

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 (CH₄) exchange. We studied the short-
13 term effects of thinning, clear-cutting and stump harvesting on the CH₄ 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 CH₄, whereas the clear-cut plot and the stump harvested
18 plot were net CH₄ sources. The CH₄ 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 CH₄
22 production by archaea. Reduced evapotranspiration after harvesting leads to wetter soils,

23 decreased CH₄ consumption and increased CH₄ production, and should be accounted for
24 in the CH₄ budget of managed forests.

25

26 **1. Introduction**

27 Methane (CH₄) 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 CH₄ by methanotrophic bacteria in the aerobic
30 part of the soil profile (Harriss et al., 1982) and production of CH₄ 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 CH₄ (Van Amstel 2012). Consumption in soils is the
35 second largest sink of CH₄ after tropospheric oxidation by hydroxyl radicals with a global
36 sink capacity estimated recently at 28-32 Tg CH₄ y⁻¹ (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 CH₄ 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 CH₄ 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 CH₄ exchange by altering soil conditions such as soil moisture (Zerva and Menucuccini,
45 2005; Castro et al., 2000), water table depth (Zerva and Menucuccini, 2005) bulk density

46 (Mojeremane et al., 2012), soil temperature (Zerva and Menucuccini, 2005; Thibodeau et
47 al., 2000), nutrient content (Smolander et al., 1998) and pH (Smolander et al., 1998). CH₄
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 CH₄ between the atmosphere
51 and the deeper soil levels where CH₄ 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 CH₄ 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 CH₄ 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 CH₄
57 production, with higher temperatures leading to higher CH₄ 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 CH₄ 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 CH₄, though possibly at a lower rate (Hutsch et al., 1993).

64

65 Summarizing the effects of forest management practices on CH₄ 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 CH₄ 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 CH₄ sink to soil CH₄ 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 CH₄ exchange (Huttunen et
77 al., 2003).

78

79 Site preparation by mounding at clear-cuts can have a negative impact on CH₄ exchange
80 from a climate perspective. In one study, compaction of the soil by excavators during
81 mounding increased CH₄ emissions (Mojeremane et al., 2012). CH₄ 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 CH₄ emissions (Castro et al.,
85 2000). Drainage can also reduce CH₄ emissions following clear-cutting, but its positive
86 effect on CH₄ emissions was outweighed by increases in CO₂ 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 CO₂ emissions in Sweden. To our knowledge there are no
91 publications on the effects of stump harvesting on CH₄ 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 CH₄ exchange in a forest. Reduced CH₄ 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 CH₄ 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 CH₄ 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 CH₄ 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 CH₄ exchange.

108

109 **2. Methods**

110 *2.1 Site description*

111 The CH₄ exchange measurements took place in a forested area on the southern edge of
112 the boreal zoon, 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 CH₄, CO₂ and H₂O. The chambers had a volume of 110 litres and
154 covered a surface-area of 0.2 m². 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 8th and 20th of October 2010 and 2nd 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 m² 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 cm² 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 (H₂O), 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 cm² 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 CH₄ concentration (dC<sub>CH₄}/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 r² 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 r² value was then selected. The CH₄ flux ($J_{CH_4 flux}$) was</sub>

226 calculated as $J_{CH_4 flux} = \frac{dC}{dt} \frac{V}{A}$, where C is the molar density (μmol m⁻³), V (m³) is the

227 chamber volume and A (m²) is ground surface area. Fluxes with an r² value higher than

228 0.3 were generally kept for further analyses. An r² 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 σ 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 (± 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 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 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 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 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 CH_4
268 exchange were to be modelled. A variable with a larger coefficient has a higher impact on
269 the 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 σ 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 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 CH₄ exchange*

295 The mean CH₄ exchange of all measurement locations within the plots were as follows:
296 the undisturbed plot and the thinned plot were net CH₄ 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 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 T₃ and T₄ at the thinned plot shifted
301 between net daily CH_4 sinks and net daily 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 CH₄ exchange at the undisturbed and thinned plots*

307 Linear regression analyses between 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 CH_4 uptake at
311 locations T₃ and T₄ which decreased with increasing temperatures, and net CH_4 uptake at
312 locations T₂ and T₄, which decreased with decreasing soil moisture (Table 2). Figure 5
313 shows an example of the CH_4 exchange response to temperature and soil water conditions
314 at plot U₄.

315 Monthly multiple linear regression analyses (Table 3) added some temporal
316 information to the CH_4 exchange at the undisturbed and thinned plots. At the undisturbed
317 plot the water table depth affected 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 T₁ and T₃ in August 2009 and at
323 locations T₁ and T₂ 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 CH₄ exchange at all measurement locations.

327

328 *3.4 Drivers of CH₄ 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 CH₄ had either a relatively short distance to water table, or were disturbed
331 by site preparation, or both, although there were exceptions. Plot S₄ and S₅ had the same
332 water table depth and were not disturbed by site preparation, but plot S₄ was a CH₄ sink
333 while plot S₅ was a CH₄ 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 CH₄
336 emissions, or in one case with a higher net uptake. Both negative and positive significant
337 correlations between CH₄ 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 CH₄ exchange and water table depth, so
341 that a deeper water table depth gave higher CH₄ emissions (Table 2). The multiple linear

342 regression confirmed the significantly negative correlation between CH₄ exchange and
343 temperature at 6 measurement locations.

344

345 **4. Discussion**

346 All measurement locations at the undisturbed forest plot were sinks of CH₄ 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 CH₄, although reduced in comparison to the undisturbed plot. By
350 contrast, the clear-cut and stump harvested plots were net sources of CH₄. 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 CH₄
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 CH₄ exchange for the
357 autumn period October to November at the thinned site did not differ much from the
358 mean CH₄ 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 CH₄ sink to CH₄ 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 CH₄ 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 CH₄ sources. This is
369 consistent with results by Zerva and Menucuccini (2005) and Castro et al, (2000).
370 Temporal shifts to CH₄ emissions after snowmelt and summer precipitation, as were seen
371 at measurement locations T₃ and T₄, 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 (C₂, C₃, C₄, C₅, S₁) 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 T₃, when it had temporarily shifted to a CH₄ source, had volumetric soil moisture
376 content above 40%. Net emissions were also measured at measurement location S₂ and S₅
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 CH₄ were
381 further than average above the water table for those plots (Fig.4).

382
383 Temperature seemed to have a stronger impact on CH₄ exchange in drier conditions.
384 Figure 5 illustrates a high correlation, $r^2 = 0.74$, between soil temperature and CH₄
385 exchange at measurement location U₄, 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 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 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 CH_4 , we would expect a positive correlation between soil temperature and CH_4
399 exchange, so that higher temperatures led to higher net emissions of 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 CH_4 exchange. The result is
403 difficult to explain since 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 CH_4 exchange is negatively
410 correlated to soil temperature during this period.

411

412 The highest CH₄ 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 O₂ and increase the
418 soil's water retention, thereby promoting the activity of methanogenic archaeans
419 (Wachinger et al., 2000). The one disturbed measurement location, which showed net
420 CH₄ consumption, S₃, 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 CH₄
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 CH₄ sink strength
428 of forests on abandoned agricultural land was more than 100 years (Prieme et al., 1997;
429 Smith et al., 2000). Increasing CH₄ uptake with time after afforestation can be an effect
430 of an increase in the population of CH₄ 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 CH₄ 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 CH₄ 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 CH₄. 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 CH₄ budget in
446 managed forests, especially if the recovery time for the soil CH₄ sink is several decades.
447 In this study the effects of thinning on the CH₄ 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 CH₄ exchange shows
454 that the undisturbed plot and the thinned plot remained net CH₄ sinks, while the clear-cut
455 and stump harvested plots were net CH₄ sources. Linear regression analyses between CH₄
456 exchange and climatic variables showed that for most measurement locations at the

457 undisturbed and thinned plots, net CH₄ 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 CH₄ 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 CH₄
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 ^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

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

687 ^b pH (BaCl₂) for the undisturbed and thinned plots and pH (H₂O) 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 CH₄
 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 CH₄ exchange. The correlation analyses are based on data from the
 694 entire measurement period.

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	<i>C</i> <i>Soil temperature</i>	<i>P</i> <i>Soil temperature</i>	<i>C</i> <i>Soil moisture</i>	<i>P</i> <i>Soil moisture</i>	<i>C</i> <i>Water table depth</i>	<i>P</i> <i>Water table depth</i>	<i>r</i> 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	*	<i>a</i>	<i>a</i>	0.09
S ₂	-0.16	*	-0.10	0.09	<i>a</i>	<i>a</i>	0.07
S ₃	-0.02	0.82	-0.09	0.21	<i>a</i>	<i>a</i>	0.002
S ₄	-0.16	*	-0.009	0.9	<i>a</i>	<i>a</i>	0.05
S ₅	-0.34	**	-0.46	*	<i>a</i>	<i>a</i>	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

696

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

700

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

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702

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 CH₄ exchange. The r² shows how well the variables all together explain the variance in the CH₄ exchange. S.m represents soil moisture, S.t, soil**
 705 **temperature and W.t, water table depth.**

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	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

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	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

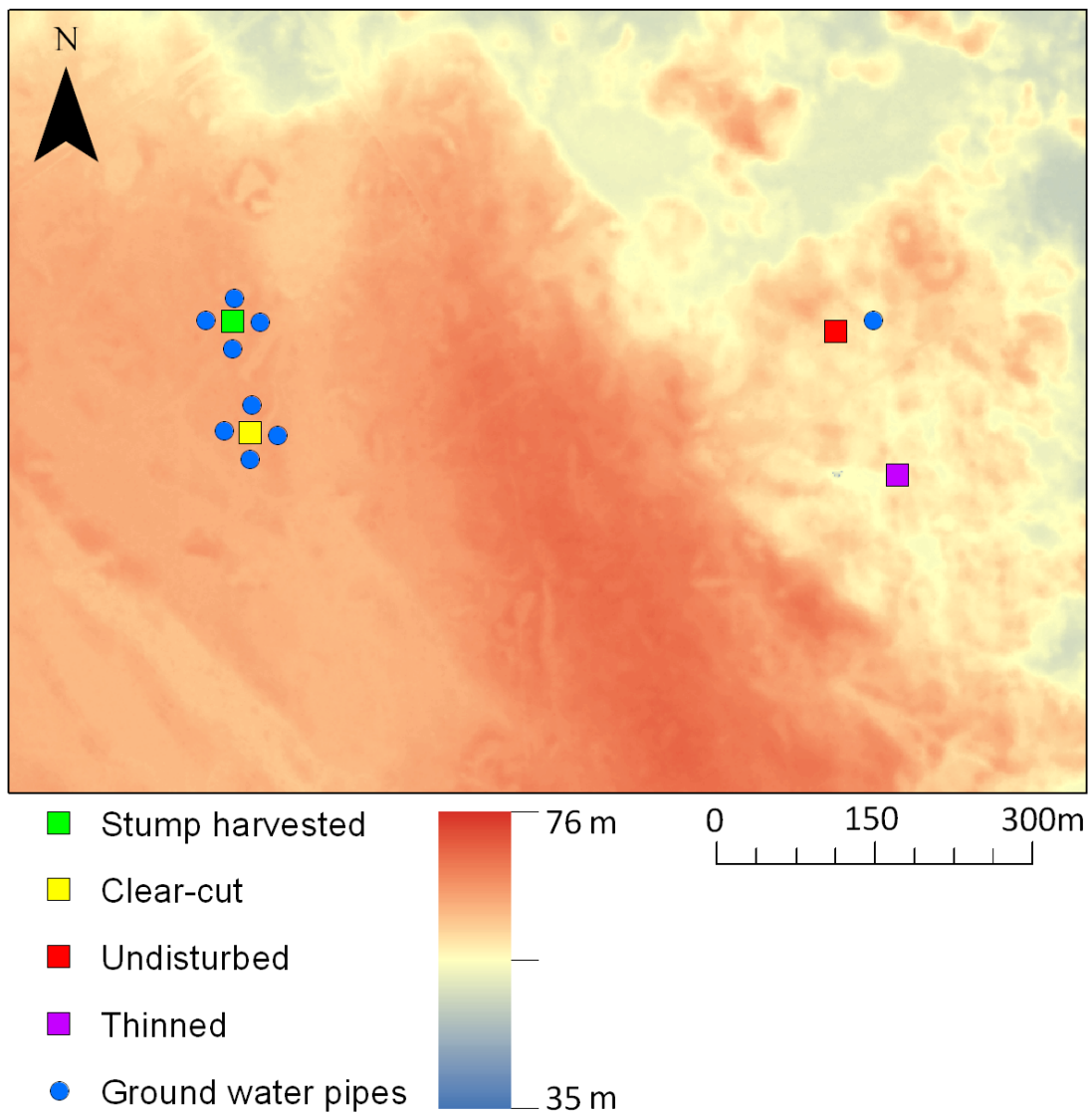
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	S ₁			S ₂			S ₃			S ₄			S ₅		
	r ²	S.m.	S.t.	r ²	S.m.	S.t.	r ²	S.m.	S.t.	r ²	S.m.	S.t.	r ²	S.m.	S.t.
Oct 10	0.09	-	-0.29	0.07	-0.27	-	0.002	-	-	0.05	0.10	0.10	0.09	-	-0.28

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	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	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
-Nov 10																				

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712 Fig.1. Schematic picture of the different plots and some of the ground water pipes. Three more pipes are
 713 located within the clear-cut and at the stump-harvested plots, but are covered by the plot symbol. The
 714 background consists of a digital elevation model showing the height above sea level for each square meter.
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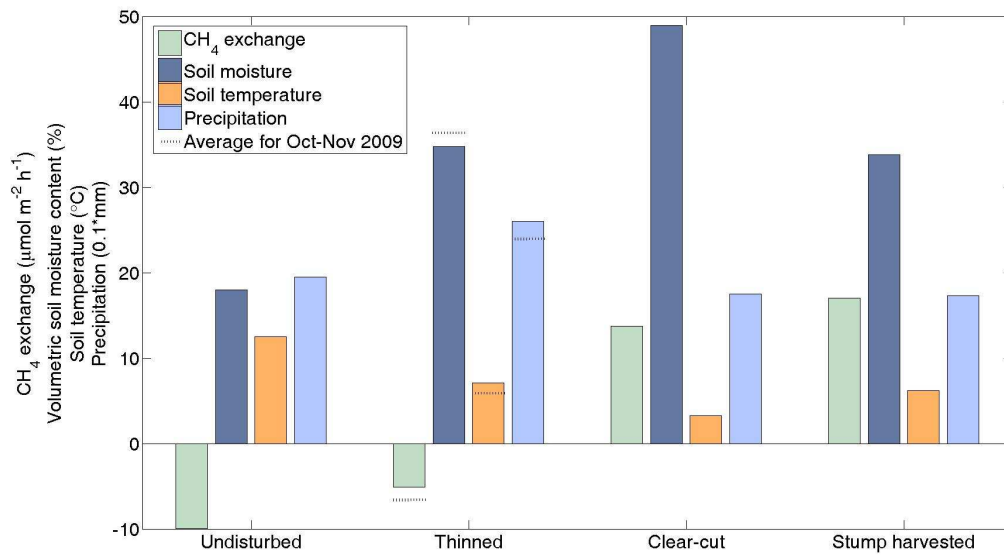
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722 Fig.2. Average CH₄ exchange rates, soil moisture and soil temperature at the four sampling plots. Data
 723 from the entire measurement period at each plot is included. The dashed line at the thinned plot represents
 724 average values for October 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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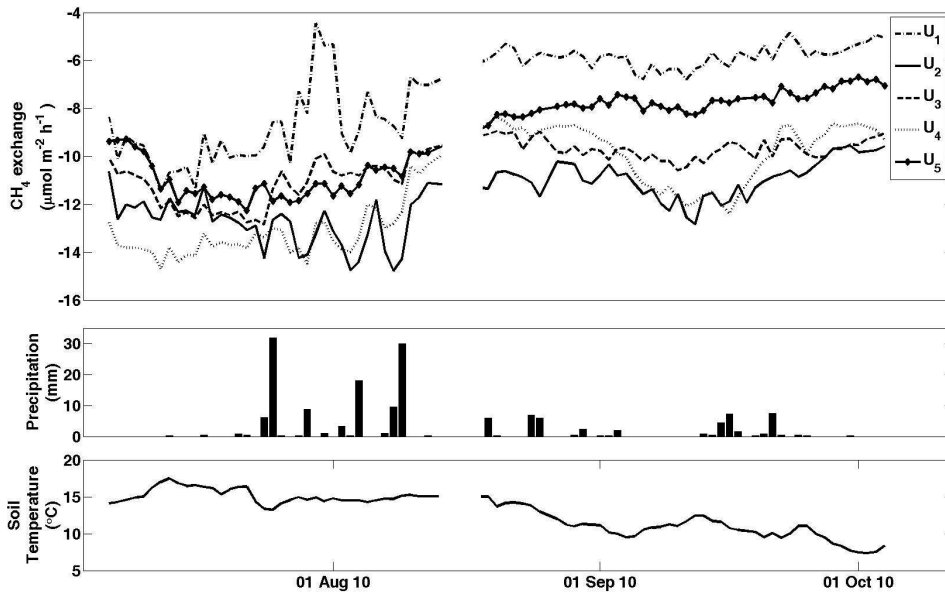
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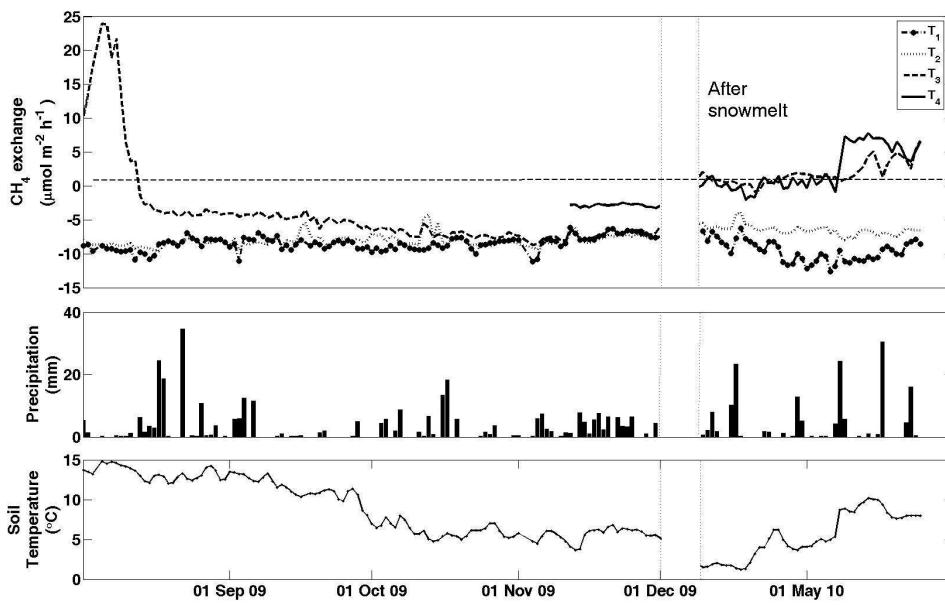
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739 Fig.3a



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741 Fig.3b



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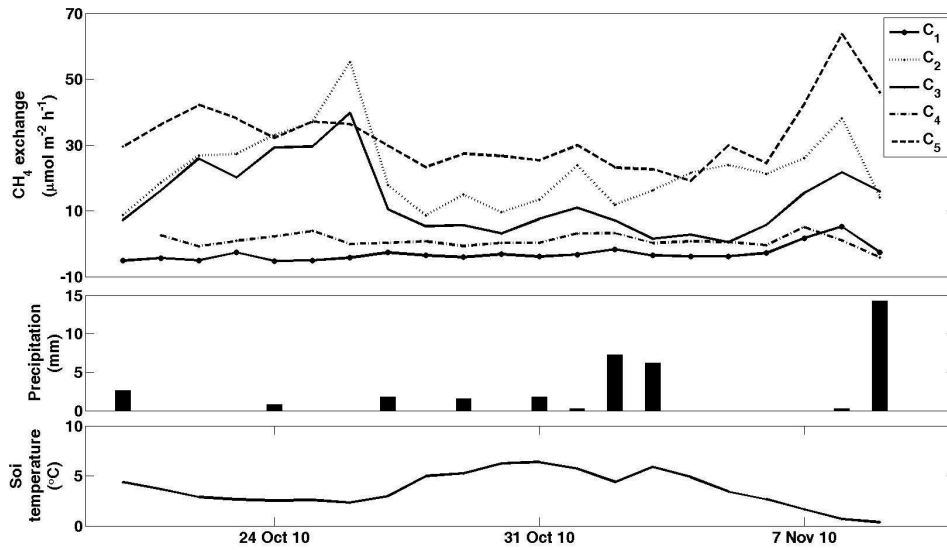
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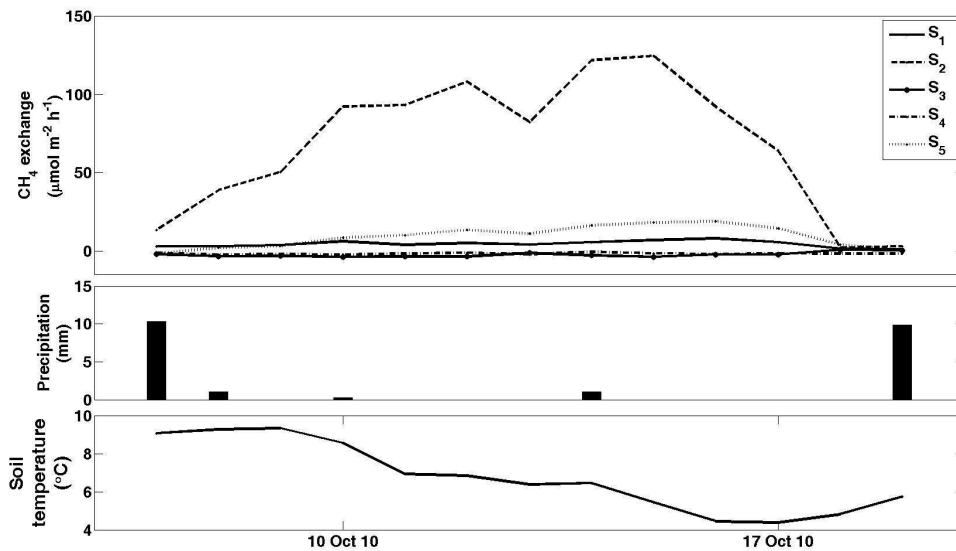
747 Fig.3c)



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750 Fig.3d)



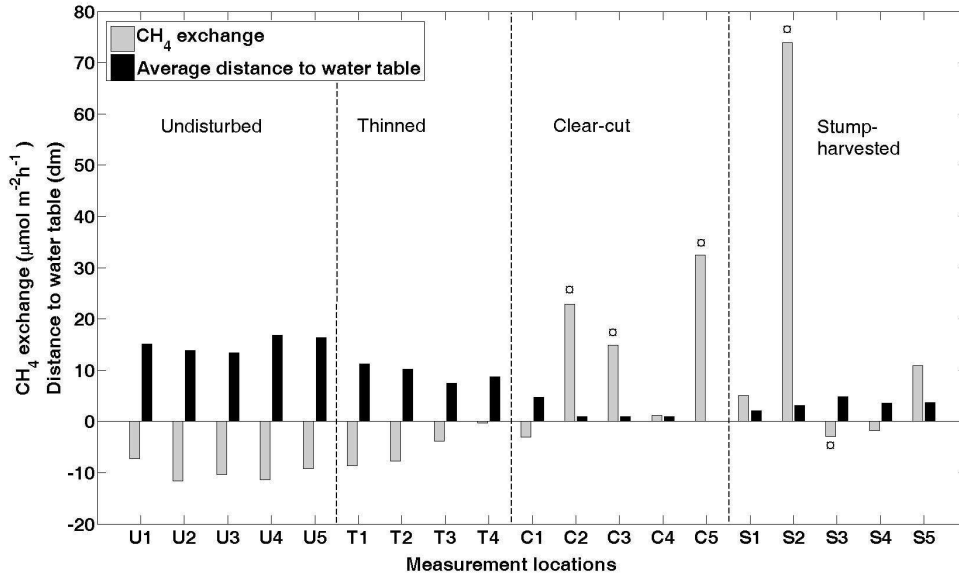
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752 Fig.3. Time series of daily mean CH₄ exchange, daily precipitation and daily mean soil temperature at the

753 measurement locations. Fig.3a) Undisturbed plot, Fig.3b) Thinned plot, Fig.3c) Clear-cut plot, Fig.3d)

754 Stump harvested plot.

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757 Fig.4. CH₄ exchange ($\mu\text{mol m}^{-2}\text{h}^{-1}$) at all individual measurement locations with associated level of ground
758 water table. The water table depth at plot C₅ 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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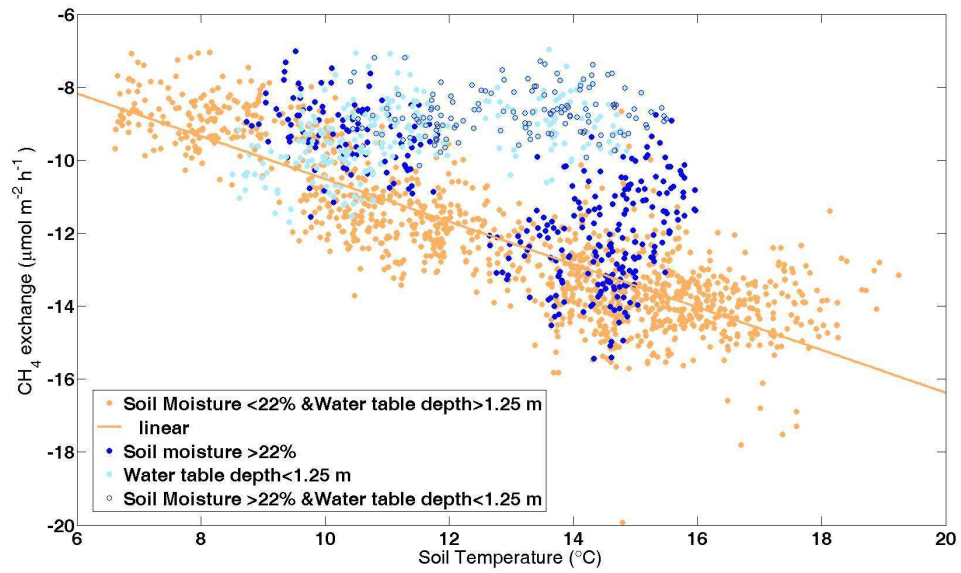
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776 Fig.5. Correlation between CH₄ exchange (μmol m⁻² h⁻¹) and soil temperature (°C) at measurement location

777 U₄. The different colours represent different soil moisture and water table depths.

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