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### ► **To cite this version:**

Kim Yrjälä, Tero Tuomivirta, Heli Juottonen, Anuliina Putkinen, Kaisa Lappi, et al.. CH<sub>4</sub> production and oxidation processes in a boreal fen ecosystem after long-term water table drawdown. *Global Change Biology*, 2010, 17 (3), pp.1311. 10.1111/j.1365-2486.2010.02290.x . hal-00599524

**HAL Id: hal-00599524**

**<https://hal.science/hal-00599524>**

Submitted on 10 Jun 2011

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## CH<sub>4</sub> production and oxidation processes in a boreal fen ecosystem after long-term water table drawdown

Journal:	<i>Global Change Biology</i>
Manuscript ID:	GCB-10-0362
Wiley - Manuscript type:	Primary Research Articles
Date Submitted by the Author:	04-May-2010
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Keywords:	greenhouse gas, peatlands, methanogens, methanotrophs, microbial community, DGGE, T-RFLP
Abstract:	Mires, especially sedge dominated fens, are sources of the greenhouse gas CH <sub>4</sub> . Climate change scenarios predict a lowering water table (WT) in mires. To study the effect of WT drawdown on CH <sub>4</sub> dynamics in a fen ecosystem, we took advantage of a WT drawdown gradient near a ground water extraction plant. Methane fluxes, CH <sub>4</sub> production and oxidation potentials, were related to microbial communities responsible for the processes in four mire locations (wet, semi-wet, semi-dry and dry). Principal component analyses (PCA) performed on the vegetation, pH, CH <sub>4</sub> and WT results clearly separated the four sampling locations in the gradient. Long-term lowering of WT was associated with decreased coverage of Sphagnum and aerenchymatic plants, decreased CH <sub>4</sub> field emissions and CH <sub>4</sub> production potential. Based on mcrA T-RF the methanogen community structure correlated best with the methane production and coverage of aerenchymatic plants along the gradient. Methanosarcinaceae and Methanocellales were found at the pristine wet end of the gradient, whereas the Fen cluster

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4 characterized the dry end. The methane-oxidizing bacterial (MOB)  
5 community consisted exclusively of Methylocystis bacteria, but  
6 interestingly of five different alleles (T, S, R, M, and O) of the  
7 particulate methane monooxygenase marker gene pmoA. The M  
8 allele was dominant in the wet locations, and the occurrence of  
9 alleles O, S and T increased with drainage. The R allele that  
10 characterized the upper peat layer correlated with CH<sub>4</sub> oxidation  
11 potential. These results advance our understanding of mire  
12 dynamics after long-term WT drawdown and of the microbiological  
13 bases of methane emissions from mires.  
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For Review Only

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3 **CH<sub>4</sub> production and oxidation processes in a boreal fen ecosystem after long-term water**  
4 **table drawdown**  
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10 **Running title: CH<sub>4</sub> production and oxidation processes**  
11

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48 Keywords: greenhouse gas, peatlands, methanogens, methanotrophs, microbial communities,  
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50 DGGE, T-RFLP  
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**Abstract**

Mires, especially sedge dominated fens, are sources of the greenhouse gas CH<sub>4</sub>. Climate change scenarios predict a lowering water table (WT) in mires. To study the effect of WT drawdown on CH<sub>4</sub> dynamics in a fen ecosystem, we took advantage of a WT drawdown gradient near a ground water extraction plant. Methane fluxes, CH<sub>4</sub> production and oxidation potentials, were related to microbial communities responsible for the processes in four mire locations (wet, semi-wet, semi-dry and dry). Principal component analyses (PCA) performed on the vegetation, pH, CH<sub>4</sub> and WT results clearly separated the four sampling locations in the gradient. Long-term lowering of WT was associated with decreased coverage of *Sphagnum* and aerenchymatic plants, decreased CH<sub>4</sub> field emissions and CH<sub>4</sub> production potential. Based on *mcrA* T-RF the methanogen community structure correlated best with the methane production and coverage of aerenchymatic plants along the gradient. Methanosarcinaceae and Methanocellales were found at the pristine wet end of the gradient, whereas the Fen cluster characterized the dry end. The methane-oxidizing bacterial (MOB) community consisted exclusively of *Methylocystis* bacteria, but interestingly of five different alleles (T, S, R, M, and O) of the particulate methane monooxygenase marker gene *pmoA*. The M allele was dominant in the wet locations, and the occurrence of alleles O, S and T increased with drainage. The R allele that characterized the upper peat layer correlated with CH<sub>4</sub> oxidation potential. These results advance our understanding of mire dynamics after long-term WT drawdown and of the microbiological bases of methane emissions from mires.

## Introduction

In the Northern hemisphere mires extend over vast areas that typically are water-saturated ecosystems where a part of the plant litter production avoids aerobic decomposition and accumulates as peat. The high water table (WT) creates anaerobic microbial habitats where methanogenesis occurs (Rydin *et al.* 2006). Hence boreal mires act as methane (CH<sub>4</sub>) sources into the atmosphere. Due to climate change, a growing attention has been devoted to these areas, where over one-third of the global terrestrial carbon is stored (Gorham, 1991). The rise of earth temperatures may have profound effects on the microbial life of these ecosystems and thus on microbially-mediated gas emissions (IPCC 2007).

Methane, which is a 25 times more powerful greenhouse gas than carbon dioxide, is produced microbiologically in the final stage of anaerobic degradation of organic matter (Whalen, 2005). Methane is solely produced by methanogens that are classified into Euryarchaeota. Methanogens are highly diverse constituting of four classes and six orders of archaea. Methane-producing archaeal communities have been described from various mire ecosystems (Edwards *et al.* 1998; Basiliko *et al.* 2003; Galand *et al.* 2003; Galand *et al.* 2005; Galand *et al.* 2005; Juottonen *et al.* 2008; Putkinen *et al.* 2009) including a range of nutrient conditions (Juottonen *et al.* 2005) and mire successional stages (Merilä *et al.* 2006). Methanogens of Methanosarcinales, Methanomicrobiales, Methanobacteriales and Methanocellales (Rice cluster I) have frequently been detected.

The CH<sub>4</sub> emissions are, however, dependent on the activity and abundance of methane-oxidizing bacteria (MOB) that are able to oxidize CH<sub>4</sub> to CO<sub>2</sub> in aerobic conditions (Hanson and Hanson 1996). The aerobic layer of peat is roughly defined by the WT position (Bubier & Moore, 1993). Low emissions in mires can occur when the CH<sub>4</sub> never reaches the atmosphere because it is consumed by MOB in the uppermost aerobic layer (Whalen, 2005). In this way the CH<sub>4</sub> flux to

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3 the atmosphere is the sum of the functionally opposite actions of archaea and bacteria involved in  
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5 the CH<sub>4</sub> cycle. The highest MOB activity in mires is observed just above the WT, where CH<sub>4</sub> and  
6  
7 oxygen levels are adequate for CH<sub>4</sub> oxidation (Sundh *et al.* 1994). While estimates of the  
8  
9 oxidation efficiency of the produced CH<sub>4</sub> in different mires vary considerably, estimates of  
10  
11 between 20% in *Carex* dominated fens (Popp *et al.* 2000) and 78% in *Sphagnum* dominated bogs  
12  
13 (Yavitt *et al.* 1988) have been given. The latter phenomena is explained by the fact that MOB  
14  
15 inhabit *Sphagnum* species providing the plant CO<sub>2</sub> through CH<sub>4</sub> oxidation under wet conditions  
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17 (Raghoebarsing *et al.* 2005; Larmola *et al.* 2010).  
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22 MOB are traditionally divided into two taxonomic groups, type I and II, within the  
23  
24 Proteobacteria. Type I MOB includes genera like *Methylobacter* and *Methylomicrobium*, which  
25  
26 belong to the Gammaproteobacteria. The type II MOB, *Methylocystis*, *Methylosinus*,  
27  
28 *Methylocella* and *Methylocapsa* belong to the Alphaproteobacteria (Hanson & Hanson 1996;  
29  
30 Dedysch, 2009). These types differ in their carbon assimilation pathway, phylogenetic affiliation,  
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32 and intracellular membrane arrangement.  
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36 The methanogenic and methanotrophic communities in Finnish mires have been studied  
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38 by molecular genetic methods. Methanogens were analyzed by using both functional, *mcrA*  
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40 (Galand *et al.* 2002a), and phylogenetic 16S rRNA marker genes (Galand *et al.* 2003). MOB  
41  
42 have been studied by functional (*pmoA*) marker gene analysis in a pristine and drained fen and  
43  
44 bog within a mire complex (Jaatinen *et al.* 2005). The fingerprinting of Finnish fen MOB was  
45  
46 improved by modifications of the *pmoA* reverse primer for DGGE analysis protocols (Tuomivirta  
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48 *et al.* 2009). Methanogens and methanotrophs in mires have, however, rarely been analyzed  
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50 within the same study (McDonald *et al.* 1999).  
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55 The CH<sub>4</sub> turnover in mires is highly dependent on the ecohydrological conditions. In  
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57 climate change scenarios where the raise of temperature is 3 °C, the summertime WT in northern  
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3 mires is expected to drop 10-20 cm (Gorham 1991; Roulet *et al.* 1992; Gitay *et al.* 2001). A WT  
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5 drawdown of that magnitude (15 cm) has occurred in the northern Suonukkasuo fen where a  
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7 groundwater extraction plant has generated a WT gradient that has gradually changed part of the  
8  
9 wet fen into a forested peatland (Jaatinen *et al.* 2008). Such a persistent change in the WT  
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11 influence the plant community structure (Weltzin *et al.* 2000; Weltzin *et al.* 2003) that may lead  
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13 to complete replacement with species better adapted to the new conditions (Laine *et al.* 1995;  
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15 Strack *et al.* 2006).  
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20 The WT gradient was studied combining methane gas flux measurements, environmental  
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22 data and measurements of microbial communities responsible for CH<sub>4</sub> turnover. This gradient  
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24 study prompted the formulation of hypotheses concerning CH<sub>4</sub> turnover in relation to detected  
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26 microbial communities, namely: (1) as the WT drawdown affects the plant cover and stimulate  
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28 tree growth, the CH<sub>4</sub> emissions are reduced in the resulting dryer conditions; (2) the emissions in  
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30 WT drawdown conditions decrease primarily as a consequence of decrease in potential CH<sub>4</sub>  
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32 production and simultaneous decrease in diversity of methanogens; (3) the potential CH<sub>4</sub>  
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34 oxidation decreases when there is less CH<sub>4</sub> available; (4) the depth is an important factor  
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36 determining microbial community structure, both that of methanogens and of methanotrophs; (5)  
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38 there are specific types of methane-producing archaea and MOB that are favored by the WT  
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40 drawdown.  
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## 48 **Materials and methods**

### 49 **Experimental site and sampling**

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53 The study site, Suonukkasuo, is a mesotrophic pine fen located in Rovaniemi, northern Finland  
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55 (66°28'N, 25°51'E) within the aapa mire zone. Mesotrophic pine fens (RhSR in the Finnish mire  
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3 site-type nomenclature of Laine and Vasander (2005)) are typically sites where wet lawns and  
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5 drier hummocks form a mosaic-like vegetation pattern. A groundwater extraction plant on an  
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7 esker bordering the mire downstream has affected the WT at the study site since 1959, resulting  
8  
9 in a clear hydrological gradient where the pristine wet fen (location S4) becomes semi-wet  
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11 (location S3), semi-dry (location S2), and finally a dry pine dominated mesotrophic peatland  
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13 forest (MtkgII, location S1).  
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16  
17 The average long term water-table (WT) values for the ground-frost free periods of the  
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19 years 2001–2003 and 2005 expressed as distances from soil surface were 26, 21, 15 and 9 cm for  
20  
21 the locations S1 to S4, respectively. The differences in WT between locations were statistically  
22  
23 significant, except between locations S1 and S2 ( $p=0.066$ ). The first- and third-quartile ranges of  
24  
25 the WTs were 21–30, 13–30, 10–21 and 5–13 cm for the locations S1 to S4, respectively. The  
26  
27 momentary WT at the time of sampling in 2006 was 32, 50, 47 and 23 cm, respectively. The  
28  
29 hydrological gradient is reflected in vegetation composition as reported in Jaatinen *et al.* (2008).  
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34 Sampling was conducted in September 2006. Intact triplicate peat cores were taken from  
35  
36 the four locations using a corer (size 4 x 6 cm) to a depth of 70 cm. Depth samples were prepared  
37  
38 by dividing peat cores at 10 cm intervals. The samples between 0 - 50 cm depth were used for  
39  
40 estimation of the methanotroph activity and community analyses and the samples between depths  
41  
42 20 - 70 cm for the respective analyses for methanogens. For convenience we call the samples  
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44 between 0 to 10 cm as 0 cm, between 10 to 20 cm as 10 cm and so on. To measure the peat dry  
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46 weight subsamples were kept at 105 °C for over 12 h and subsequently weighted.  
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## 52 **Field CH<sub>4</sub> measurements**

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54 Gas efflux measurement plots ( $n = 3$ ) were installed at each location in June 2001 (Dahlin *et al.*,  
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56 2003). Collars made of metal tubes (diameter 31.5 cm) were inserted 15-30 cm deep in peat. An  
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3 aluminum groove was attached on the top of each collar. A closed chamber (height 30 cm)  
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5 equipped with a fan was placed on the groove filled with water before sampling to seal the  
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7 chamber. At each sampling occasion, four successive samples of 30 ml were taken from the  
8  
9 chamber with plastic syringes during a 35-minute measurement period at 10 minute intervals (5,  
10  
11 15, 25, 35 minutes). The syringes were then taken to laboratory and analyzed for CH<sub>4</sub>  
12  
13 concentrations within 24 hours from sampling by a gas chromatograph equipped with a FI  
14  
15 detector. CH<sub>4</sub> fluxes were calculated from a linear change of CH<sub>4</sub> concentrations during the  
16  
17 sampling period of 35 minutes. Obvious ebullition events were deleted from the data.  
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#### 24 **Measurements of potential CH<sub>4</sub> production and oxidation**

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26 Measurements of potential CH<sub>4</sub> production and oxidation (4.13 μmol in 125 ml infusion bottle)  
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28 with incubation at 15 °C were carried out as described in Juottonen *et al.* (2008) and Jaatinen *et*  
29  
30 *al.* (2005), respectively.  
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#### 34 **Analysis of methanogen communities by *mcrA*-TRFLP**

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36 DNA for methanogen community analysis was extracted from 0.25 g of wet mass peat with  
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38 PowerSoil DNA Isolation Kit (MoBio Laboratories). Methyl coenzyme M reductase (*mcrA*) gene  
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40 fragments were amplified with the primers of Luton *et al.* (2002). The reactions (50 μl) contained  
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42 1 × PCR buffer with 2 mM MgCl<sub>2</sub> (Biotools), 200 μM dNTPs, 0.4 μM of both primers, 1U of  
43  
44 DNA polymerase (Biotools), and 1-2 μl of undiluted DNA extract as template. The reaction  
45  
46 conditions were initial denaturation (94 °C, 3 min) followed by 31 cycles of 94 °C 45 s, 52 °C 1  
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48 min, 72 °C 1 min 30 s, and a final elongation (72 °C, 7 min). In PCR for T-RFLP, the forward  
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50 primer was 5'-labelled with 6-carboxyfluorescein (FAM).  
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3 For T-RFLP, approximately 25-50 ng of PCR products was digested with 3 U of *MspI*  
4 (Fermentas) at 37 °C overnight. The T-RFLP analysis was carried out as described in Juottonen  
5  
6 (*et al.* (2008)). The range of fragment lengths included in the analysis was 75 to 500 bp. Minimum  
7  
8 peak height threshold was 100 fluorescence units. Results are presented based on relative peak  
9  
10 area. For identification of T-RFs, three clone libraries (S4 20 cm; S2 30 cm; S1 50cm) were  
11  
12 constructed as in Juottonen *et al.* (2008). Inserts from clone colonies were re-amplified with  
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14 *mcrA* primers (33-54 clone per library) and screened by RFLP with *MspI*. From RFLP groups  
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16 with > 5 clones, 2-5 clones from each group were sequenced, and from groups with < 5 clones,  
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18 one member was sequenced as in Juottonen *et al.* (2008). Terminal restriction fragments were  
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20 identified based on *in silico* digestion of the sequences and T-RFLP analysis of clones.  
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### 29 **Investigation of MOB by DGGE analysis of the *pmoA* marker gene**

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31 DNA for methane-oxidizing bacteria (MOB) community analysis was extracted from ca. 0.5 g  
32  
33 wet mass peat using the FastDNA kit for soil (MP Biomedicals, Ohio, USA) according to Yeates  
34  
35 & Gillings (1998) modified as in Tuomivirta *et al.* (2009). A region of subunit  $\alpha$  of particulate  
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37 methane monooxygenase (*pmoA*) was PCR targeted with the A189f/A621r with a GC-clamp  
38  
39 attached to the reverse primer (see Tuomivirta *et al.* 2009 for details). Also broad specificity  
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41 A189f/A682r (Holmes *et al.* 1995) primers were applied for reference (Tuomivirta *et al.* 2009).  
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46 Fingerprinting of the MOB diversity was performed in a denaturing gradient gel  
47  
48 electrophoresis (DGGE) described in Jaatinen *et al.* (2005). The DGGE gel photographs were  
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50 screened for the presence (1) or absence (0) of *pmoA* bands using the AlphaImager 2.1 program  
51  
52 of the AlphaDigiDoc gel documentation system (Alpha Innotech Corp., CA. US). A binary  
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54 matrix was generated with this data using only the positions of successfully sequenced bands.  
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3 Single DGGE bands of interest were excised from the gel, purified and sequenced as described in  
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5 Tuomivirta *et al.* (2009) and Larmola *et al.* (2010).  
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### 10 **Sequence analysis and phylogeny**

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12 *mcrA* and *pmoA* sequences were compared to database sequences with BLAST (Altschul *et al.*  
13  
14 1997) analysis of the National Center for Biotechnology Information (NCBI). Deduced amino  
15  
16 acid sequences of *mcrA* together with selected reference sequences were aligned with ClustalW  
17  
18 (Larkin *et al.* 2007). Suitable evolutionary model was selected with ProtTest (Abascal *et al.*  
19  
20 2005). Maximum likelihood trees were constructed with PhyML (Guindon & Gascuel 2003) with  
21  
22 model LG+G+F. Bootstrap values were generated from 100 replicates in PhyML. Pairwise  
23  
24 distance calculations of nucleotide *pmoA* sequences were analyzed with MEGA 4.0 (Tamura *et*  
25  
26 *al.* 2007). The *mcrA* and *pmoA* sequences have been submitted to the EMBL database under  
27  
28 accession nos. FN564006-FN564029 (*mcrA*) and GQ279342-GQ279346 (*pmoA*).  
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### 36 **Statistical evaluation**

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38 Methane fluxes between locations were compared by one-way analysis of variance (ANOVA).  
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40 Significance of pairwise differences was assessed by Tukey test. The effect of categorical  
41  
42 variables depth, location and their interaction on potential CH<sub>4</sub> production and oxidation were  
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44 compared with generalized linear models (GLM). Tukey post hoc test was applied to determine  
45  
46 which pairs of means differ significantly. Because location and depth had significant interactions,  
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48 ANOVA followed by Tukey test was performed separately for each depth. Level of significance  
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50 in all statistical analyses was P=0.05.  
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55 We applied principal component analysis (PCA) to compare the four locations based on  
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57 their environmental variables, i.e., long-term and momentary WT, CH<sub>4</sub> field emission and  
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3 oxidation and production potential, coverage of *Sphagnum* and aerenchymatic plants, and pH. To  
4  
5 examine variation in methanogen and MOB communities, we first applied detrended  
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7 correspondence analysis (DCA). Based on the DCA showing rather small compositional  
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9 variation, (ter Braak & Prentice 1988) we applied redundancy analysis (RDA) to test which  
10  
11 environmental variables best explained variation in methanogen and MOB communities. The  
12  
13 significance of the above listed explanatory factors was assessed using Monte Carlo permutation  
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15 test. The multivariate analyses were carried out with Canoco for Windows (ter Braak & Smilauer  
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## Results

### Methane emissions

In the years (2001—2004) preceding the sampling for microbial community analysis, the CH<sub>4</sub> emissions from location S4, were substantial, averaging 73 mg m<sup>-2</sup> day<sup>-1</sup> (Fig. 1). As a result of WT drawdown, the emissions were much smaller in the locations S3 (22 mg m<sup>-2</sup> day<sup>-1</sup>), S2 (0.9 mg m<sup>-2</sup> day<sup>-1</sup>) and S1 (1.9 mg m<sup>-2</sup> day<sup>-1</sup>; Fig. 1). Similarly to long term WT the emissions differed significantly between all pairs of locations (P=0.001—0.004) except for locations S2 and S1.

### Methane production and oxidation potential

The wettest location S4 had the highest CH<sub>4</sub> production potential at depths from 20 to 50 cm (P=0.001—0.036, Fig. 2) in correspondence with the flux rates recorded in earlier years. The S4 production was 43.2 nmol g dry weight<sup>-1</sup> day<sup>-1</sup> compared to 0.4 (S3, p=0.005), 4.0 (S2, p=0.010) and 0.4 (S1, p=0.005) at the depth of 20 cm. The production potential of the three other dryer

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3 locations was much lower and did not differ between the locations at any depth. The laboratory  
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5 measurements showed that location and depth significantly affected the CH<sub>4</sub> production potential  
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7 through the WT gradient (p<0.001).  
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10 The highest methane oxidation potential was observed in location S3, 561.2 nmol g dry  
11 weight<sup>-1</sup> day<sup>-1</sup>, but the sampling depth influenced the oxidation potential (p=0.004) in addition to  
12 location (p=0.033) (Fig. 2). In the top layer the potential was significantly higher in S3 than in  
13 S2, 62.2 nmol g dry weight<sup>-1</sup> day<sup>-1</sup> (p=0.042) and S1, 28.9 nmol g dry weight<sup>-1</sup> day<sup>-1</sup> (p=0.031)  
14 and second highest in S4, 177,7 nmol g dry weight<sup>-1</sup> day<sup>-1</sup>. The dry S1 location had the lowest  
15 potential oxidation rate. The oxidation potential did not differ between locations in deeper peat  
16 layers.  
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### 29 **Environmental factors characterizing the WT gradient**

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31 Principal component analyses (PCA) performed on the vegetation, potential CH<sub>4</sub> production and  
32 oxidation, CH<sub>4</sub> field emissions, pH, and long term and momentary (date of sampling) water-table  
33 depth clearly separated the four sampling locations along the first principal axis (PC1 in Fig. 3a).  
34  
35 With the provided measurements the second principal axis (PC2) separated all samples according  
36 to depth. Increase in long term WT, coverage of *Sphagnum* and aerenchymatic plants, high CH<sub>4</sub>  
37 field emissions together with CH<sub>4</sub> production potential characterized the pristine end of the PC1  
38 (Fig. 3b). Decreasing momentary WT and CH<sub>4</sub> oxidation potential together with increasing pH  
39 characterized the peat layers with increasing depth along PC2.  
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### 53 **Microbial communities involved in the CH<sub>4</sub> cycle along the gradient**

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55 T-RFLP fingerprinting of *mcrA* representing methanogens resulted in twelve T-RFs (Table 1). In  
56 the RDA T-RFs 468 and 471 were combined since the large size of T-RFs prohibited reliable  
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3 distinction between them. According to RDA the methanogen community structure showed  
4  
5 highest correlation with methane production and coverage of aerenchymatic plants along the  
6  
7 gradient (RD1 in Fig. 4a-c). The second RDA axis showed that the pH influenced the community  
8  
9 structure according to depth. The first RDA axis separated the four locations when the  
10  
11 methanogen communities at different depths were analyzed together with environmental factors  
12  
13 (Fig. 4b). The top layers were most variable through the gradient, but deeper down they became  
14  
15 more alike.  
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20 In the wet end of the gradient with higher CH<sub>4</sub> production potential the methanogen  
21  
22 diversity was highest with 8 to 10 T-RFs. The locations S2 and S1 sampled from three depths  
23  
24 showed lower diversity with 6 T-RFs.  
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26  
27 The occurrence of the T-RFs 115 bp (Methanocellales), 272 bp (putatively  
28  
29 Methanosarcinaceae) and 298 bp (Methanosarcinaceae) correlated most strongly with the wet  
30  
31 location S4 (Fig. 4c, Fig. 5). In addition to identified methanogens, T-RF 193 bp affiliated with a  
32  
33 cluster with no cultured representatives in the phylogenetic tree (Fig. 5). The T-RF 278 bp,  
34  
35 representing Methanomicrobiales-associated Fen cluster, was one of two T-RFs prone to the dry  
36  
37 end of the gradient despite of overall decrease in methanogen groups along the gradient.  
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41 In analysis of MOB communities, the broad specificity *pmoA* primer set A189f/A682r did  
42  
43 not produce correct amplicons (Tuomivirta *et al.* 2009). Five different *pmoA* alleles (T, S, R, M,  
44  
45 and O), all *Methylocystis* spp according to sequence comparisons, could, however, be isolated  
46  
47 from the gradient by PCR-DGGE and sequencing with the A189f/A621r primer set (Table 2).  
48  
49 RDA (Fig. 6a) of the *pmoA* alleles showed that their occurrence was best correlated with CH<sub>4</sub>  
50  
51 oxidation potential, pH and vegetation. Similarly to methanogen communities (Fig. 4a) the  
52  
53 locations from wet to dry were separated along the first RDA axis, and the second RDA axis  
54  
55 characterized the depth of the peat (Fig. 6b). The two wettest locations had similar MOB  
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3 communities in their whole profile (Fig. 6b). The deep layers (30 - 40 cm) of the locations S4, S3  
4  
5 and S2 were also characterized by a similar MOB. The MOB community of the dry location S1  
6  
7 differed from the other sites. The M allele, dominating the wet end of the gradient (Fig. 6a) was  
8  
9 identical to a previously detected Finnish fen sequence FJ930087 (Tuomivirta *et al.* 2009) and  
10  
11 was most different from the other alleles with 11 to 12 point mutations. The R allele inhabiting  
12  
13 the wetter part of the gradient was identical to sequences FJ930090 and FJ930091 of a Finnish  
14  
15 fen (Tuomivirta *et al.* 2009), AY309209, a North-American fen (Nold, personal communication),  
16  
17 and the sequence GQ121280 (Larmola *et al.* 2010) occurring in methane oxidizing community  
18  
19 within *Sphagnum* mosses. Drying correlated with increasing abundances of alleles O, S and T.  
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21 The R allele dominated the pristine location and the upper layer of the peat (Fig. 6a).  
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## 29 Discussion

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34 Generally the study supports the five hypotheses concerning CH<sub>4</sub> turnover in relation to detected  
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36 microbial communities along WT drawdown gradient. The study of greenhouse gas turnover  
37  
38 along a peatland WT gradient showed that drying appeared to cause a dramatic reduction in CH<sub>4</sub>  
39  
40 emissions and in potential CH<sub>4</sub> production in agreement with our hypotheses 1 and 2. Despite  
41  
42 more oxic conditions the methane oxidation also decreased substantially along the gradient. The  
43  
44 phenomena supported our third hypothesis on the superior role of the availability of CH<sub>4</sub> for the  
45  
46 potential CH<sub>4</sub> oxidation over the direct WT control. In agreement with the fifth hypothesis drying  
47  
48 decreased the diversity of the methanogen communities and brought forth an adapted group of  
49  
50 archaea, the Fen cluster methanogens, which was characteristic of dryer conditions. As  
51  
52 hypothesized (hypothesis 4) the depth appeared to be an important factor for the community  
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54 structure of methanogens and of methanotrophs. The depth effect in WT drawdown brought  
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3 about a peculiar shift in methanotroph populations showing specific *pmoA* allele types of  
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5 *Methylocystis* bacteria distributed to specific locations in the gradient. Previously, at the same  
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7 site, the CO<sub>2</sub> flux increased from location S4 to S1 and fungi and bacteria benefited from the WT  
8  
9 drawdown whereas actinobacteria did not (Jaatinen *et al.* 2008).  
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13 Separation of the four locations along the WT gradient and the sampling depths (peat  
14  
15 layers) was clear and could statistically be explained by eight variables. The WT gradient was  
16  
17 best described in PCA by coverage of aerenchymatic plants, high CH<sub>4</sub> emissions at the wet end,  
18  
19 coverage of *Sphagnum* moss and CH<sub>4</sub> production potential in this order. The CH<sub>4</sub> oxidation was  
20  
21 reduced as a consequence of WT drawdown but not as clearly as the production. This may well  
22  
23 be indicative of the difference in the two processes of production (anaerobic) and the following  
24  
25 consumption (aerobic) of CH<sub>4</sub>. The CH<sub>4</sub> oxidation potential indeed correlated positively with the  
26  
27 WT of the time of sampling and the coverage of *Sphagnum*, whereas production correlated with  
28  
29 other variables like pH and emissions (Fig. 3b). The high oxidation in wet locations seemed to be  
30  
31 coupled with high CH<sub>4</sub> production potential. When more CH<sub>4</sub> is potentially produced by  
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33 methanogenic archaea, more is simultaneously oxidized by the methanotrophic bacteria.  
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39 Very recently methane oxidation was reported from 23 different *Sphagnum* species  
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41 originating from a Finnish boreal mire site and the activity was related to a *Methylocystis*  
42  
43 signature similar to the R allele of this study (Larmola *et al.* 2010). The correlation of the  
44  
45 oxidation potential with *Sphagnum* coverage might be a direct regulation instead of a covariation  
46  
47 with more pristine conditions.  
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51 The methanogen community structure according to T-RFLP analysis changed with  
52  
53 decrease in diversity along the gradient. The maximum CH<sub>4</sub> production potential for each vertical  
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55 peat core correlated with the diversity of methanogens so that decreasing production was  
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57 reflected in decreasing diversity. WT gradients have mainly been studied in meso- and  
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3 microcosms (see, however, Talbot *et al.* 2010), and as far as we know reports from natural  
4  
5 gradients combined with microbial community analysis of the CH<sub>4</sub> are lacking. In agreement  
6  
7 with our results from the gradient, experimental field studies in Canada (Strack *et al.* 2004) and  
8  
9 in Ireland (Laine *et al.* 2009) have shown decrease in CH<sub>4</sub> emission as a result of lowered WT.  
10  
11 Short term effects of WT on carbon balance in pore water from acidic, oligotrophic mire have  
12  
13 been reported from a mesocosm study (Blodau *et al.* 2004) where decreased CH<sub>4</sub> production and  
14  
15 emission was reported as a result of lower WT. Short term effect of drought (4 week) on the  
16  
17 methanogen community structure in a bog and a fen mesocosm could not be observed (Kim *et al.*  
18  
19 2008), but a significant decrease in the *mcrA* abundance was detected in the fen mesocosm.  
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25         Sampling depth has been shown to affect the methanogen community structure in mires  
26  
27 (Galand *et al.* 2002b) where the changing conditions with depth (oxygen and quality of growth  
28  
29 substrates for the microbes active in methanogenesis) will select for methanogen groups. The  
30  
31 RDA analysis of the methanogen communities together with environmental factors showed  
32  
33 nicely how the locations differ at the surface, but become much alike in the deepest sampling  
34  
35 layer where the conditions in the gradient apparently are more similar (Fig. 4b). The discrepancy  
36  
37 of location S2 to the general trend may well be explained by larger pH variation at this location  
38  
39 (results not shown) and lowest emissions telling that this location is the most disturbed one in the  
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41 gradient.  
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46         The methanogen group most strongly associated with the pristine end of the gradient was  
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48 Methanosarcinaceae. In the drier locations, Methanosarcinaceae T-RFs were less abundant or  
49  
50 absent. This finding was surprising considering that many members Methanosarcinaceae are  
51  
52 versatile methanogens that are able to use several different substrates for growth (Garcia *et al.*  
53  
54 2000). They also possess enzymes for detoxification of oxygen, which could favor their  
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56 occurrence in the dry end of the gradient, which is the opposite of what was observed. Additional  
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3 data, such as availability of methanogenic substrates along the gradient, would be required to  
4  
5 better explain the disappearance of Methanosarcinaceae at the dry end. A minor group also found  
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7 primarily at the wet end was an uncultured cluster (Mx cluster in Fig. 5) which has been detected  
8  
9 in other wetland ecosystems (Juottonen *et al.* 2005; Castro *et al.* 2004; Smith *et al.* 2007) and in  
10  
11 animal feces (Ufnar *et al.* 2007), and it has been proposed to form an entirely new order of  
12  
13 methanogens (Mihajlovski *et al.* 2008). Only two methanogenic groups were typical to the dry  
14  
15 end of the gradient, and they were affiliated with the Fen cluster which has commonly been found  
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17 in Finnish mires (Juottonen *et al.* 2008). One member of this cluster, *Methanoregula boonei*, was  
18  
19 isolated from an acidic bog and has the lowest pH optimum known for a methanogen (Bräuer *et*  
20  
21 *al.* 2006). It is tempting to say that the Fen cluster/Methanoregula-type hydrogenotrophic  
22  
23 methanogens are well adapted to the conditions of boreal fens characterized by changing WT and  
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25 low pH.  
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31 All detected MOBs were by *pmoA* sequence analysis found to be of the *Methylocystis*  
32  
33 genus, but differed by minute changes, point mutations, in the gene (Table 2). This suggests a  
34  
35 phylogenetically very narrow MOB population of this fen. RDA showed that the occurrence of  
36  
37 the five alleles was clearly dependent on location and peat layer in the gradient. It can be  
38  
39 assumed that before WT drawdown, when the whole site was botanically a homogenous fen, all  
40  
41 the locations had a similar MOB population with dominating alleles R and T in surface peat and  
42  
43 then changing to T and M alleles in the deeper peat. Continual drainage of the fen has a selective  
44  
45 pressure on MOB. The R allele was lost upon drying since methanotrophy in *Sphagnum* mosses  
46  
47 is only related to high WT (Larmola *et al.* 2010). For reasons we do not know the most different  
48  
49 M allele, in respect to other ones, disappears in WT drawdown and is replaced by the O and S  
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51 alleles through out the peat layer. The S allele could originate from the generalist T through a  
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3 single silent point mutation in *pmoA*. The O has probably been introduced to the location as it  
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5 contains four silent point mutations in respect with S.  
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8 *Methylocystis* was a dominating genus also in Russian and German bogs, which showed  
9  
10 that 60-95% of MOB belonged to type II with *Methylocystis* being the dominant genus (Dedysh  
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12 *et al.* 2003). A study, in which stable isotope probing (SIP) with PLFA, mRNA and microarray  
13  
14 methods were used, revealed the dominance of type II genera *Methylocystis* and *Methylosinus* in  
15  
16 blanket peat samples from England (Chen *et al.* 2008). Bearing in mind that also *Sphagnum*  
17  
18 species possess *Methylocystis* (Larmola *et al.* 2010), one can say that it most likely dominates in  
19  
20 northern peatlands.  
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24 With regard to climate change effect on boreal fens, the average drop in WT between  
25  
26 location S4 (wet fen) and location S3 (semi-wet) was ca. 6 cm. This was accompanied by a  
27  
28 statistically significant drop in potential CH<sub>4</sub> production together with a reduction in emissions  
29  
30 from previous years. The potential oxidation changed in the other direction with increasing  
31  
32 amounts of CH<sub>4</sub> oxidized at location S3 as compared to location S4. This would indicate that  
33  
34 already a small, 6 cm, WT drawdown will change the CH<sub>4</sub> turnover. The methanogen community  
35  
36 structure most clearly shifted between locations S3 and S2 and the distribution of the  
37  
38 methanotrophic allele types is also changing most clearly in this part of the gradient. It can,  
39  
40 however, be stated that as the underlying microbial communities are changing with a 12 cm  
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42 drop in WT their activity is already altered after the 6-cm initial drop in WT.  
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48 Comparison of behavior of methanogens and methanotrophs in the WT gradient using  
49  
50 CH<sub>4</sub> production and oxidation measurements showed a difference in sensitivity to changing  
51  
52 conditions. Much of the methanogenic activity is evidently lost already in the semi-wet location  
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54 S3 and after that decreases drastically, whereas the methanotroph potential activity is high in the  
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56 wet locations and decreases much less in the dryer locations. This can be explained by more oxic  
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3 conditions that should favor these aerobic bacteria. The drop is best explained by the lack of  
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5 substrate; CH<sub>4</sub>.  
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8 As a general conclusion, we have been able to show that even a minor WT drawdown,  
9  
10 mimicking the climate change impact affects the dynamics of CH<sub>4</sub> production and oxidation in a  
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12 mire. This study thus shows how ecohydrology shapes the dynamics of mires changing the plant  
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14 community structures, and has a drastic effect on the microbial communities that are the basis for  
15  
16 the environmentally important function of greenhouse gas turnover.  
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## 19 20 21 22 **Acknowledgements**

23  
24 We thank Sirpa Tiikainen for the valuable laboratory help with MOB. This study was financed by  
25  
26 the Academy of Finland (project number 109816).  
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Table 1 Identification of T-RFs detected in analysis methanogens in the mires forming a water table (WT) gradient. The occurrence of PCR-T-RFLP detected methanogens in the WT gradient formed by the four locations S4-S1 and the relative abundance of T-RFs in each location.

T-RF (bp)	Methanogen group	Occurrence of T-RF (%)			
		S4	S3	S2	S1
105	no sequences	3	2	-	-
115	Methanocellales	6	4	-	-
193	Mx cluster	5	1	2	-
243	Methanosarcinaceae	-	-	-	1
251	Methanocellales	13	18	7	6
272	Methanosarcinaceae <sup>a</sup>	14	6	5	1
278	Fen cluster (Methanomicrobiales)	31	41	70	69
293	Fen cluster (Methanomicrobiales)	16	15	3	14
298	Methanosarcinaceae	2	-	-	-
468	Methanobacteriaceae	9 <sup>b</sup>	13 <sup>b</sup>	13 <sup>b</sup>	8 <sup>b</sup>
471	Fen cluster (Methanomicrobiales)				
489	Methanosarcinaceae	1	-	-	-
		wet	semi	semi	dry
			wet	dry	

<sup>a</sup> No sequences were detected in this study but identification is based on sequences from other mire sites (Juottonen *et al.*, unpublished data).

<sup>b</sup> Includes T-RFs 468 and 471 bp.

Table 2 Number of point mutations (integers) between different *pmoA* allele sequences and standard errors (in parenthesis) of pairwise distance calculations. Accession numbers in Genbank are GQ279342 (T), GQ279343 (S), GQ279344 (R), GQ279345 (M) and GQ279346 (O), respectively.

Sequence of <i>pmoA</i>					
O	5	4	7	11	
M	12	11	12		
R	2	3			
S	1				
T					
	T	S	R	M	O
T		[0.00198 ]	[0.00286 ]	[0.00977 ]	[0.00513 ]
S	0.00122		[0.00376 ]	[0.00918 ]	[0.00455 ]
R	0.00244	0.00367		[0.01011 ]	[0.00648 ]
M	0.01518	0.0139	0.01522		[0.00944 ]
O	0.00616	0.00492	0.00867	0.01382	

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3 Fig. 1 Average methane emission 2001-2004 from the four locations forming a water table (WT)  
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5 gradient, from wet fen location S4 to dry forested location S1.  
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10 Fig. 2 (a) The potential methane production, (b) the potential methane oxidation in the four  
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12 locations S4 - S1. The depths are given as distance from the surface of the mires.  
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17 Fig. 3 (a) Principal component analysis (PCA) of environmental factors, emissions, vegetation,  
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19 water table (WT) for locations S4 to S1 coupled with CH<sub>4</sub> production and oxidation. The  
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21 direction of the arrow describes the correlation between measured factors. The length of the  
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23 arrow gives the degree of explanation of each variable in the ordination. The two first principal  
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25 components together explained 55.3% of the variation. Eigenvalues of the first and second axis  
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27 were 0.366 and 0.186, respectively. (b) Score plot of the PCA.  
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34 Fig. 4 (a) Redundancy analysis (RDA) of statistically significant environmental factors and  
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36 methanogen communities. The length of an arrow describes the degree of explanation of  
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38 environmental factor. The first two axes explained 28.0% of the compositional variation. (b)  
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40 RDA of methanogen phylotypes (T-RFs) at different depths and environmental factors. (c) RDA  
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42 of T-RFs detected in the water table (WT) gradient. The length of arrow describes how well the  
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44 phylotype correlates with locations in the gradient.  
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50 Fig. 5 Maximum likelihood tree of partial *mcrA* sequences (128 aa) from Suonukkasuo fen clones  
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52 (in bold) and reference methanogen sequences. Size of terminal restriction fragment is indicated  
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54 for each group. Scale indicates 10% sequence divergence. Nodes with bootstrap values >95% are  
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56 marked with filled circles and >75% with open circles. The tree was rooted with *Methanopyrus*  
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3 *kandleri*. In bold sequence names Suon1, Suon2 and Suon4 refer to locations S1, S2 and S4 of  
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6 the water table gradient.  
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10 Fig. 6 (a) RDA of methanotroph *pmoA* alleles showing correlation strength (length of arrow) with  
11 statistically significant environmental factors. The first two axes explained 47.1% of the  
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13 compositional variation. (b) The change in methanotroph communities according to depth and  
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15 environmental factors picturing the WT gradient.  
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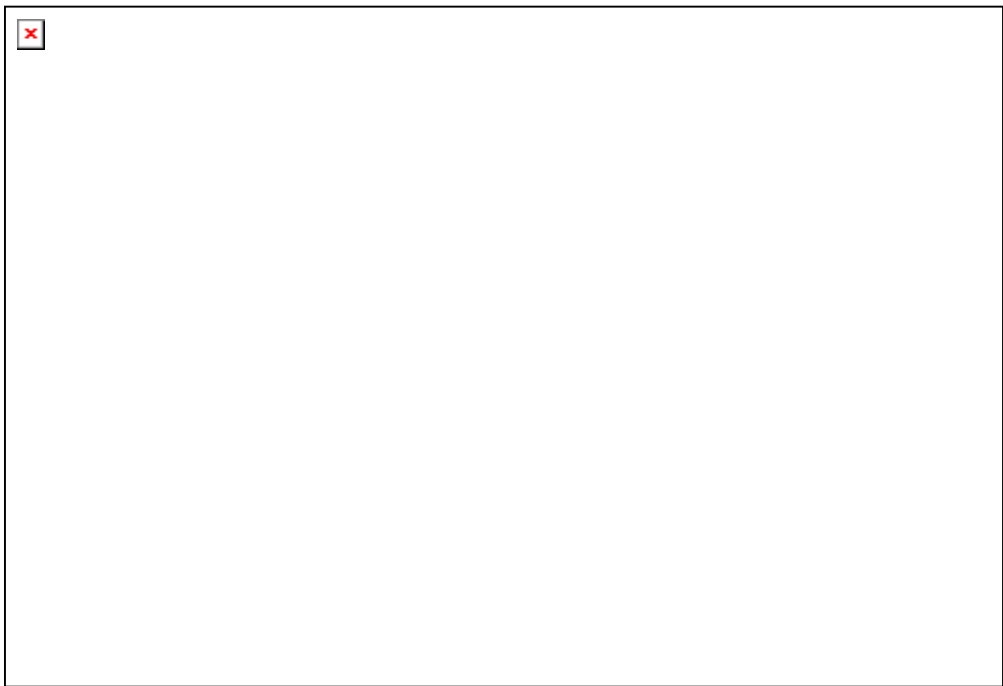


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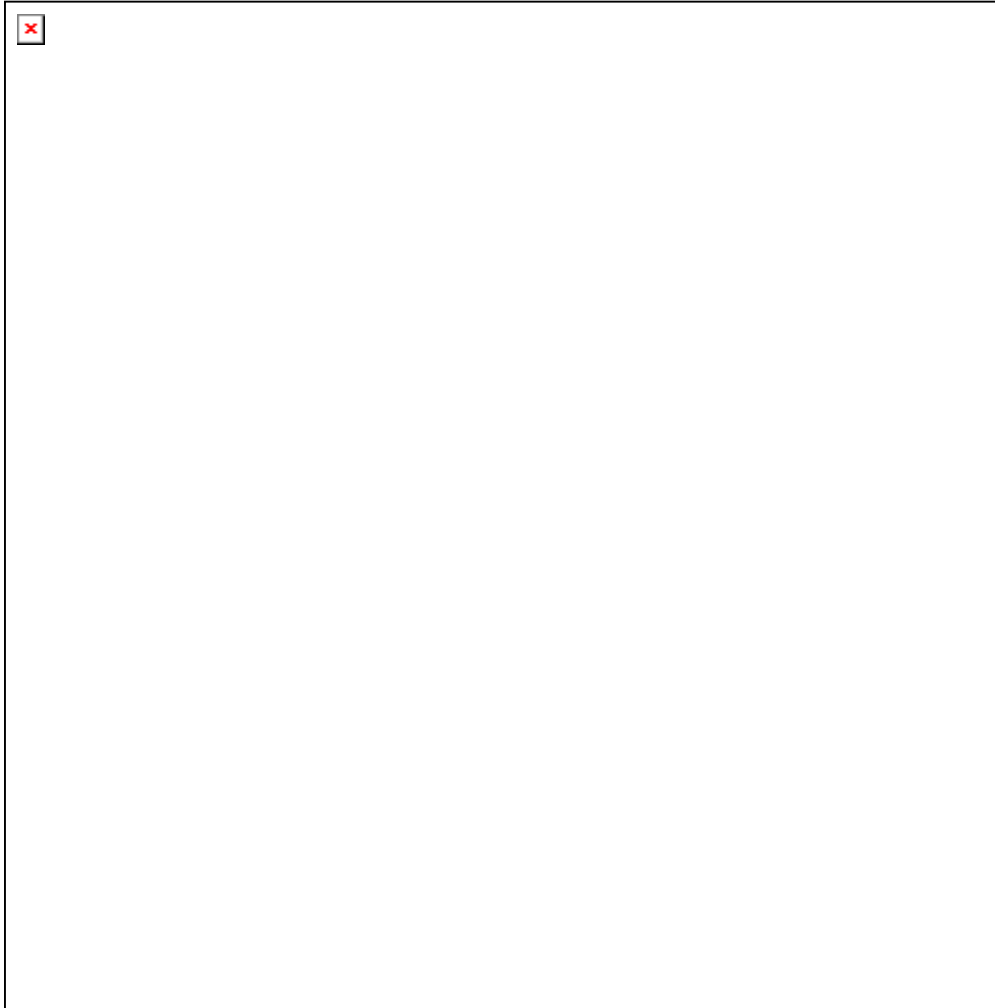
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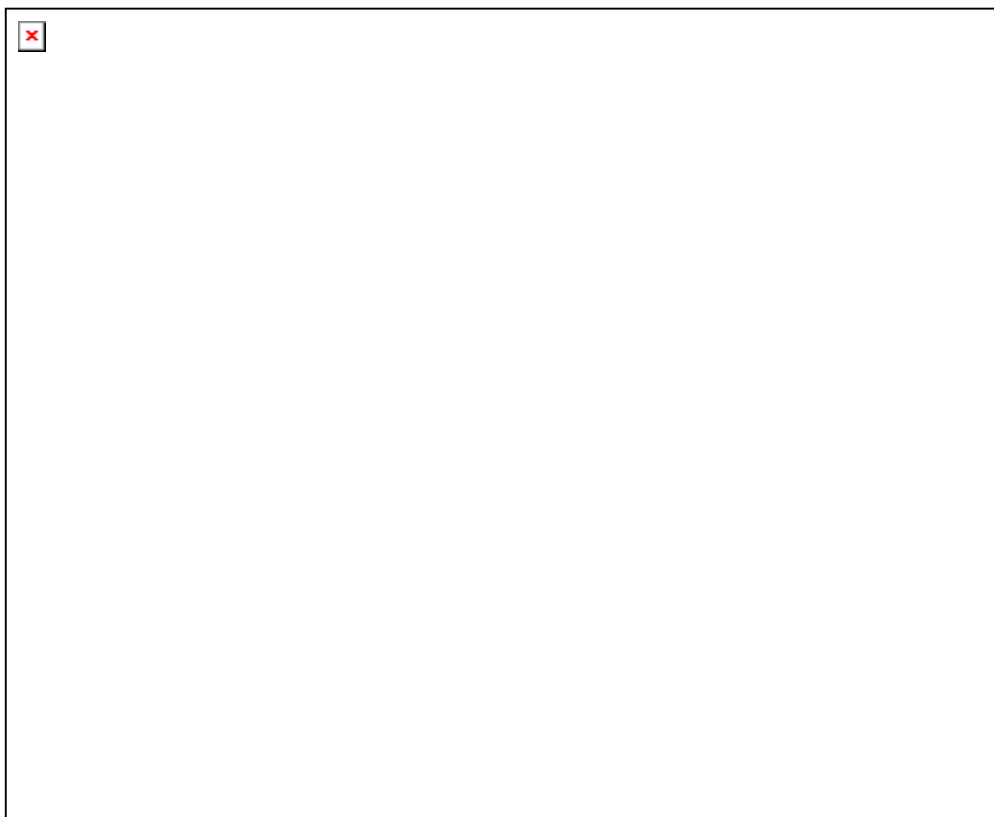
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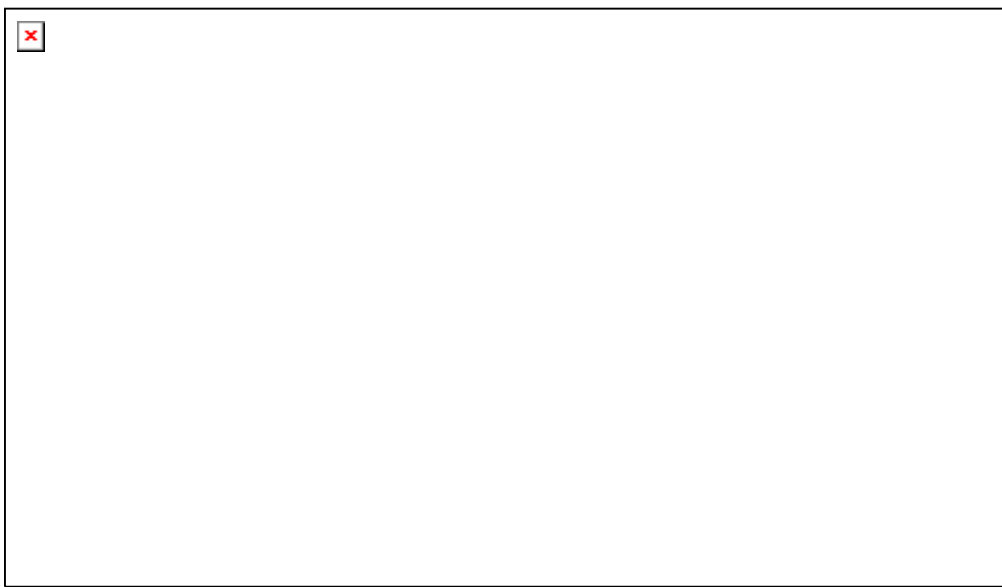
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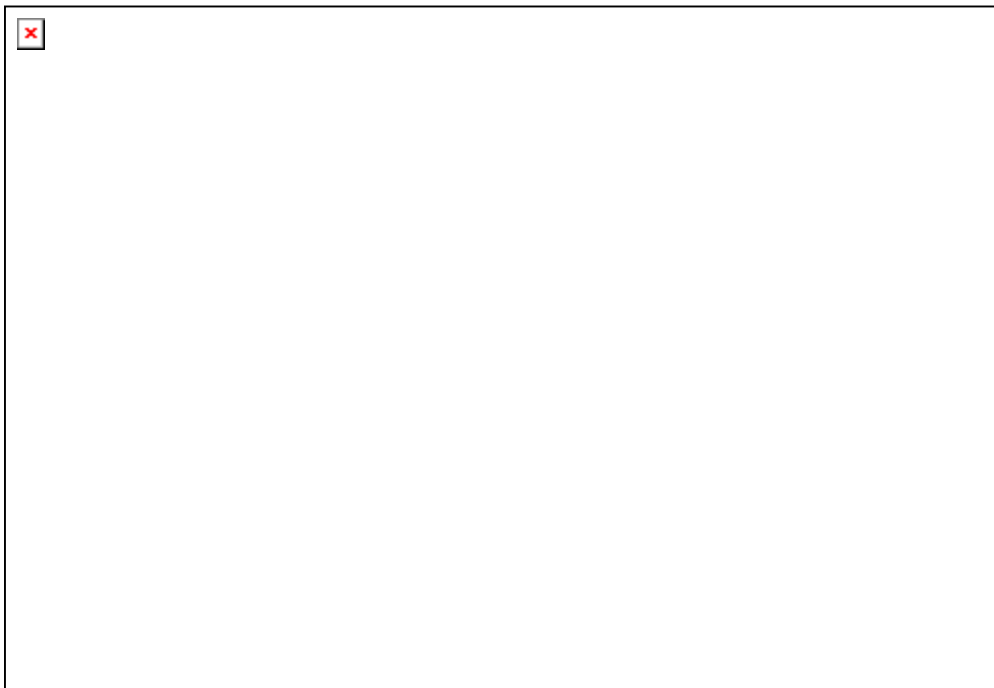
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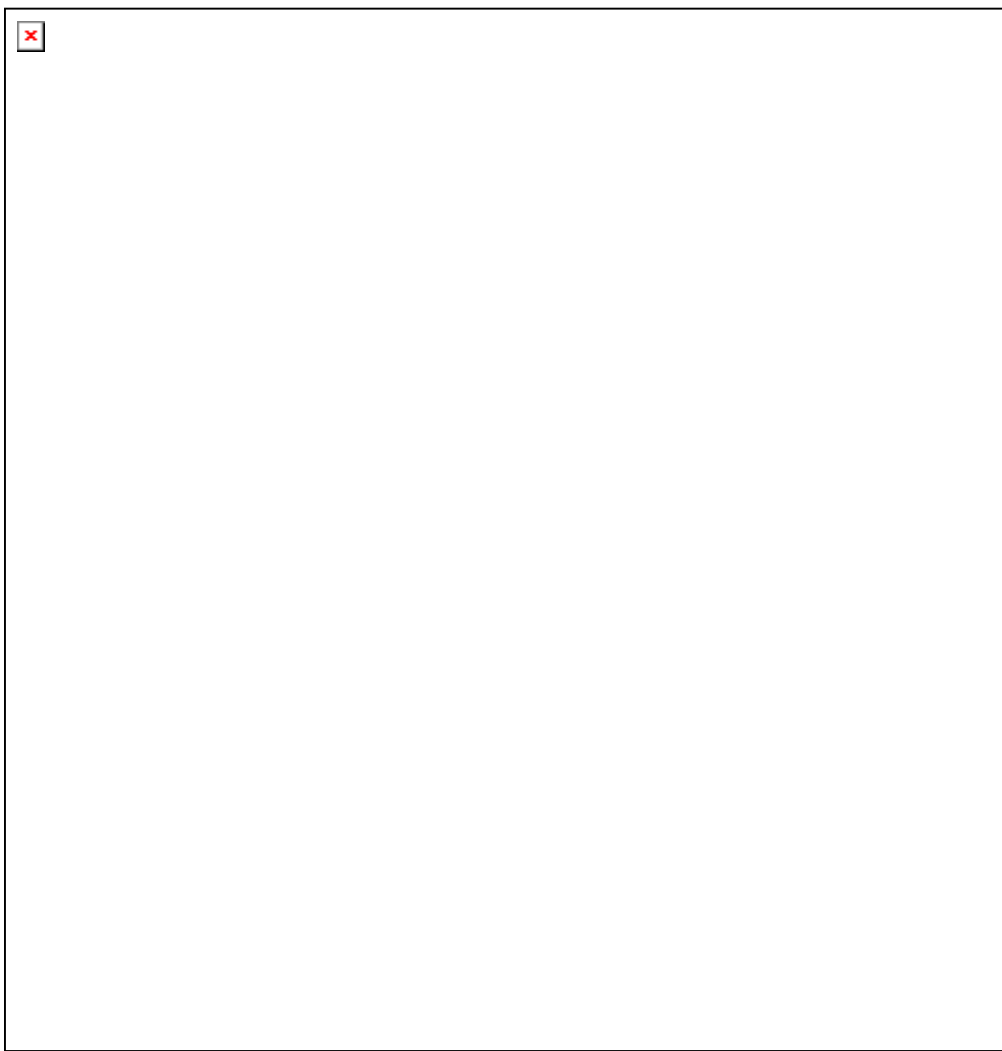
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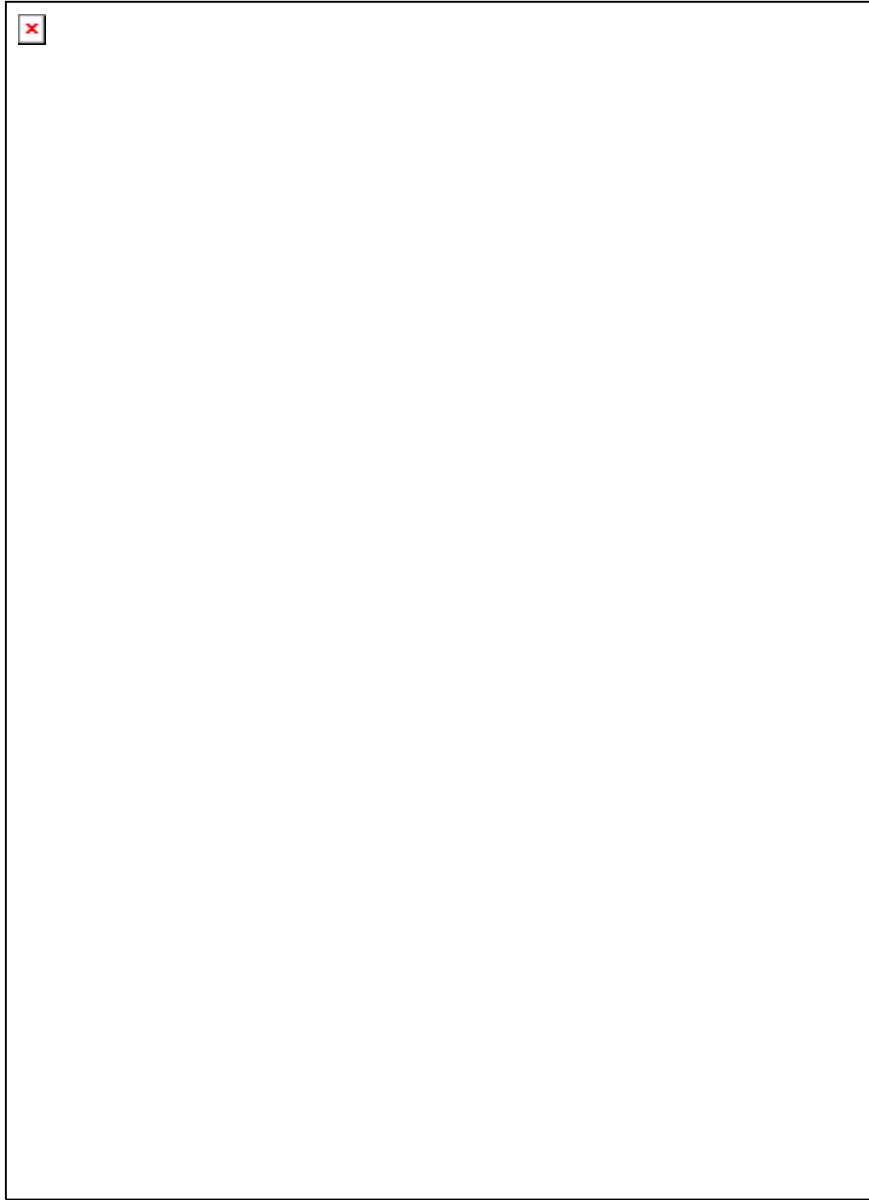
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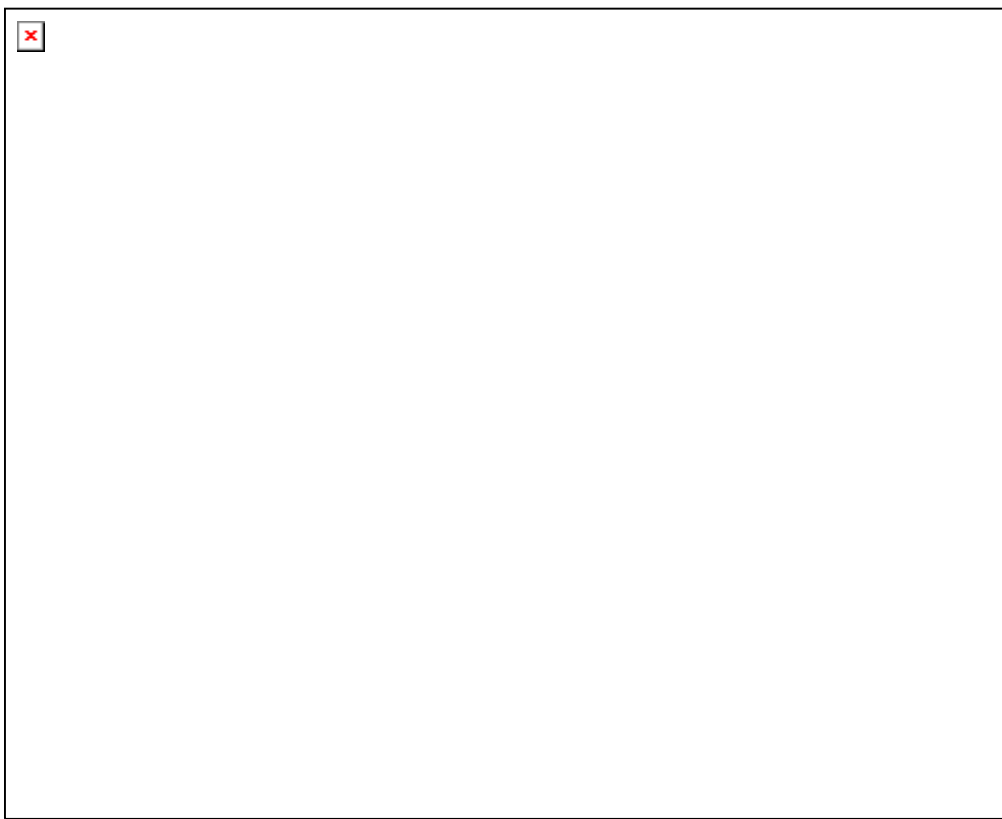
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