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 (CH_4) exchange. We studied the short-

13 term effects of thinning, clear-cutting and stump harvesting on the 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 CH_4, whereas the clear-cut plot and the stump harvested

18 plot were net CH_4 sources. The 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 CH_4

22 production by archea. Reduced evapotranspiration after harvesting leads to wetter soils,

23   decreased CH_4 consumption and increased CH_4 production, and should be accounted for

24   in the CH_4 budget of managed forests.

25

26   **1. Introduction**

27   Methane (CH_4) 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_4 by methanotrophic bacteria in the aerobic

30   part of the soil profile (Harriss et al., 1982) and production of CH_4 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_4 (Van Amstel 2012). Consumption in soils is the

35   second largest sink of CH_4 after tropospheric oxidation by hydroxyl radicals with a global

36   sink capacity estimated recently at 28-32 Tg CH_4 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 CH_4 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_4 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_4 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). CH_4

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_4 between the atmosphere

51   and the deeper soil levels where CH_4 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_4 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_4 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_4

57   production, with higher temperatures leading to higher CH_4 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_4 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_4, though possibly at a lower rate (Hutsch et al., 1993).

64

65   Summarizing the effects of forest management practices on CH_4 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_4 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_4 sink to soil CH_4 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_4 exchange (Huttunen et

77   al., 2003).

78

79   Site preparation by mounding at clear-cuts can have a negative impact on CH_4 exchange

80   from a climate perspective. In one study, compaction of the soil by excavators during

81   mounding increased CH_4 emissions (Mojeremane et al., 2012). CH_4 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_4 emissions (Castro et al.,

85   2000). Drainage can also reduce CH_4 emissions following clear-cutting, but its positive

86   effect on CH_4 emissions was outweighed by increases in CO_2 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_2 emissions in Sweden. To our knowledge there are no

91   publications on the effects of stump harvesting on CH_4 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_4 exchange in a forest. Reduced CH_4 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_4 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_4 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_4 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_4 exchange.

108

109 **2. Methods**

110 *2.1 Site description*

111 The CH_4 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 CH_4, CO_2 and H_2O. The chambers had a volume of 110 litres and

154   covered a surface-area of 0.2 m^2. 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 Ml-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 m^2 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^2 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_2O), 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^2 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_4 concentration (dC_CH_4/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^2 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^2 value was then selected. The CH_4 flux ($J_{CH4\,flux}$) was

226   calculated as $J_{CH4\,flux} = \dfrac{dC}{dt}\dfrac{V}{A}$, where C is the molar density (μmol m^{-3}), V (m^3) is the

227   chamber volume and A (m^2) is ground surface area. Fluxes with an r^2 value higher than

228   0.3 were generally kept for further analyses. An r^2 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 $MDF = \dfrac{\sigma}{t}$, 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 μmol m^{-2} h^{-1}. For daily average values of hourly

239 measurements this value is reduced to < 1 μmol m^{-2}h^{-1} since the MDF value should be

240 divided by the square root of the number of measurements. It is important to consider that

241 fluxes below the MDF cannot be securely detected, but small fluxes could very well be

242 real and therefore they are kept in the analyses.

243

244 Correction of the measured CH_4 concentrations for dilution by water vapour was only

245 possible at the undisturbed, clear-cut and stump harvested plots after water vapour

246 measurements started in June 2010. This means that daytime data (global radiation > 20

247 W/m^2) from the thinned plot had to be excluded from the analyses. During night the

248 dilution effect had very little impact.

249

250 The impact of the environmental variables soil temperature, soil moisture, and water table

251 depth on CH_4 exchange was analysed separately by Spearman linear correlations using

252   the corr function, and by multiple linear regression on standardized data using the

253   function stepwisefit (both Matlab version R2009b). The stepwise regression analyses

254   were performed by bi-directional elimination. P-values were used in the selection

255   process. The analysis was made on standardized data to adjust for the disparity in

256   variable sizes, which makes the outcome of the analyses, the coefficients, comparable.

257   The coefficients are the number that the variables would be multiplied with if CH_4

258   exchange were to be modelled, a variable with a larger coefficient has a higher impact on

259   the CH_4 exchange. Standardization for a data point x_i was made by $x_i = \dfrac{x_i - \bar{x}}{\sigma}$ where $\bar{x}$

260   is the average of all data points and σ is the standard deviation of all data. An R^2 value

261   for the overall model was also calculated showing how much of the variance in CH_4

262   exchange that is not explained by the environmental variables included in the analyses.

263

264   The significance of mean values at the measurement locations was calculated with the

265   ttest function (also Matlab version R2009b).

266

267   **3. Results**

268   *3.1 Environmental conditions*

269   There were differences in soil moisture and soil temperatures among the plots. On

270   average the undisturbed forest plot, with measurements exclusively from the summer

271   season, July through September, had the driest and warmest records, and also the

272   measurement locations were further above the ground water table than at other plots

273   (Fig.2, Table 1). The clear-cut plot, which was measured in October and November,

274   showed the coldest and wettest conditions including the highest water table. Four of the

275   five measurement locations at this plot were on average less than 15 cm above the ground

276   water table (Fig.2, Table 1). The thinned plot and the stump harvested plot had similar

277   average moisture and temperature conditions, but the measurements at the thinned plot

278   proceeded over a longer time period and thus the conditions varied more. The thinned

279   plot also had a generally deeper ground water table than the stump harvested plot (Fig.2,

280   Table 1).

281   Soil N and C content and pH were higher at the clear-cut and stump harvested

282   plots than at the undisturbed and thinned plots (Table 1).

283

284   *3.2 CH_4 exchange*

285   The mean CH_4 exchange of all measurement locations within the plots were as follows:

286   the undisturbed plot and the thinned plot were net CH_4 sinks of -10 μmol m^{-2}h^{-1} and -5

287   μmol m^{-2}h^{-1} respectively, while the clear-cut plot and at the stump harvested plot were

288   net sources of 13.6 μmol m^{-2}h^{-1} and 17 μmol m^{-2}h^{-1}, respectively (Fig.2). However, the

289   CH_4 exchange varied within the plots. At the clear-cut and stump harvested plots, both

290   net sources and net sinks existed (Fig.3). Plot T_3 and T_4 at the thinned plot shifted

291   between net daily CH_4 sinks and net daily CH_4 sources on a few occasions (Fig.3b).

292   Fluxes ranged from -7.2 to -11.6 μmol m^{-2}h^{-1} at the undisturbed plot, from -0.3 to -8.6

293   μmol m^{-2}h^{-1}at the thinned plot, from –3.0 to 32.5 μmol m^{-2}h^{-1} at the clear-cut plot and

294   from -2.9 to 74.0 μmol m^{-2}h^{-1} at the stump harvested plot (Fig.3).

295

296   *3.3 Drivers of CH_4 exchange at the undisturbed and thinned plots*

297   Linear regression analyses between CH_4 exchange and climatic variables showed that for

298   most measurement locations at the undisturbed and thinned plots, consumption

299   significantly ($p<0.001$) increased with decreasing soil water content, decreasing water

300   table depth and increasing temperatures. Exceptions to this were net CH_4 uptake at

301   locations T_3 and T_4 which decreased with increasing temperatures, and net CH_4 uptake at

302   locations T_2 and T_4, which decreased with decreasing soil moisture (Table 2). Figure 5

303   shows an example of the CH_4 exchange response to temperature and soil water conditions

304   at plot U_4.

305   Monthly multiple linear regression analyses (Table 3) added some temporal

306   information to the CH_4 exchange at the undisturbed and thinned plots. At the undisturbed

307   plot the water table depth affected CH_4 consumption in August. In September 2010

308   temperature was the most influential variable at all measurement locations. In July 2010

309   the result was less distinct, showing some measurement locations with a higher

310   dependency on water table depth and soil moisture, and some measurement locations

311   with a higher dependency on temperature. The clearest result at the thinned plot was a

312   dependency on soil moisture at measurement locations T_1 and T_3 in August 2009 and at

313   locations T_1 and T_2 in April 2010 (Table 3). Soils were wetter than average in August and

314   April due to heavy rains in June and July 2009, and snowmelt in spring 2010. However,

315   according to the r^2 value of the overall model there are lot of unexplained variance in the

316   CH_4 exchange at all measurement locations.

317

318 *3.4 Drivers of CH$_4$ exchange at the clear-cut and stump harvested plots*

319 Generally at the clear-cut and stump harvested plots, the measurement locations with net

320 emissions of CH$_4$ had either a relatively short distance to water table, or were disturbed

321 by site preparation, or both, although there were exceptions. Plot S$_4$ and S$_5$ had the same

322 water table depth and were not disturbed by site preparation, but plot S$_4$ was a CH$_4$ sink

323 while plot S$_5$ was a CH$_4$ source (Fig.4).

324   At the majority of the measurement locations on the clear-cut and stump

325 harvested plots, higher temperatures correlated significantly ($p<0.05$) with lower CH$_4$

326 emissions, or in one case with a higher net uptake. Both negative and positive significant

327 correlations between CH$_4$ exchange and soil moisture was found at a few measurement

328 locations but the soil moisture range at those measurement locations was very small. At

329 two measurement locations with net emissions at the clear-cut plot, there was a

330 significant ($p<0.05$) negative correlation between CH$_4$ exchange and water table depth, so

331 that a deeper water table depth gave higher CH$_4$ emissions (Table 2). The multiple linear

332 regression confirmed the significantly negative correlation between CH$_4$ exchange and

333 temperature at 6 measurement locations.

334

335 **4. Discussion**

336 All measurement locations at the undisturbed forest plot were sinks of CH$_4$ throughout

337 the measurement period, which is consistent with the generally drained, drier and warmer

338 soil conditions at the plot (Fig.2). The measurement locations at the thinned plot were

339 also net sinks of CH$_4$, although reduced in comparison to the undisturbed plot. By

340 contrast, the clear-cut and stump harvested plots were net sources of CH$_4$. Since the

341 measurements at the different plots were conducted at different times of the year,

342 seasonality and annual variations can probably explain some of the differences in CH_4

343 exchange and soil conditions. However, it is not likely that differences in water table

344 depth between the plots are due solely to seasonal variations. In the autumn of 2010 the

345 water table was on average more than 1 m higher at the clear-cut and stump harvested

346 plots than at the undisturbed plot. In addition to this, the mean CH_4 exchange for the

347 autumn period October to November at the thinned site did not differ much from the

348 mean CH_4 exchange for the whole measurement period, indicating that average seasonal

349 variations are small (Fig.2). Precipitation was on average higher during the measurement

350 period at the thinned site than during measurements at the other plots, which did not

351 cause a switch from CH_4 sink to CH_4 source. The clear-cut and stump harvested plots are

352 located on a plateau which is uphill from the thinned and undisturbed plots and hence

353 topography should not be responsible for the higher water table at the clear-cut and stump

354 harvested plots (Fig.1).

355   Water table depth, soil moisture and soil temperature were all shown to be

356 important drivers of CH_4 exchange, as demonstrated by the linear and multiple linear

357 regression analyses. However it appears that the rise of water table and increased soil

358 moisture caused some of the measurement locations to shift to CH_4 sources. This is

359 consistent with results by Zerva and Menucuccini (2005) and Castro et al, (2000).

360 Temporal shifts to CH_4 emissions after snowmelt and summer precipitation, as were seen

361 at measurement locations T_3 and T_4, were also reported by Wang and Bettany, (1995).

362   A majority of net emitting measurement locations at the clear-cut and stump

363 harvested plots (C_2, C_3, C_4, C_5, S_1) were positioned less than 21 cm above the water table,

364   and had a volumetric soil moisture content above 40% (Table 1). Also measurement

365   location T_3, when it had temporarily shifted to a CH_4 source, had volumetric soil moisture

366   content above 40%. Net emissions were also measured at measurement location S_2 and S_5

367   with water table depths at 30-40 cm and volumetric soil moisture contents of 23-40%.

368   Fiedler and Sommer (2000) found a threshold value of water table depth at 15 cm, below

369   which only minor annual emissions were measured. The three measurement locations at

370   the clear-cut and stump harvested plots which showed net consumption of CH_4 were

371   further than average above the water table for those plots (Fig.4).

372

373   Temperature seemed to have a stronger impact on CH_4 exchange in drier conditions.

374   Figure 5 illustrates a high correlation, $r^2 = 0.74$, between soil temperature and CH_4

375   exchange at measurement location U_4, when excluding data points with soil moisture

376   above 22% and a distance to the water table of less than 1.25 m. The threshold value of

377   22% was selected after visual inspection of the data. If all the data from wetter conditions

378   were included (volumetric soil moisture content > 22 % and water table < 1.25 m away),

379   the corresponding r^2 equals 0.47. This is consistent with the results from the multiple

380   linear regression analyses showing that water table depth had a significant impact on the

381   CH_4 exchange at all measurement locations in August 2010, when the water table depth

382   varied strongly. In contrast, during September, there were no major precipitation events

383   and soil temperature was the most influential variable. Soil moisture was rarely below 30

384   % at the thinned plot, thus the temperature dependence was less. In autumn, September

385   to November 2009, all measurement locations at the thinned plot were stable sinks of

386   CH_4, even though the soil temperature was at times below 5˚C.

387   At the clear-cut and stump harvested plots, where most measurement locations were net

388   sources of CH_4, we would expect a positive correlation between soil temperature and CH_4

389   exchange, so that higher temperatures led to higher net emissions of CH_4. Methanogens

390   generally respond better than methanotrophs to increased temperatures (Dunfield et al.,

391   1993). However this was not the case: a majority of the measurement locations showed a

392   significantly negative correlation between temperature and CH_4 exchange. The result is

393   difficult to explain since CH_4 production and oxidation are not measured separately. Soil

394   temperature profiles at the clear-cut and stump harvested plots (data not shown) show

395   that during the measurement period, changes in surface temperature, associated with

396   periods of cloudy conditions and precipitation, at 5 cm depth are larger than at 20 and 40

397   cm depth. Methanotrophs are expected to be located closer to the soil surface than

398   methanogens and the larger temperature increase at the surface might compensate their

399   lower response to temperature, which could explain why net CH_4 exchange is negatively

400   correlated to soil temperature during this period.

401

402   The highest CH_4 emissions were found at four of the five disturbed measurement

403   locations: that is, sites of bare soil where organic and mineral soils were mixed. The soil

404   at disturbed measurement locations seemed less compact than at measurement locations

405   with intact vegetation, so the disturbance probably did not inhibit diffusion. Possibly the

406   availability of fresh organic material was higher at disturbed measurement locations.

407   Fresh, labile organic matter would promote heterotrophic uptake of O_2 and increase the

408   soil's water retention, thereby promoting the activity of methanogenic archeans

409   (Wachinger et al., 2000). The one disturbed measurement location, which showed net

410   CH$_4$ consumption, S$_3$, was positioned on top of a mound with relatively large distance to

411   the ground water table (Fig.4).

412

413   Since this is a study of the short-term effects of forest management practices on CH$_4$

414   exchange, there are no data on how long-lived these effects are. Sudden shifts from sinks

415   to sources and back again due to changes in soil water conditions are evident, as we have

416   seen at the thinned plot (Fig.3b). It might take years (Tate et al., 2006) to several decades

417   for a soil to regain its full sink capacity. The recovery time for the soil CH$_4$ sink strength

418   of forests on abandoned agricultural land was more than 100 years (Prieme et al., 1997;

419   Smith et al., 2000). Increasing CH$_4$ uptake with time after afforestation can be an effect

420   of an increase in the population of CH$_4$ oxidizing bacteria with time (Barcena et al.,

421   2014) or better soil diffusivity and soil aeration with time (Christiansen & Gundersen,

422   2011; Peichl et al., 2010). A better soil aeration with time could be due to an increase in

423   root biomass, which means that the roots over time loosen the soil and absorb more water

424   (Peichl et al., 2010). Hiltbrunner et al, (2012) found that the soil CH$_4$ sink capacity of

425   abandoned agricultural land increased with stand age up to 120 years, due to the

426   increased transpiration of older forests and their ability to shield the forest floor from

427   precipitation, which resulted in more favourable conditions for methanotrophic activity.

428

429   Uptake rates by forest landscapes might be overestimated (Grunwald et al., 2012; Fiedler

430   et al., 2005). A study by Grunwald et al, (2012) found that wet forests were as important

431   as wetlands for the CH$_4$ budget of European forests, and Fiedler et al, (2005) found that if

432   2.3% of a forest area consisted of wet soil the forest could turn from a sink to a source of

433   CH_4. As mentioned, after clear-cutting, water table depth decreased and soil moisture

434   increased. Wetter soils and a higher ground water table are common consequences of

435   clear-cutting, and it is therefore important to consider their impact on the CH_4 budget in

436   managed forests, especially if the recovery time for the soil CH_4 sink is several decades.

437   In this study the effects of thinning on the CH_4 exchange were not as pronounced as for

438   clear-cutting, although the plot average consumption was reduced in comparison to the

439   undisturbed plot. Any forest management practice that reduces disturbance and leaves a

440   continuous forest cover might be a better alternative from a global warming perspective.

441

442   **5. Conclusions**

443   Our study on the short term effects of boreal forest management on CH_4 exchange shows

444   that the undisturbed plot and the thinned plot remained net CH_4 sinks, while the clear-cut

445   and stump harvested plots were net CH_4 sources. Linear regression analyses between CH_4

446   exchange and climatic variables showed that for most measurement locations at the

447   undisturbed and thinned plots, net CH_4 uptake increased significantly with decreasing soil

448   moisture, decreasing water table depth and increasing temperatures. A higher water table

449   and increased soil moisture were likely to be responsible for the shift to CH_4 emissions at

450   the clear-cut and stump harvested plots. At most of the measurement locations, which

451   showed net emissions, the soil was almost saturated and the water table was within a few

452   decimetres of the soil surface. Clear-cutting of the forest resulted in a raised ground water

453   table and in increased soil moisture. These effects should be accounted for in the CH_4

454   budget of managed forests.

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664 Table 1. Information regarding vegetation, C and N pool, pH, soil moisture (5th and 95th percentiles) and

665 depth to water table at the individual chamber locations. Chamber locations were named U1-U5 at the

666 undisturbed plot, T1-T4 at the thinned plot, C1-C5 at the clear-cut plot and S1-S5 at the stump harvested

667 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

668

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

670 [b] pH (BaCl2) for the undisturbed and thinned plots and pH (H2O) for the clear-cut and stump harvested

671 plots were measured at 0-10 cm depth in the mineral soil.

672

673

674   Table 2. Correlation coefficients *C* and corresponding *P*-values for the linear regressions between CH_4

675   exchange and soil temperature, soil moisture and water table depth. The r^2 shows how well the variables all

676   together explain the variance in the CH4 exchange.

677

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

678
679   ** significant, $p < 0.001$

680   * significant, $p < 0.05$

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

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

683

684

Table 3. Coefficients from multiple linear regression analyses. A value is given only if the variable significantly contributes to explain the variation in the CH$_4$ exchange. The r^2 shows how well the variables all together explain the variance in the CH4 exchange. S.m represents soil moisture, S.t, soil temperature and W.t, water table depth.

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

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

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

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

Stump harvested
Clear-cut
Undisturbed
Thinned
Ground water pipes

76 m

35 m

0   150   300m
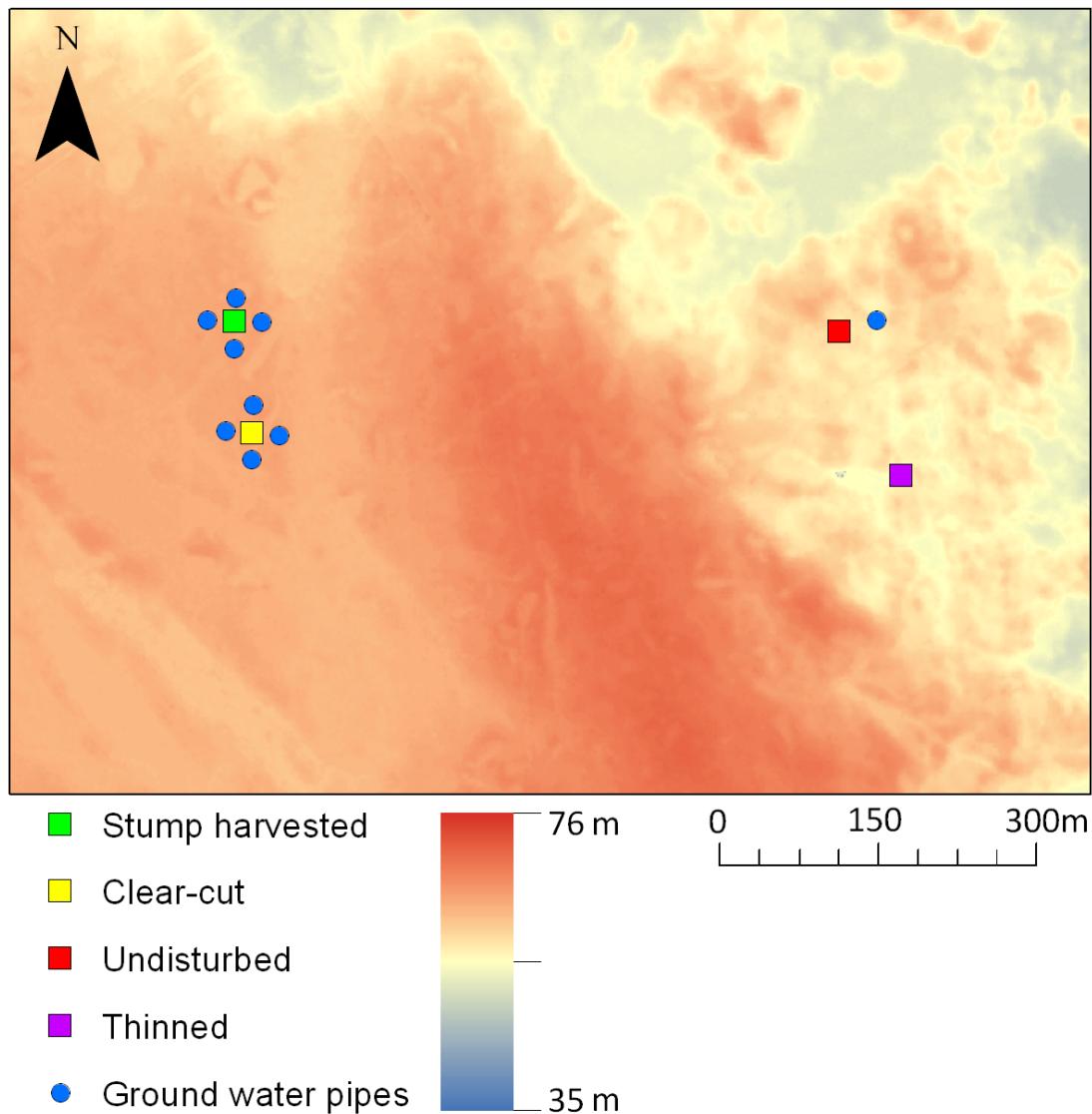
Fig.1. Schematic picture of the different plots and some of the ground water pipes. Three more pipes are

696   located within the clear-cut and at the stump-harvested plots, but are covered by the plot symbol. The

697   background consists of a digital elevation model showing the height above sea level for each square meter.

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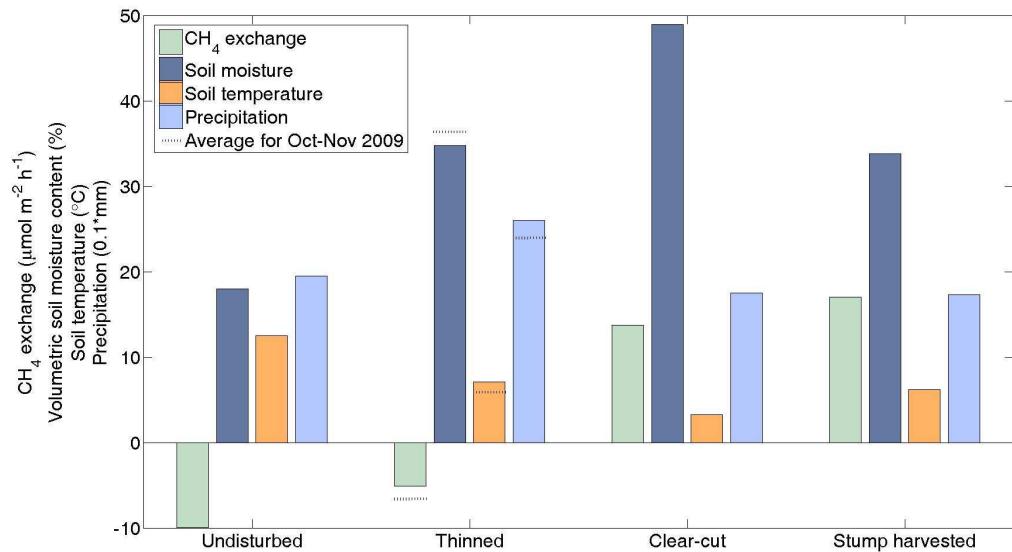
Fig.2. Average CH_4 exchange rates, soil moisture and soil temperature at the four sampling plots. Data

from the entire measurement period at each plot is included. The dashed line at the thinned plot represents

average values for October and November, since measurements at the clear-cut and stump harvested plots

were conducted during this part of the year.

721   Fig.3a
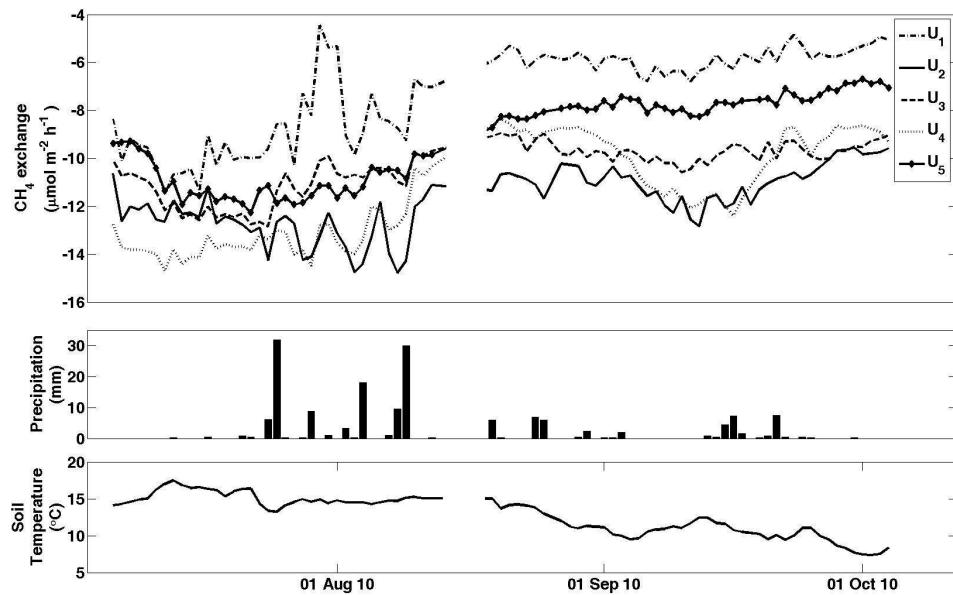
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723   Fig.3b
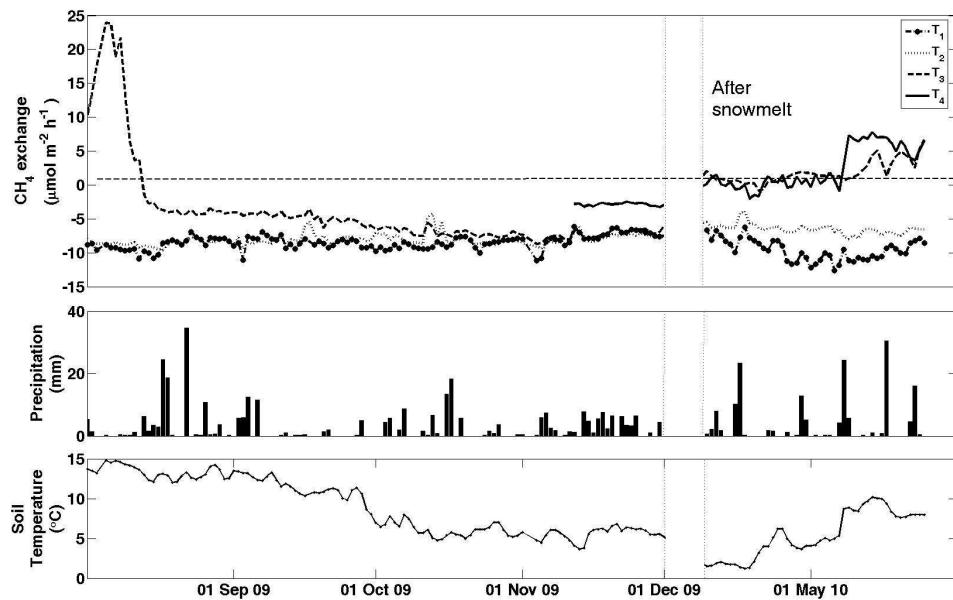
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729   Fig.3c)
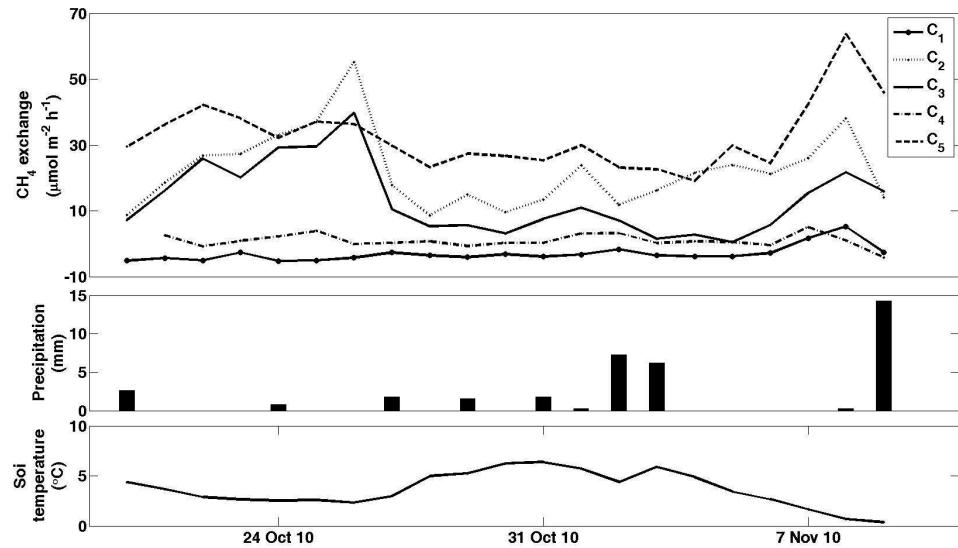
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732   Fig.3d)
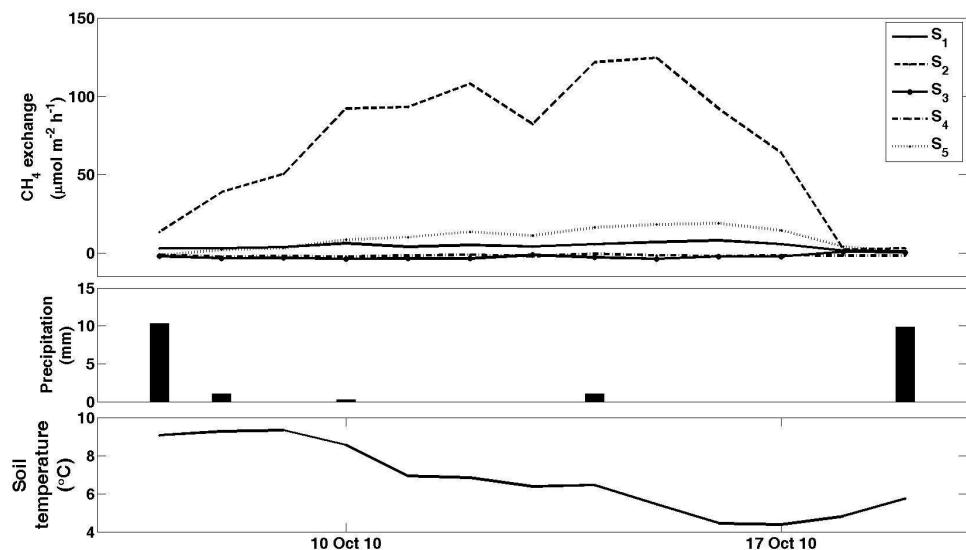
733

734   Fig.3a. Time series of daily mean CH$_4$ exchange, daily precipitation and daily mean soil temperature at the

735   measurement locations. 3a) Undisturbed plot, 3b) Thinned plot, 3c) Clear-cut plot, 3d) Stump harvested

736   plot.

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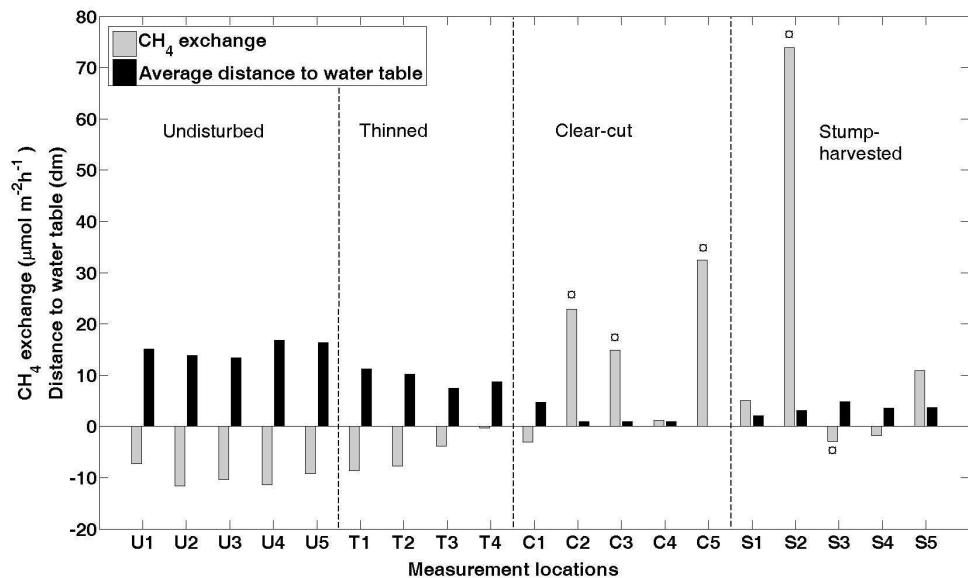
739 Fig.4. CH$_4$ exchange (μmol m^{-2} h^{-1}) at all individual measurement locations with associated level of ground

740 water table. The water table depth at plot C$_5$ is close to zero and that is why the bar is not visible in the

741 diagram.

742 ¤ Measurement locations where soil surface was disturbed during site preparation.

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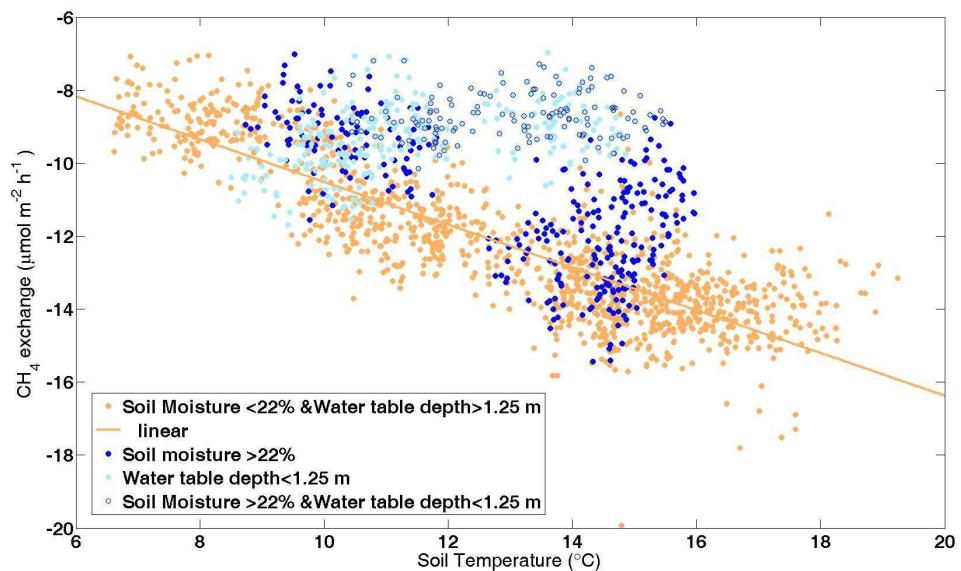
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757

758   Fig.5. Correlation between CH_4 exchange (μmol m^{-2} h^{-1}) and soil temperature ($^\circ$C) at measurement location

759   U_4. The different colours represent different soil moisture and water table depths.

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