whalen and Reeburgh, 1990). Temperature is also an important driver of CH<sub>4</sub>  
57 production, with higher temperatures leading to higher CH<sub>4</sub> production, while  
58 consumption by methanotrophs is less strongly enhanced (Dunfield et al., 1993).

59 Increased nitrogen content in the soil has been shown to inhibit CH<sub>4</sub> consumption in  
60 several studies (Steudler et al., 1989; Hutsch et al., 1993; Wang and Ineson, 2003). This  
61 is due to competition by certain nitrifiers, which might occupy the same niche in the soil.  
62 These nitrifiers have an enzyme similar to methanotrophs and are also able to oxidize  
63 CH<sub>4</sub>, though possibly at a lower rate (Hutsch et al., 1993).

64

65 Summarizing the effects of forest management practices on CH<sub>4</sub> exchange is difficult  
66 since relatively few studies have been made on this topic, and they have covered a range  
67 of management practices, soil types and forests. However, several studies reported that  
68 clear-cutting led to reduced CH<sub>4</sub> uptake, possibly due to increased soil moisture (Wu et

69 al., 2011), increased nitrogen availability (Steudler et al., 1991; Bradford et al., 2000),  
70 changes in pH, (Bradford et al., 2000) and erosion (Kagotani et al., 2001). A shift from  
71 soil CH<sub>4</sub> sink to soil CH<sub>4</sub> source has been reported due to a rise in water table depth  
72 combined with increases in substrate availability (Zerva and Mencuccini, 2005) and due  
73 to increases in soil moisture (Castro et al., 2000). The same shift from sink towards  
74 emission has been seen following soil compaction by skid trails and machinery, as a part  
75 of clear-cutting (Teepe et al., 2004) and thinning (Keller et al., 2005). One study on a  
76 clear-cut drained peat soil showed no substantial changes in CH<sub>4</sub> exchange (Huttunen et  
77 al., 2003).

78

79 Site preparation by mounding at clear-cuts can have a negative impact on CH<sub>4</sub> exchange  
80 from a climate perspective. In one study, compaction of the soil by excavators during  
81 mounding increased CH<sub>4</sub> emissions (Mojeremane et al., 2012). CH<sub>4</sub> emissions from  
82 stagnant water in hollows created during mounding can sometimes exceed the  
83 consumption in the mineral soil on top of the mounds (Mojeremane et al., 2010).  
84 However, bedding after clear-cutting has resulted in reduced CH<sub>4</sub> emissions (Castro et al.,  
85 2000). Drainage can also reduce CH<sub>4</sub> emissions following clear-cutting, but its positive  
86 effect on CH<sub>4</sub> emissions was outweighed by increases in CO<sub>2</sub> emissions when drainage  
87 was conducted on saturated peaty soils (Mojeremane et al., 2012).

88

89 Stump harvesting for bioenergy production has recently been proposed as a way of  
90 substituting fossil fuel CO<sub>2</sub> emissions in Sweden. To our knowledge there are no  
91 publications on the effects of stump harvesting on CH<sub>4</sub> exchange, although it is likely to

92 have a similar effect to other clear-cutting and site preparation actions. There are a few  
93 studies on the effect of thinning on CH<sub>4</sub> exchange in a forest. Reduced CH<sub>4</sub> uptake due to  
94 increased nitrogen availability has been reported (Thibodeau et al., 2000). A study at  
95 three thinned plots in a temperate beech forest reported slightly reduced emissions at one  
96 plot, whereas the other two were not significantly different from the control plots  
97 (Dannenmann et al., 2007). Another study in a temperate forest actually showed an  
98 increased CH<sub>4</sub> uptake after thinning, as opposed to a decrease at two adjacent clear-cut  
99 areas (Bradford et al., 2000). Some studies found no significant changes in CH<sub>4</sub> exchange  
100 after thinning (Wu et al., 2011; Sullivan et al., 2008).

101

102 The objective of this study was to quantify the short-term CH<sub>4</sub> exchange at four sites: an  
103 undisturbed forest plot, a thinned forest plot, a clear-cut plot with stumps remaining, and  
104 a clear-cut plot with stumps removed. The comparison between the different treatments is  
105 facilitated because all four sites are within a defined area and have a common soil type.  
106 We also wanted to investigate how soil moisture, soil temperature and water table depths  
107 influenced the soil CH<sub>4</sub> exchange.

108

## 109 **2. Methods**

### 110 *2.1 Site description*

111 The CH<sub>4</sub> exchange measurements took place in a forested area on the southern edge of  
112 the boreal zone, at Norunda research station in central Sweden, 60°05' N, 17°29' E.  
113 Hourly automated chamber measurements were made using a system that was moved  
114 between 4 differently managed plots (Fig.1). One plot contained undisturbed 120-year-

115 old mixed pine (*Pinus sylvestris*) and spruce (*Picea abies*) forest, which had not been  
116 thinned or fertilized in several decades. The other three plots were recently (2009-2010)  
117 impacted by either thinning, clear-cutting or stump harvesting. Thinning was done in  
118 order to simulate continuous cover forestry, rather than to increase growth.

119 Measurements were made using four chambers at the thinned plot, and five  
120 chambers at each of the other plots. The chamber locations were named U1-U5 at the  
121 undisturbed plot, T1-T4 at the thinned plot, C1-C5 at the clear-cut plot and S1-S5 at the  
122 stump harvested plot. At the clear-cut and stump harvested plots half of the chamber  
123 frames were positioned on bare soil, where organic and mineral soil layers were mixed.  
124 The disturbance was caused either by stump harvesting, or by site preparation to facilitate  
125 the establishment and growth of new plants. The remaining frames were placed on soil  
126 surfaces with intact vegetation. The clear-cut and stump harvested plots had been  
127 fertilized in 1976, 1988 and 1998.

128 Ground vegetation was sparse and dominated by bilberry (*Vaccinium myrtillus*)  
129 and feather mosses (*Hylocomium splendens* and *Pleurozium schreberi*). There were more  
130 shrubs and grass at the clear-cut site, following the soil's disturbance. The soil was a  
131 glacial till (Lundin et al., 1999) with an organic layer of 3-10 cm depth. For the period  
132 1980-2010, the mean air temperature was 6.5 °C, and the mean annual precipitation was  
133 576 mm (measured 30 km south of Norunda).

134

## 135 2.2 *Timing of measurements*

136 Thinning took place in November 2008, the clear-cutting in February 2009 and stump  
137 harvesting in May 2010. Both the clear-cut plot and the stump harvested plot were

138 mounded and planted in May 2010. The chamber frames were installed in 2005 at the  
139 undisturbed and thinned plots, and in June 2010 at the clear-cut and stump harvested  
140 plots, to allow time for soil and vegetation to recover from the disturbance.

141 Due to equipment limitations, measurements were conducted at one plot at a time.  
142 Measurements at the thinned plot were made from 1 August 2009 to 31 May 2010, at the  
143 undisturbed plot from 07 July 2010 to 04 October 2010, at the stump-harvested plot from  
144 07 October 2010 to 20 October 2010 and at the clear-cut plot from 21 October to 9  
145 November 2010. Winter data at the thinned plot from 01 December 2009 to 14 April  
146 2010 were not used in the analyses due to uncertainties in the measurements caused by  
147 snow and frost.

148

### 149 *2.3 Equipment*

150 We used automated, transparent chambers of Polymethyl methacrylate in combination  
151 with a high precision off-axis integrated cavity output spectroscopy (ICOS) laser gas-  
152 analyser (DLT-100, Los Gatos Research (LGR)) for simultaneous concentration  
153 measurements of CH<sub>4</sub>, CO<sub>2</sub> and H<sub>2</sub>O. The chambers had a volume of 110 litres and  
154 covered a surface-area of 0.2 m<sup>2</sup>. Gas concentrations in the chambers were measured  
155 after closure by recirculating the air through the gas analyser for 6 min. The flow rate  
156 between chambers and manifolds was 8-10 l/min. This air stream was sub-sampled and  
157 passed through the analyser at a flow rate of 1.2 l/min. A fan was installed in each  
158 chamber, designed to ensure sufficient mixing of chamber headspace air without  
159 disturbing the laminar boundary layer at the ground. Soil moisture was measured in the  
160 chambers at 0-5 cm depth with a MI-2x thetaProbe from DeltaT Devices. The soil

161 temperature was measured at 5 cm depth inside the chambers using a type T  
162 thermocouple. Soil temperature measurements at the thinned plot did not work properly  
163 and so temperature data from the undisturbed plot, 125 meters away, was used instead.

164

165 *2.4 Water table*

166 There were differences in height between the chamber frames relative to the ground  
167 water table. One pipe with continuous measurements of the ground water table was  
168 located 125 m from the thinned plot and 30 meters from the undisturbed plot (Fig. 1). The  
169 groundwater table at these plots was treated as horizontal. At the clear-cut and stump  
170 harvested plots, the ground water table was measured manually in seven pipes at each  
171 plot, on the 8<sup>th</sup> and 20<sup>th</sup> of October 2010 and 2<sup>nd</sup> of November 2010. Some of these pipes  
172 are shown in Fig.1. An inverse distance-weighting model was used to calculate the height  
173 of the ground water table in relation to the ground surface for 40 m<sup>2</sup> areas surrounding the  
174 chamber frames. The ground water table was also measured continuously at one position  
175 on the clear-cut plot.

176

177 *2.5 Soil sampling*

178 Soil samples were taken in order to determine organic carbon (C) and nitrogen (N)  
179 content and pH in the top 20 cm of the soil including the humus layer, where the  
180 chambers had been positioned. The litter layer was not taken into account. Sampling was  
181 done in November 2010 at the clear-cut and stump harvested plots and in September  
182 2012 at the undisturbed and thinned plots.

183

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

192

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

205

206 At the undisturbed and thinned plots a cylindrical metal corer with an 11 cm<sup>2</sup> opening  
207 was pressed horizontally into the humus layer, and also at 5 cm and 10 cm depth in the  
208 mineral layer. At some of the measurement locations (T1, T4, U2, U6) large stones, rocks  
209 and roots occupied a large volume of the mineral soil so that sampling at 10 cm depth in  
210 the mineral soil was not possible. The soil samples were kept below 5°C until they were  
211 analysed.

212

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

219

## 220 *2.6 Data analyses*

221 The rate of change of CH<sub>4</sub> concentration (dC<sub>CH<sub>4</sub></sub>/dt) within the chamber was calculated  
222 using a linear fit to the first two minutes of concentration data measured by the gas  
223 analyser, beginning immediately after chamber closure. We calculated the r<sup>2</sup> values for  
224 the fits of five different slopes, which were lagged at 10 seconds intervals after chamber  
225 closure. The fit with the highest r<sup>2</sup> value was then selected. The CH<sub>4</sub> flux ( $J_{CH_4flux}$ ) was

226 calculated as  $J_{CH_4flux} = \frac{dC}{dt} \frac{V}{A}$ , where C is the molar density (μmol m<sup>-3</sup>), V(m<sup>3</sup>) is the

227 chamber volume and A (m<sup>2</sup>) is ground surface area. Fluxes with an r<sup>2</sup> value higher than  
228 0.3 were generally kept for further analyses. An r<sup>2</sup> of 0.3 was the limit when the fluxes

229 were significantly different from zero. A few outliers that passed the  $r^2$  limit were  
230 visually sorted out based on normalized root mean square error. Data kept for further  
231 analyses corresponded to 98 % of the data at the undisturbed plot, 97 % of the data at the  
232 thinned plot, 84 % of the data at the clear-cut plot and 77 % of the data at the stump  
233 harvested plot.

234

235 Minimum flux detection limit (MDF) was calculated as  $MDF = \frac{\sigma}{t}$ , where  $t$  is the  
236 measurement time for one specific measurement and  $\sigma$  is the standard deviation for the  
237 concentration measurement. For a chamber the size as used in this study, the MDF for a  
238 single measurement was  $2.8 \mu\text{mol m}^{-2} \text{h}^{-1}$ . For daily average values of hourly  
239 measurements this value is reduced to  $< 1 \mu\text{mol m}^{-2}\text{h}^{-1}$  since the MDF value should be  
240 divided by the square root of the number of measurements. It is important to reflect on  
241 that while fluxes below the MDF cannot be securely detected, they must still be  
242 considered. For example, consider time series where fluxes decrease smoothly from an  
243 emission peak to an uptake. In the transition phase from net emissions to net uptake,  
244 fluxes will be close to zero. Removing fluxes  $<\text{MDF}$  could possible bias the result  
245 towards a stronger sink or source than what times series from the individual chambers  
246 give support for. Therefore also the fluxes within the MDF interval will be kept in the  
247 analyses. Sorting out fluxes within the MDF interval for a single measurement ( $\pm 2.8$   
248  $\mu\text{mol m}^{-2} \text{h}^{-1}$ ) would lead to a decrease in the number of flux measurements with 0%,  
249 16%, 13% and 30 % for the undisturbed, thinned, clear-cut and stump harvested plots  
250 respectively and not change the mean exchange of  $\text{CH}_4$  at any of the plots with more than

251 0.6  $\mu\text{mol m}^{-2} \text{h}^{-1}$ . Nonetheless, the MDF is a valuable tool for determining how large  
252 portion of the data that is uncertain in a statistical sense.

253

254 Correction of the measured  $\text{CH}_4$  concentrations for dilution by water vapour was only  
255 possible at the undisturbed, clear-cut and stump harvested plots after water vapour  
256 measurements started in June 2010. This means that daytime data (global radiation  $> 20$   
257  $\text{W/m}^2$ ) from the thinned plot had to be excluded from the analyses. During night the  
258 dilution effect had very little impact.

259

260 The impact of the environmental variables soil temperature, soil moisture, and water table  
261 depth on  $\text{CH}_4$  exchange was analysed separately by Spearman linear correlations using  
262 the corr function, and by multiple linear regression on standardized data using the  
263 function stepwisefit (both Matlab version R2009b). The stepwise regression analyses  
264 were performed by bi-directional elimination. P-values were used in the selection  
265 process. The analysis was made on standardized data to adjust for the disparity in  
266 variable sizes, which makes the outcome of the analyses, the coefficients, comparable.  
267 The coefficients are the number that the variables would be multiplied by if  $\text{CH}_4$   
268 exchange were to be modelled. A variable with a larger coefficient has a higher impact on

269 the  $\text{CH}_4$  exchange. Standardization for a data point  $x_i$  was made by  $x_i = \frac{x_i - \bar{x}}{\sigma}$  where  $\bar{x}$   
270 is the average of all data points and  $\sigma$  is the standard deviation of all data. An  $R^2$  value  
271 for the overall model was also calculated showing how much of the variance in  $\text{CH}_4$   
272 exchange that is not explained by the environmental variables included in the analyses.

273

274 The significance of mean values at the measurement locations was calculated with the  
275 *ttest* function (also Matlab version R2009b).

276

277 **3. Results**

278 *3.1 Environmental conditions*

279 There were differences in soil moisture and soil temperatures among the plots. On  
280 average the undisturbed forest plot, with measurements exclusively from the summer  
281 season, July through September, had the driest and warmest records, and also the  
282 measurement locations were further above the ground water table than at other plots  
283 (Fig.2, Table 1). The clear-cut plot, which was measured in October and November,  
284 showed the coldest and wettest conditions including the highest water table. Four of the  
285 five measurement locations at this plot were on average less than 15 cm above the ground  
286 water table (Fig.2, Table 1). The thinned plot and the stump harvested plot had similar  
287 average moisture and temperature conditions, but the measurements at the thinned plot  
288 proceeded over a longer time period and thus the conditions varied more. The thinned  
289 plot also had a generally deeper ground water table than the stump harvested plot (Fig.2,  
290 Table 1).

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

293

294 *3.2 CH<sub>4</sub> exchange*

295 The mean CH<sub>4</sub> exchange of all measurement locations within the plots were as follows:  
296 the undisturbed plot and the thinned plot were net CH<sub>4</sub> sinks of -10  $\mu\text{mol m}^{-2} \text{h}^{-1}$  and -5

297  $\mu\text{mol m}^{-2} \text{h}^{-1}$  respectively, while the clear-cut plot and at the stump harvested plot were  
298 net sources of  $13.6 \mu\text{mol m}^{-2} \text{h}^{-1}$  and  $17 \mu\text{mol m}^{-2} \text{h}^{-1}$ , respectively (Fig.2). However, the  
299  $\text{CH}_4$  exchange varied within the plots. At the clear-cut and stump harvested plots, both  
300 net sources and net sinks existed (Fig.3). Plot T<sub>3</sub> and T<sub>4</sub> at the thinned plot shifted  
301 between net daily  $\text{CH}_4$  sinks and net daily  $\text{CH}_4$  sources on a few occasions (Fig.3b).  
302 Fluxes ranged from -7.2 to -11.6  $\mu\text{mol m}^{-2} \text{h}^{-1}$  at the undisturbed plot, from -0.3 to -8.6  
303  $\mu\text{mol m}^{-2} \text{h}^{-1}$  at the thinned plot, from -3.0 to 32.5  $\mu\text{mol m}^{-2} \text{h}^{-1}$  at the clear-cut plot and  
304 from -2.9 to 74.0  $\mu\text{mol m}^{-2} \text{h}^{-1}$  at the stump harvested plot (Fig.3).  
305

### 306 *3.3 Drivers of $\text{CH}_4$ exchange at the undisturbed and thinned plots*

307 Linear regression analyses between  $\text{CH}_4$  exchange and climatic variables showed that for  
308 most measurement locations at the undisturbed and thinned plots, consumption  
309 significantly ( $p<0.001$ ) increased with decreasing soil water content, decreasing water  
310 table depth and increasing temperatures. Exceptions to this were net  $\text{CH}_4$  uptake at  
311 locations T<sub>3</sub> and T<sub>4</sub> which decreased with increasing temperatures, and net  $\text{CH}_4$  uptake at  
312 locations T<sub>2</sub> and T<sub>4</sub>, which decreased with decreasing soil moisture (Table 2). Figure 5  
313 shows an example of the  $\text{CH}_4$  exchange response to temperature and soil water conditions  
314 at plot U<sub>4</sub>.

315 Monthly multiple linear regression analyses (Table 3) added some temporal  
316 information to the  $\text{CH}_4$  exchange at the undisturbed and thinned plots. At the undisturbed  
317 plot the water table depth affected  $\text{CH}_4$  consumption in August. In September 2010  
318 temperature was the most influential variable at all measurement locations. In July 2010  
319 the result was less distinct, showing some measurement locations with a higher

320 dependency on water table depth and soil moisture, and some measurement locations  
321 with a higher dependency on temperature. The clearest result at the thinned plot was a  
322 dependency on soil moisture at measurement locations  $T_1$  and  $T_3$  in August 2009 and at  
323 locations  $T_1$  and  $T_2$  in April 2010 (Table 3). Soils were wetter than average in August and  
324 April due to heavy rains in June and July 2009, and snowmelt in spring 2010. However,  
325 according to the  $r^2$  value of the overall model there are lot of unexplained variance in the  
326  $\text{CH}_4$  exchange at all measurement locations.

327

### 328 *3.4 Drivers of $\text{CH}_4$ exchange at the clear-cut and stump harvested plots*

329 Generally at the clear-cut and stump harvested plots, the measurement locations with net  
330 emissions of  $\text{CH}_4$  had either a relatively short distance to water table, or were disturbed  
331 by site preparation, or both, although there were exceptions. Plot  $S_4$  and  $S_5$  had the same  
332 water table depth and were not disturbed by site preparation, but plot  $S_4$  was a  $\text{CH}_4$  sink  
333 while plot  $S_5$  was a  $\text{CH}_4$  source (Fig.4).

334 At the majority of the measurement locations on the clear-cut and stump  
335 harvested plots, higher temperatures correlated significantly ( $p<0.05$ ) with lower  $\text{CH}_4$   
336 emissions, or in one case with a higher net uptake. Both negative and positive significant  
337 correlations between  $\text{CH}_4$  exchange and soil moisture was found at a few measurement  
338 locations but the soil moisture range at those measurement locations was very small. At  
339 two measurement locations with net emissions at the clear-cut plot, there was a  
340 significant ( $p<0.05$ ) negative correlation between  $\text{CH}_4$  exchange and water table depth, so  
341 that a deeper water table depth gave higher  $\text{CH}_4$  emissions (Table 2). The multiple linear

342 regression confirmed the significantly negative correlation between CH<sub>4</sub> exchange and  
343 temperature at 6 measurement locations.

344

345 **4. Discussion**

346 All measurement locations at the undisturbed forest plot were sinks of CH<sub>4</sub> throughout  
347 the measurement period, which is consistent with the generally drained, drier and warmer  
348 soil conditions at the plot (Fig.2). The measurement locations at the thinned plot were  
349 also net sinks of CH<sub>4</sub>, although reduced in comparison to the undisturbed plot. By  
350 contrast, the clear-cut and stump harvested plots were net sources of CH<sub>4</sub>. Since the  
351 measurements at the different plots were conducted at different times of the year,  
352 seasonality and annual variations can probably explain some of the differences in CH<sub>4</sub>  
353 exchange and soil conditions. However, it is not likely that differences in water table  
354 depth between the plots are due solely to seasonal variations. In the autumn of 2010 the  
355 water table was on average more than 1 m higher at the clear-cut and stump harvested  
356 plots than at the undisturbed plot. In addition to this, the mean CH<sub>4</sub> exchange for the  
357 autumn period October to November at the thinned site did not differ much from the  
358 mean CH<sub>4</sub> exchange for the whole measurement period, indicating that average seasonal  
359 variations are small (Fig.2). Precipitation was on average higher during the measurement  
360 period at the thinned site than during measurements at the other plots, which did not  
361 cause a switch from CH<sub>4</sub> sink to CH<sub>4</sub> source. The clear-cut and stump harvested plots are  
362 located on a plateau which is uphill from the thinned and undisturbed plots and hence  
363 topography should not be responsible for the higher water table at the clear-cut and stump  
364 harvested plots (Fig.1).

365 Water table depth, soil moisture and soil temperature were all shown to be  
366 important drivers of CH<sub>4</sub> exchange, as demonstrated by the linear and multiple linear  
367 regression analyses. However it appears that the rise of the water table and increased soil  
368 moisture caused some of the measurement locations to shift to CH<sub>4</sub> sources. This is  
369 consistent with results by Zerva and Menuccini (2005) and Castro et al, (2000).  
370 Temporal shifts to CH<sub>4</sub> emissions after snowmelt and summer precipitation, as were seen  
371 at measurement locations T<sub>3</sub> and T<sub>4</sub>, were also reported by Wang and Bettany, (1995).

372 A majority of net emitting measurement locations at the clear-cut and stump  
373 harvested plots (C<sub>2</sub>, C<sub>3</sub>, C<sub>4</sub>, C<sub>5</sub>, S<sub>1</sub>) were positioned less than 21 cm above the water table,  
374 and had a volumetric soil moisture content above 40% (Table 1). Also measurement  
375 location T<sub>3</sub>, when it had temporarily shifted to a CH<sub>4</sub> source, had volumetric soil moisture  
376 content above 40%. Net emissions were also measured at measurement location S<sub>2</sub> and S<sub>5</sub>  
377 with water table depths at 30-40 cm and volumetric soil moisture contents of 23-40%.  
378 Fiedler and Sommer (2000) found a threshold value of water table depth at 15 cm, below  
379 which only minor annual emissions were measured. The three measurement locations at  
380 the clear-cut and stump harvested plots which showed net consumption of CH<sub>4</sub> were  
381 further than average above the water table for those plots (Fig.4).

382  
383 Temperature seemed to have a stronger impact on CH<sub>4</sub> exchange in drier conditions.  
384 Figure 5 illustrates a high correlation,  $r^2 = 0.74$ , between soil temperature and CH<sub>4</sub>  
385 exchange at measurement location U<sub>4</sub>, when excluding data points with soil moisture  
386 above 22% and a distance to the water table of less than 1.25 m. The threshold value of  
387 22% was selected after visual inspection of the data. If all the data from wetter conditions

388 were included (volumetric soil moisture content > 22 % and water table < 1.25 m away),  
389 the corresponding  $r^2$  equals 0.47. This is consistent with the results from the multiple  
390 linear regression analyses showing that water table depth had a significant impact on the  
391  $\text{CH}_4$  exchange at all measurement locations in August 2010, when the water table depth  
392 varied strongly. In contrast, during September, there were no major precipitation events  
393 and soil temperature was the most influential variable. Soil moisture was rarely below 30  
394 % at the thinned plot, thus the temperature dependence was less. In autumn, September  
395 to November 2009, all measurement locations at the thinned plot were stable sinks of  
396  $\text{CH}_4$ , even though the soil temperature was at times below 5°C.

397 At the clear-cut and stump harvested plots, where most measurement locations were net  
398 sources of  $\text{CH}_4$ , we would expect a positive correlation between soil temperature and  $\text{CH}_4$   
399 exchange, so that higher temperatures led to higher net emissions of  $\text{CH}_4$ . Methanogens  
400 generally respond better than methanotrophs to increased temperatures (Dunfield et al.,  
401 1993). However this was not the case: a majority of the measurement locations showed a  
402 significantly negative correlation between temperature and  $\text{CH}_4$  exchange. The result is  
403 difficult to explain since  $\text{CH}_4$  production and oxidation are not measured separately. Soil  
404 temperature profiles at the clear-cut and stump harvested plots (data not shown) show  
405 that during the measurement period, changes in surface temperature, associated with  
406 periods of cloudy conditions and precipitation, at 5 cm depth are larger than at 20 and 40  
407 cm depth. Methanotrophs are expected to be located closer to the soil surface than  
408 methanogens and the larger temperature increase at the surface might compensate their  
409 lower response to temperature, which could explain why net  $\text{CH}_4$  exchange is negatively  
410 correlated to soil temperature during this period.

411

412 The highest CH<sub>4</sub> emissions were found at four of the five disturbed measurement  
413 locations: that is, sites of bare soil where organic and mineral soils were mixed. The soil  
414 at disturbed measurement locations seemed less compact than at measurement locations  
415 with intact vegetation, so the disturbance probably did not inhibit diffusion. Possibly the  
416 availability of fresh organic material was higher at disturbed measurement locations.  
417 Fresh, labile organic matter would promote heterotrophic uptake of O<sub>2</sub> and increase the  
418 soil's water retention, thereby promoting the activity of methanogenic archeans  
419 (Wachinger et al., 2000). The one disturbed measurement location, which showed net  
420 CH<sub>4</sub> consumption, S<sub>3</sub>, was positioned on top of a mound with relatively large distance to  
421 the ground water table (Fig.4).

422

423 Since this is a study of the short-term effects of forest management practices on CH<sub>4</sub>  
424 exchange, there are no data on how long-lived these effects are. Sudden shifts from sinks  
425 to sources and back again due to changes in soil water conditions are evident, as we have  
426 seen at the thinned plot (Fig.3b). It might take years (Tate et al., 2006) to several decades  
427 for a soil to regain its full sink capacity. The recovery time for the soil CH<sub>4</sub> sink strength  
428 of forests on abandoned agricultural land was more than 100 years (Prieme et al., 1997;  
429 Smith et al., 2000). Increasing CH<sub>4</sub> uptake with time after afforestation can be an effect  
430 of an increase in the population of CH<sub>4</sub> oxidizing bacteria with time (Barcena et al.,  
431 2014) or better soil diffusivity and soil aeration with time (Christiansen & Gundersen,  
432 2011; Peichl et al., 2010). A better soil aeration with time could be due to an increase in  
433 root biomass, which means that the roots over time loosen the soil and absorb more water

434 (Peichl et al., 2010). Hiltbrunner et al, (2012) found that the soil CH<sub>4</sub> sink capacity of  
435 abandoned agricultural land increased with stand age up to 120 years, due to the  
436 increased transpiration of older forests and their ability to shield the forest floor from  
437 precipitation, which resulted in more favourable conditions for methanotrophic activity.

438

439 Uptake rates by forest landscapes might be overestimated (Grunwald et al., 2012; Fiedler  
440 et al., 2005). A study by Grunwald et al, (2012) found that wet forests were as important  
441 as wetlands for the CH<sub>4</sub> budget of European forests, and Fiedler et al, (2005) found that if  
442 2.3% of a forest area consisted of wet soil the forest could turn from a sink to a source of  
443 CH<sub>4</sub>. As mentioned, after clear-cutting, water table depth decreased and soil moisture  
444 increased. Wetter soils and a higher ground water table are common consequences of  
445 clear-cutting, and it is therefore important to consider their impact on the CH<sub>4</sub> budget in  
446 managed forests, especially if the recovery time for the soil CH<sub>4</sub> sink is several decades.  
447 In this study the effects of thinning on the CH<sub>4</sub> exchange were not as pronounced as for  
448 clear-cutting, although the plot average consumption was reduced in comparison to the  
449 undisturbed plot. Any forest management practice that reduces disturbance and leaves a  
450 continuous forest cover might be a better alternative from a global warming perspective.

451

## 452 **5. Conclusions**

453 Our study on the short term effects of boreal forest management on CH<sub>4</sub> exchange shows  
454 that the undisturbed plot and the thinned plot remained net CH<sub>4</sub> sinks, while the clear-cut  
455 and stump harvested plots were net CH<sub>4</sub> sources. Linear regression analyses between CH<sub>4</sub>  
456 exchange and climatic variables showed that for most measurement locations at the

457 undisturbed and thinned plots, net CH<sub>4</sub> uptake increased significantly with decreasing soil  
458 moisture, decreasing water table depth and increasing temperatures. A higher water table  
459 and increased soil moisture were likely to be responsible for the shift to CH<sub>4</sub> emissions at  
460 the clear-cut and stump harvested plots. At most of the measurement locations, which  
461 showed net emissions, the soil was almost saturated and the water table was within a few  
462 decimetres of the soil surface. Clear-cutting of the forest resulted in a raised ground water  
463 table and in increased soil moisture. These effects should be accounted for in the CH<sub>4</sub>  
464 budget of managed forests.

465

#### 466 **Acknowledgement**

467 Support for this work was provided by Formas and by the Linnaeus Centre LUCCI  
468 (<http://www.lucci.lu.se/index.html>) funded by the Swedish Research Council. We thank  
469 Anders Båth and Tomas Karlsson for field assistance.

470

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681 Table 1. Information regarding vegetation, C and N pool, pH, soil moisture (5th and 95th percentiles) and  
 682 depth to water table at the individual chamber locations. Chamber locations were named U1-U5 at the  
 683 undisturbed plot, T1-T4 at the thinned plot, C1-C5 at the clear-cut plot and S1-S5 at the stump harvested  
 684 plot.

ID	Time period	Vegetation/ Bare soil	Carbon <sup>a</sup> (kg m <sup>-2</sup> )	Nitrogen <sup>a</sup> (kg m <sup>-2</sup> )	pH <sup>b</sup>	Soil moisture, (%)	Depth to water table (cm)
T <sub>1</sub>	01 August 2009-31 May 2010	Mosses, bilberry	6.7	0.22	3.1	28.8-45.8	54-154
T <sub>2</sub>	01 August 2009-31 May 2010	Mosses, bilberry	5.0	0.17	3.1	25.0-40.0	44-144
T <sub>3</sub>	01 August 2009-31 May 2010	Mosses, bilberry	5.5	0.24	3.5	33.5-55.6	15-116
T <sub>4</sub>	11 December 2009-31 May 2010	Mosses, bilberry	3.3	0.10	3.0	19.2-36.3	29-129
U <sub>1</sub>	07 July 2010-04 October 2010	Mosses, bilberry	2.6	0.17	3.3	6.0-27.3	120-173
U <sub>2</sub>	07 July 2010-04 October 2010	Mosses, bilberry	6.1	0.29	3.2	10.0-33.4	107-160
U <sub>3</sub>	07 July 2010-04 October 2010	Mosses, bilberry	no data	no data	no data	9.4-37.0	102-155
U <sub>4</sub>	07 July 2010-04 October 2010	Mosses, bilberry	2.3	0.09	3.3	6.6-32.9	136-190
U <sub>5</sub>	07 July 2010-04 October 2010	Mosses, bilberry	3.9	0.15	3.4	7.8-23.5	132-185
S <sub>1</sub>	07 October 2010-20 October 2010	Mosses, bilberry	14.1	0.45	4.4	42.0-42.9	20-21
S <sub>2</sub>	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 <sub>3</sub>	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 <sub>4</sub>	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 <sub>5</sub>	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 <sub>1</sub>	21 October 2010-09 November 2010	Mosses, bilberry	4.7	0.16	4.2	41.5-46.2	44-50
C <sub>2</sub>	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 <sub>3</sub>	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 <sub>4</sub>	21 October 2010-09 November 2010	Mosses, bilberry	9.5	0.30	4.2	56.6-57.6	6-13
C <sub>5</sub>	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

685  
 686 <sup>a</sup> C and N pool to a depth of 20 cm in the mineral soil (litter layer excluded).

687 <sup>b</sup> pH (BaCl<sub>2</sub>) for the undisturbed and thinned plots and pH (H<sub>2</sub>O) for the clear-cut and stump harvested  
 688 plots were measured at 0-10 cm depth in the mineral soil.

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691 Table 2. Correlation coefficients  $C$  and corresponding  $P$ -values for the linear regressions between  $\text{CH}_4$   
 692 exchange and soil temperature, soil moisture and water table depth. The  $r^2$  shows how well the variables all  
 693 together explain the variance in the  $\text{CH}_4$  exchange. The correlation analyses are based on data from the  
 694 entire measurement period.

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	$C$ Soil temperature	$P$ Soil temperature	$C$ Soil moisture	$P$ Soil moisture	$C$ Water table depth	$P$ Water table depth	$r^2$
T <sub>1</sub>	-0.09	**	0.57	**	0.12	**	0.27
T <sub>2</sub>	-0.34	**	-0.23	**	0.46	**	0.26
T <sub>3</sub>	0.34	**	0.72	**	0.45	**	0.61
T <sub>4</sub>	0.28	**	-0.72	**	0.54	**	0.68
U <sub>1</sub>	-0.61	**	0.48	**	0.51	**	0.47
U <sub>2</sub>	-0.63	**	0.39	**	0.54	**	0.47
U <sub>3</sub>	-0.57	**	0.44	**	0.55	**	0.53
U <sub>4</sub>	-0.69	**	0.54	**	0.70	**	0.78
U <sub>5</sub>	-0.82	**	0.54	**	0.69	**	0.81
S <sub>1</sub>	-0.35	**	-0.18	*	a	a	0.09
S <sub>2</sub>	-0.16	*	-0.10	0.09	a	a	0.07
S <sub>3</sub>	-0.02	0.82	-0.09	0.21	a	a	0.002
S <sub>4</sub>	-0.16	*	-0.009	0.9	a	a	0.05
S <sub>5</sub>	-0.34	**	-0.46	*	a	a	0.09
C <sub>1</sub>	-0.06	0.29	-0.13	*	0.03	0.54	0.14
C <sub>2</sub>	-0.52	**	0.25	**	-0.07	0.13	0.22
C <sub>3</sub>	-0.57	**	no data	no data	-0.47	**	0.46
C <sub>4</sub>	-0.04	0.57	0.04	0.57	-0.01	0.91	0.01
C <sub>5</sub>	-0.54	**	-0.03	0.54	-0.20	**	0.21

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697 \*\* significant,  $p < 0.001$

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\* significant,  $p < 0.05$

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a, At the time for measurements on the stump harvested plot, the water table depth was only measured

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manually on a few occasions and therefore no linear regression could be made for this period.

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703 **Table 3. Coefficients from multiple linear regression analyses. A value is given only if the variable significantly contributes to explain the variation in**  
 704 **the CH<sub>4</sub> exchange. The r<sup>2</sup> shows how well the variables all together explain the variance in the CH<sub>4</sub> exchange. S.m represents soil moisture, S.t, soil**  
 705 **temperature and W.t, water table depth.**

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	T <sub>1</sub>				T <sub>2</sub>				T <sub>3</sub>				T <sub>4</sub>			
	r <sup>2</sup>	S.m.	S.t.	W.t.	r <sup>2</sup>	S.m.	S.t.	W.t.	r <sup>2</sup>	S.m.	S.t.	W.t.	r <sup>2</sup>	S.m.	S.t.	W.t.
<b>Aug 09</b>	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
<b>Sep 09</b>	0.10	0.31	-	-	0.10	-	-0.28	-	0.28	0.52	-	-	n.d	n.d	n.d	n.d
<b>Oct 09</b>	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
<b>Nov 09</b>	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	-
<b>Apr 10</b>	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
<b>May 10</b>	0.22	0.43	-	-0.18	0.10	-	-0.29	-	0.38	-0.49	-	0.46	0.62	n.d	0.79	n.d

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	U <sub>1</sub>				U <sub>2</sub>				U <sub>3</sub>				U <sub>4</sub>				U <sub>5</sub>			
	r <sup>2</sup>	S.m.	S.t.	W.t.	r <sup>2</sup>	S.m.	S.t.	W.t.	r <sup>2</sup>	S.m.	S.t.	W.t.	r <sup>2</sup>	S.m.	S.t.	W.t.	r <sup>2</sup>	S.m.	S.t.	W.t.
<b>Jul 10</b>	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
<b>Aug 10</b>	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
<b>Sep 10</b>	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

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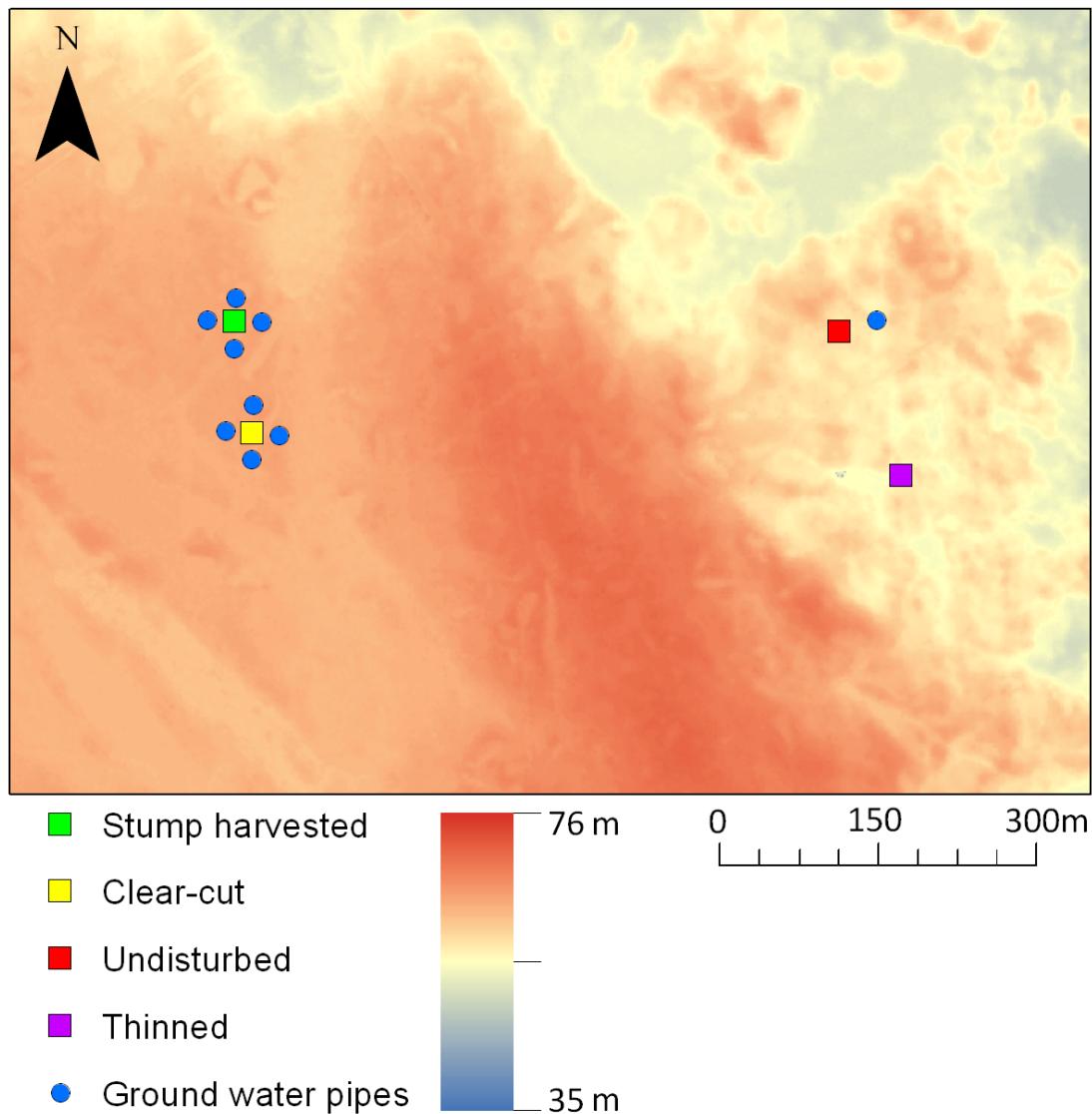
	S <sub>1</sub>				S <sub>2</sub>				S <sub>3</sub>				S <sub>4</sub>				S <sub>5</sub>		
	r <sup>2</sup>	S.m.	S.t.	r <sup>2</sup>	S.m.	S.t.	r <sup>2</sup>	S.m.	S.t.	r <sup>2</sup>	S.m.	S.t.	r <sup>2</sup>	S.m.	S.t.	r <sup>2</sup>	S.m.	S.t.	r <sup>2</sup>
<b>Oct 10</b>	0.09	-	-0.29	0.07	-0.27	-	0.002	-	-	0.05	0.10	0.10	0.09	-	-	-0.28			

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	C <sub>1</sub>				C <sub>2</sub>				C <sub>3</sub>				C <sub>4</sub>				C <sub>5</sub>			
	r <sup>2</sup>	S.m.	S.t.	W.t.	r <sup>2</sup>	S.m.	S.t.	W.t.	r <sup>2</sup>	S.m.	S.t.	W.t.	r <sup>2</sup>	S.m.	S.t.	W.t.	r <sup>2</sup>	S.m.	S.t.	W.t.
<b>Oct</b>	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
<b>-Nov 10</b>																				

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713 Fig.1. Schematic picture of the different plots and some of the ground water pipes. Three more pipes are  
714 located within the clear-cut and at the stump-harvested plots, but are covered by the plot symbol. The  
715 background consists of a digital elevation model showing the height above sea level for each square meter.

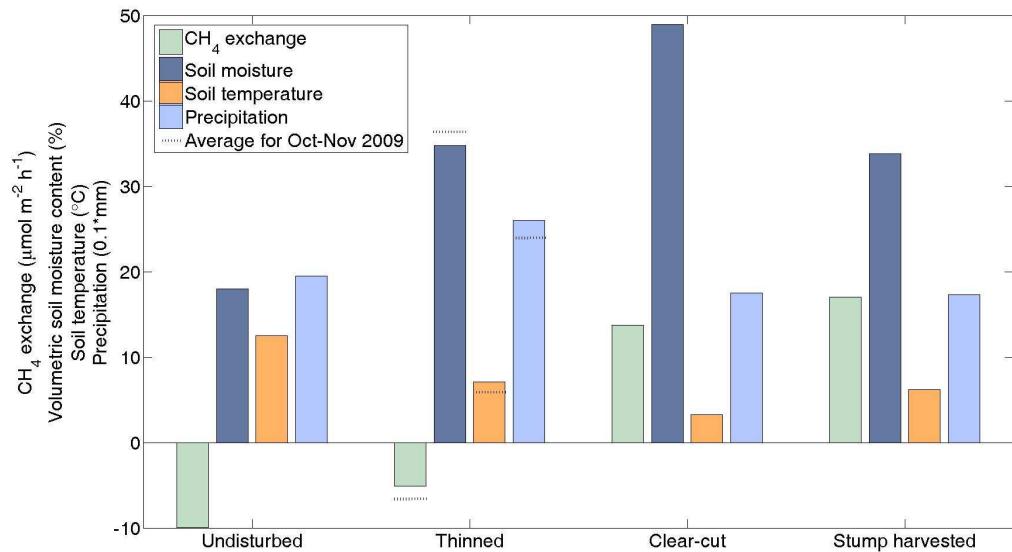
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722 Fig.2. Average CH<sub>4</sub> exchange rates, soil moisture and soil temperature at the four sampling plots. Data  
 723 from the entire measurement period at each plot is included. The dashed line at the thinned plot represents  
 724 average values for October and November, since measurements at the clear-cut and stump harvested plots  
 725 were conducted during this part of the year.

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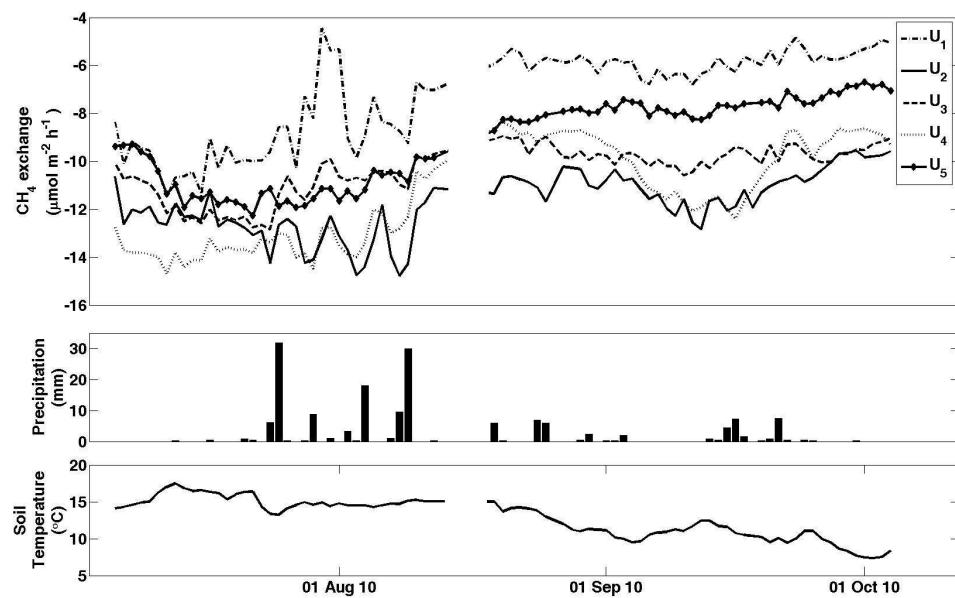
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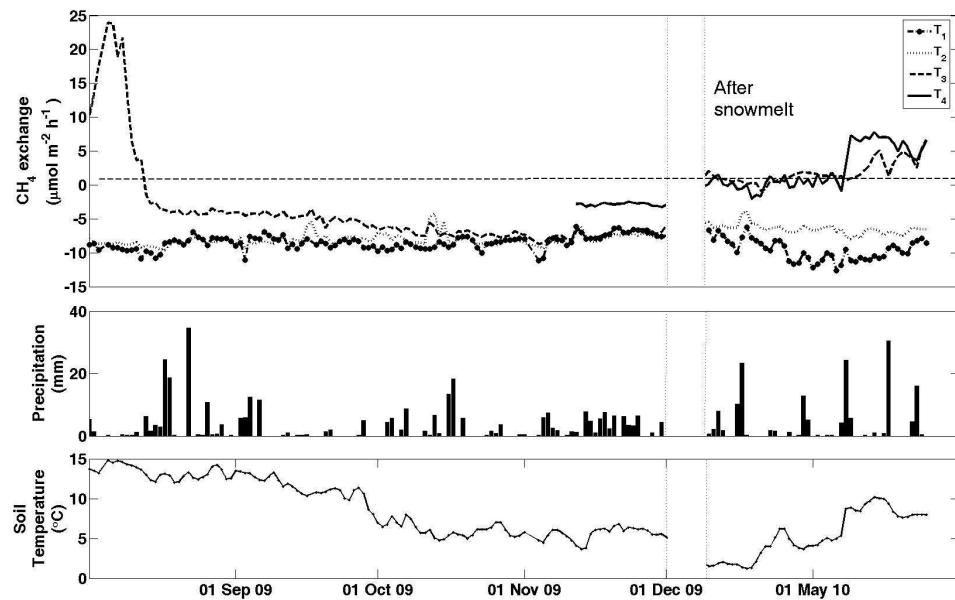
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739 Fig.3a



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741 Fig.3b



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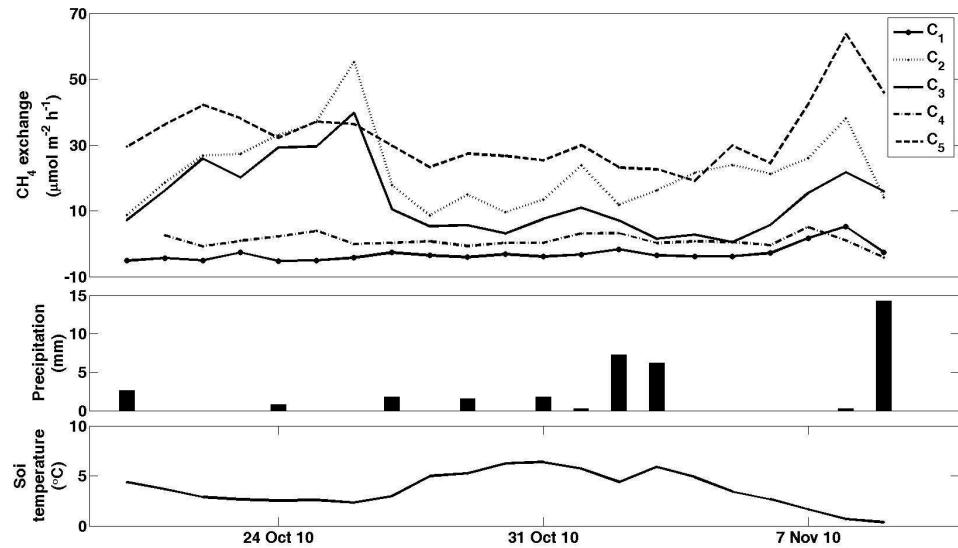
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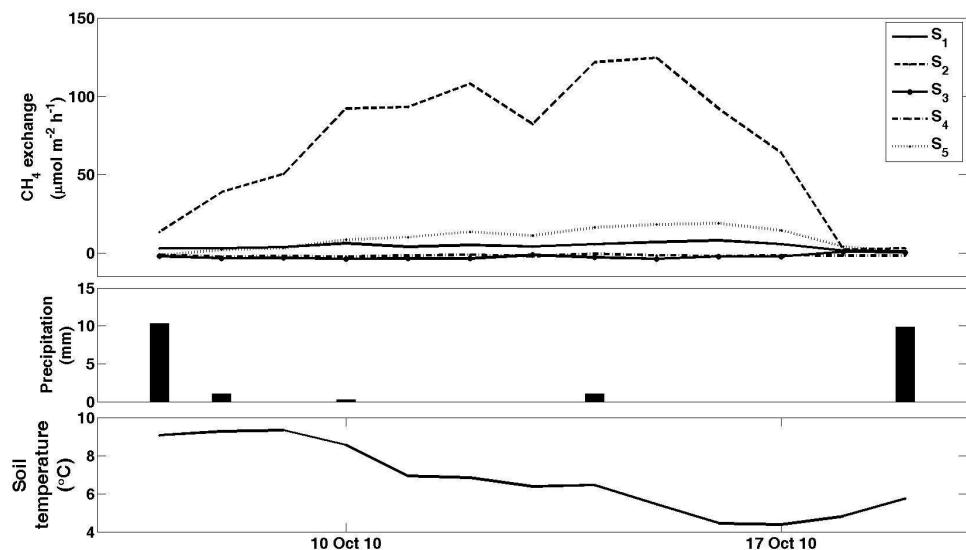
747 Fig.3c)



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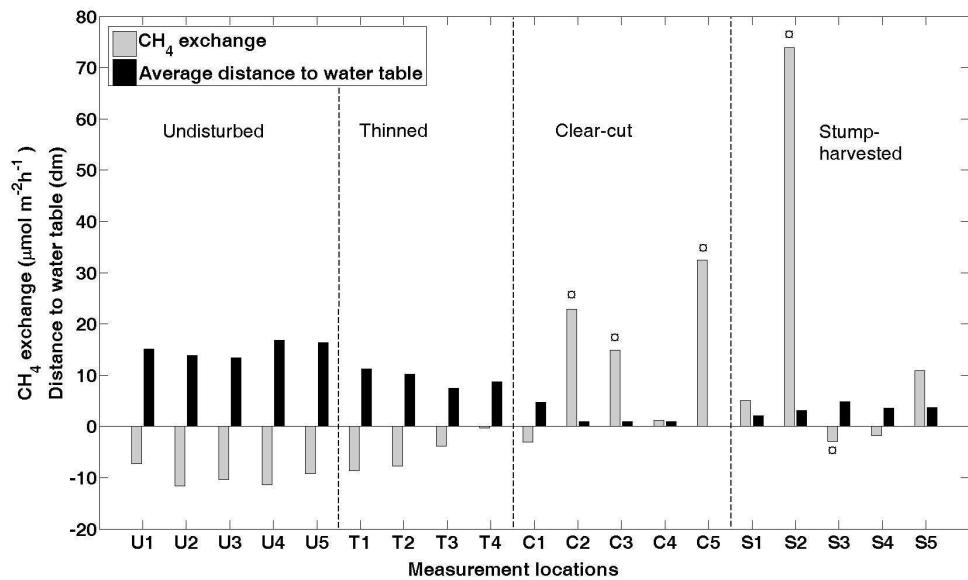
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750 Fig.3d)



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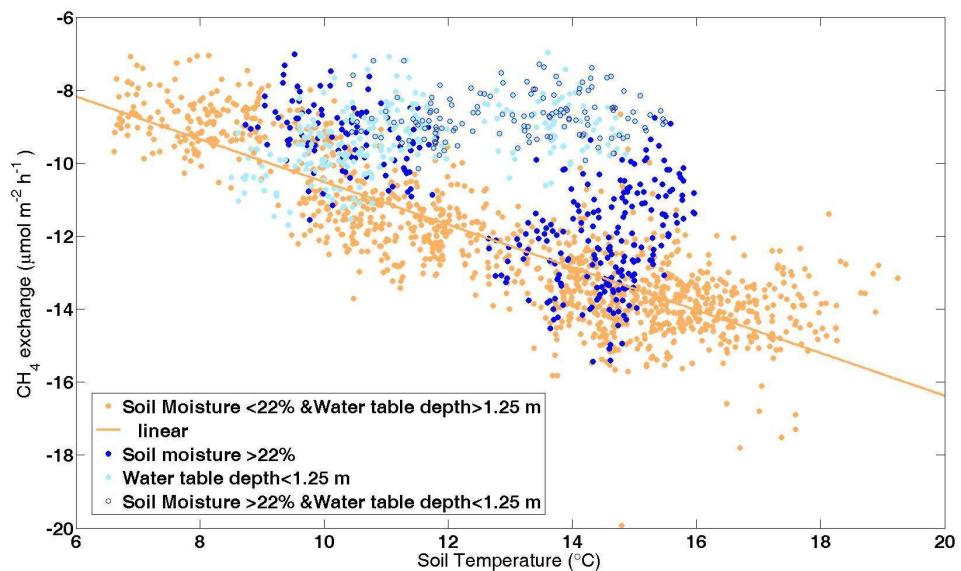
752 Fig.3. Time series of daily mean  $\text{CH}_4$  exchange, daily precipitation and daily mean soil temperature at the  
753 measurement locations. Fig.3a) Undisturbed plot, Fig.3b) Thinned plot, Fig.3c) Clear-cut plot, Fig.3d)  
754 Stump harvested plot.



757 Fig.4. CH<sub>4</sub> exchange (μmol m<sup>-2</sup> h<sup>-1</sup>) at all individual measurement locations with associated level of ground  
 758 water table. The water table depth at plot C<sub>5</sub> is close to zero and that is why the bar is not visible in the  
 759 diagram.

760 ☒ Measurement locations where soil surface was disturbed during site preparation.

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776 Fig.5. Correlation between CH<sub>4</sub> exchange (μmol m<sup>-2</sup> h<sup>-1</sup>) and soil temperature (°C) at measurement location

777 U<sub>4</sub>. The different colours represent different soil moisture and water table depths.

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