Biogeochemistry (2010) 97:89–107
DOI 10.1007/s10533-009-9322-z

Effects of site preparation for afforestation on methane fluxes at Harwood Forest, NE England

Witness Mojeremane · Robert M. Rees · Maurizio Mencuccini

Received: 22 September 2008 / Accepted: 2 April 2009 / Published online: 6 May 2009

Abstract A field experiment was established at Harwood Forest to investigate the effects of three forest management practises (drainage, mounding and fertilisation) on methane (CH_4) emissions and environmental variables (soil temperature, soil moisture content, water table depth) from 2006 to 2008. The relationship between CH_4 emissions and environmental variables was also evaluated. The experiment was laid out in a factorial split-plot design on grassland in a peaty gley soil. Drainage increased daytime soil temperature at all depths. Mounding increased soil temperature at 1 and 5 cm depth. Soil moisture content was decreased by drainage and mounding. All practises affected soil CH_4 emissions with drainage reducing emissions by 57–76% and mounding and fertilisation increasing emissions by 34–59 and 20–59%, respectively. Water table depth was the major factor controlling CH_4 emissions.

Keywords Peaty gley soil · Drainage · Mounding · Fertilisation · Methane · Afforestation

W. Mojeremane (✉) · M. Mencuccini
Institute of Atmospheric and Environmental Science, School of GeoSciences, University of Edinburgh, Crew Building, West Mains Road, Edinburgh EH9 3JN, UK
e-mail: s0564483@sms.ed.ac.uk

R. M. Rees
Scottish Agricultural College, The King's Building, West Mains Road, Edinburgh EH9 3JG, UK

Introduction

Methane is the second most important greenhouse gas after carbon dioxide (CO_2) (Schimel and Gulledge 1998; Van den Pol-van Dasselaar et al. 1999) and contributes 20% to global warming (Hütsch 2001; Dalal and Allen 2008). The atmospheric concentration of CH_4 has increased from the pre-industrial level of 0.75 to the current level of 1.75 μmol mol^{-1} (Schimel 2000; Smith et al. 2003). The increase has been attributed to anthropogenic activities such as fossil fuel exploitation, biomass burning, rice production; digestive processes from ruminants, sewage treatment plants and landfill use (Crutzen 1991; Lelieveld et al. 1998).

Soils are the most important biological sources and sinks for atmospheric CH_4 (Le Mer and Roger 2001; Dutaur and Verchot 2007). Globally, most CH_4 is produced by methanogenic bacteria during anaerobic decomposition of organic matter in waterlogged soils and in terrestrial wetlands (Lloyd et al. 1998; Hou et al. 2000; Yavitt and Williams 2000). Methane can also be produced in upland soils inside soil aggregates where anaerobic microsites occur (Dutaur and Verchot 2007). Methane emitted from soils to the atmosphere is the net balance between production and oxidation controlled by methanogens and methanotrophs (Chan and Parkin 2001; Chen et al. 2009).

Globally, an estimated 600 Tg CH_4 are released to the atmosphere annually (Lelieveld et al. 1998; Smith 2005), with over 70% originating from biogenic sources such as wetland soils, rice paddies and ruminants (IPCC 2007). Methanotrophy (the bacterial oxidation of CH_4) in soils is the major biological sink for atmospheric CH_4 in terrestrial ecosystems (Butterbach-Bahl et al. 1998; Roura-Carol and Freeman 1999; Sjögersten et al. 2007). However, there is evidence that CH_4 can also be oxidised in wetland soils in the anaerobic/aerobic interface of the soil before it is emitted into the atmosphere, but the uptake rate is comparatively low (e.g., Miura et al. 1992; Ding et al. 2003).

Various factors affect the CH_4 emission rate in soil, such as water table depth (Tuittila et al. 2000; Frenzel and Karofeld 2000; Yang et al. 2006), soil moisture content (Liblik et al. 1997; Hargreaves and Fowler 1998), soil temperature (Daulat and Clymo 1998; Saarnio et al. 1998; Ding and Cai 2007), amount and quality of organic substrate (Bossio et al. 1999; Joabsson et al. 1999; Ström et al. 2003), mineral nitrogen (N) concentration and pH (MacDonald et al. 1997; Hütsch 1998; Singh et al. 1999). Vascular plants are also important in CH_4 dynamics because they provide a major pathway for CH_4 fluxes in wetlands (Frenzel and Rudolph 1998; Bellisario et al. 1999; Joabsson and Christensen 2001) and possibly also in periodically flooded forests (e.g., Rusch and Rennenberg 1998; Terazawa et al. 2007).

Land use changes such as the cultivation of natural soils strongly reduce the strength of the soil CH_4 sink (Smith et al. 2000; Merino et al. 2004; Castaldi et al. 2006; Tate et al. 2007) and increase atmospheric CH_4 concentration (Jäckel et al. 2004) due to the disturbance effect of soil methanotrophic bacterial communities (Knief et al. 2003; Seghers et al. 2003; Tate et al. 2007). For example, Smith et al. (2000) estimated that the conversion of forests to agriculture frequently decrease the strength of soil CH_4 sink by up to 60%. Soil compaction by agricultural and forestry equipment (e.g., tractors and excavators) can also reduce the strength of the soil CH_4 sink (e.g., Hansen et al. 1993) and thus turn soils to a net sources of atmospheric CH_4 (Ruser et al. 1998). The addition of N fertilisers to soils can also enhance CH_4 emissions (Hütsch 1998, 2001; Tlustos et al. 1998; Hilger et al. 2000; Bodelier and Laanbroek 2004) as a result of the inhibition of CH_4 oxidation activity of methanotrophs by NO_3^-, NO_2^- and NH_4^+ (Reay and Nedwell 2004). The effect of land use change and N fertiliser on soil CH_4 fluxes may persist for several years after the practises were carried out (Priemé et al. 1997; Suwanwaree and Robertson 2005), especially in organic soils (Maljanen et al. 2001).

Large areas of boreal and temperate peatlands across the world have been drained and developed for commercial forestry (Laine et al. 1995a). In the UK, approximately 315,000 ha of grassland on peaty gley soils have been afforested with exotic coniferous trees for commercial purposes (Cannell et al. 1993). The productivity of forest stands established on peaty soils in the UK is increased through drainage, mounding and fertilisation (Minkkinen et al. 2008). Drainage and mounding may alter the soil physical, chemical and biological properties and affect CH_4 emissions from peaty gley soils. Potential reductions in CH_4 fluxes following draining and mounding may arise from water table lowering which improves soil aeration (Hillman 1992; Prevost et al. 1997) and increases temperature (Kirschbaum 1995; Davidson et al. 1998). These and other changes (Zerva and Mencuccini 2005a) may reduce CH_4 emissions because of decreased production and increased oxidation of CH_4 caused by lowering the water table depth.

Peatlands are natural sources of atmospheric CH_4 (Nykänen et al. 1998; Huttunen et al. 2003; Laine et al. 2007) but their CH_4 fluxes decrease following drainage and afforestation (Martikainen et al. 1995; Nykänen et al. 1998; Von Arnold et al. 2005). There is growing evidence that land use is an important factor that influences soil CH_4 fluxes, and afforestation is viewed as a potential tool for mitigating CH_4 emissions from soils (e.g., McNamara et al. 2008). However, information about the effect of site preparation for afforestation on CH_4 emissions from peaty gley soils under temperate maritime conditions such as the UK is lacking. We hypothesised that site preparation practises would alter CH_4 emissions from grassland on peaty gley soils. The objectives of the experiment described here were to (i) assess the effect of drainage, mounding and fertilisation on CH_4 emission rates of peaty gley soil in NE England, (ii) assess the effect of these practises on soil environmental variables, and (iii) investigate the relationship between CH_4 emission rates and environmental variables. Monthly averaged CH_4 emission rates, seasonal emissions and annually averaged fluxes are presented in this paper.

Materials and methods

Site description

The field investigation was carried out in an experiment established on an unimproved grassland located between two second rotation Sitka spruce stands at Harwood Forest. Harwood is located in NE England (55°10′ N, 2°3′W). The elevation varies from 200 to 400 m above sea level (Zerva and Mencuccini 2005a; Ball et al. 2007). The mean annual temperature and precipitation in the area are 7.6°C and 950 mm, respectively (Zerva and Mencuccini 2005b). The dominant soil type is a seasonally waterlogged peaty gley with a black-coloured organic-rich layer of depth varying from 15 to 40 cm (Zerva and Mencuccini 2005a; Zerva et al. 2005; Ball et al. 2007). Soil properties at the study site are shown in Table 1.

The forest covers 4,000 ha and is dominated by Sitka spruce stands established on moorland grassland which had been used for grazing domestic stock. The forest was originally established in the 1930s and further planting took place between the 1950s and the 1980s and most stands are now in their second rotation. Site preparation used for planting vary, with old stands planted on linear ridges made with single furrow ploughs and sites often have open ditches spaced at 20–30 m. Mounding has replaced ploughing as a method of soil cultivation prior to planting in the last three decades (Ball et al. 2007). Mounding consists of mechanically excavating peat to a depth of 30–40 cm and heaping it upside down next to the pit. The mounds are commonly spaced at 2 × 2 m intervals (i.e., 2,500 pits/ha) to plant conifers throughout upland Britain. The study site is dominated by *Calluna vulgaris*, *Festuca ovina*, *Eriophorum vaginatum* and *Deschampsia flexuosa* and had been used for grazing domestic stock up to the year before the experiment started.

Experimental design and establishment

The experiment has a full factorial split-plot design with six plots measuring 30 × 8 m established in May 2006. Three plots were selected at random and were drained by cutting open drainage ditches placed 1.5 m from the plot edges and excavated to a depth of 65–70 cm. Drained and undrained plots were isolated by 10 m wide buffer strips. Within each plot, four subplots measuring 8 × 6 m were established and two of them were randomly mounded. Subplots were isolated by 2 m wide buffer strips. Spot mounds were made by turning the soil upside down adjacent to the dug pit (depth 30–40 cm, width 40 cm), thus burying the litter layer and organic horizons of the original soil beneath the mineral layer of mounds. Mounds were about 40 cm wide and 15 cm high. One mounded and one unmounded subplot in each plot were randomly given a compound fertiliser supplying 81 kg N ha^{-1}, 72 kg P ha^{-1} and 35 kg K ha^{-1} as recommended by Taylor (1991). The fertiliser was applied once on 11 June 2006. Hence, the main plots allowed testing for drainage effects, whereas the subplots allowed testing for fertilisation and mounding, in isolation or combined. Each treatment was replicated three times.

Sampling and analysis of soil CH_4 fluxes

Methane measurements were conducted 31 times from 17 June 2006 to 7 May 2008 using a manual closed static chamber technique (e.g., Smith et al. 1995). Measurements were conducted after every fourth day in June 2006, weekly in July, bi-weekly between August and September 2006 and finally at approximately monthly intervals from October 2006 to May 2008. A total of sixty collars (inside diameter 40 cm, height 10 cm) were inserted to a depth of 5 cm, 3 weeks prior to the start of measurements. The collars were positioned randomly in groups of either two or three for each subplot depending on whether the subplot had been mounded. If so, the sampling was stratified in such a way that one collar was placed on top of a mound, one in a hollow and one on undisturbed ground. For unmounded subplots instead, only two collars were used, randomly placed on undisturbed ground. Mounds were estimated to cover about 8% of the total surface area of mounded subplots, and the hollows from which the peat had been excavated, estimated to occupy a similar proportion.

A total of twenty equal-sized chambers were used to measure CH_4 emission rates by placing them on top of the already positioned collars, and then rotating them until all sixty had been measured. A seal between the collar and the chamber was obtained by circular elastic rubber bands on the chamber and collar outer surface. Chambers were sealed with aluminium lids with foam rubbers on the underside and a sampling port fitted with a three-way stopcock.

Table 1 Major soil characteristics of the study site

Treatment	Depth (cm)	pH (H_2O)	BD (g cm^{-3})	Total C%	Total N%	C/N
May 2006						
Drained[a]	0–20	2.9 ± 0.01	0.19 ± 0.02	45.62 ± 1.89	2.18 ± 0.16	21.79 ± 1.15
Undrained[a]	0–20	2.9 ± 0.05	0.17 ± 0.01	44.22 ± 1.96	1.87 ± 0.16	24.76 ± 1.12
Mounded[a]	0–20	2.9 ± 0.04	0.16 ± 0.01	44.48 ± 2.16	1.99 ± 0.16	23.20 ± 1.04
Unmounded[a]	0–20	2.9 ± 0.03	0.20 ± 0.02	45.0 ± 1.67	2.06 ± 0.17	23.36 ± 1.46
Fertilised[a]	0–20	3.0 ± 0.03	0.18 ± 0.01	42.91 ± 2.21	1.91 ± 0.19	24.05 ± 1.49
Unfertilised[a]	0–20	2.9 ± 0.04	0.18 ± 0.02	46.93 ± 1.38	2.14 ± 0.13	22.51 ± 0.93
August 2007						
Drained	0–10	3.9 ± 0.01	0.13 ± 0.01	41.93 ± 1.34	1.83 ± 0.08	23.09 ± 0.60
	10–20	3.8 ± 0.02	0.19 ± 0.01	44.83 ± 2.39	1.53 ± 0.07	29.16 ± 0.76
	20–30	4.1 ± 0.02	1.0 ± 0.01	3.75 ± 0.44	0.13 ± 0.02	30.13 ± 1.20
Undrained	0–10	3.94 ± 0.02	0.13 ± 0.01	45.82 ± 0.56	2.08 ± 0.03	22.09 ± 0.47
	10–20	3.76 ± 0.02	0.20 ± 0.01	45.20 ± 1.55	1.54 ± 0.07	29.68 ± 0.56
	20–30	4.12 ± 0.04	1.12 ± 0.06	3.72 ± 0.46	0.12 ± 0.01	29.97 ± 1.10
Mounded	0–10	3.94 ± 0.01	0.13 ± 0.01	43.68 ± 1.37	1.95 ± 0.07	22.50 ± 0.57
	10–20	3.81 ± 0.02	0.21 ± 0.01	44.76 ± 2.63	1.57 ± 0.09	28.52 ± 0.70
	20–30	4.11 ± 0.03	1.07 ± 0.07	3.97 ± 0.49	0.14 ± 0.02	29.04 ± 1.16
Unmounded	0–10	3.92 ± 0.02	0.12 ± 0.01	44.07 ± 0.96	1.96 ± 0.07	22.68 ± 0.55
	10–20	3.77 ± 0.02	0.18 ± 0.00	45.27 ± 1.10	1.50 ± 0.05	30.32 ± 0.51
	20–30	4.07 ± 0.03	1.07 ± 0.04	3.51 ± 0.38	0.11 ± 0.01	31.06 ± 1.06
Fertilised	0–10	3.92 ± 0.01	0.13 ± 0.01	45.12 ± 0.75	1.94 ± 0.05	23.37 ± 0.49
	10–20	3.80 ± 0.02	0.20 ± 0.01	45.99 ± 1.37	1.59 ± 0.06	29.19 ± 0.58
	20–30	4.09 ± 0.03	1.09 ± 0.07	3.68 ± 0.36	0.12 ± 0.01	30.73 ± 1.31
Unfertilised	0–10	3.93 ± 0.01	0.12 ± 0.01	42.63 ± 1.40	1.97 ± 0.09	21.81 ± 0.53
	10–20	3.79 ± 0.02	0.19 ± 0.01	44.04 ± 2.46	1.48 ± 0.08	29.65 ± 0.74
	20–30	4.09 ± 0.03	1.05 ± 0.05	3.80 ± 0.52	0.13 ± 0.02	29.37 ± 0.92

BD bulk density, *Total C%* percentage total carbon, *Total N%* percentage total nitrogen

[a] Soil samples collected before site preparation

Air was sampled from the headspace of chambers with 60 ml polypropylene syringes and transferred into gas-tight bags (Cali-5-bond, Calibrated Instruments Inc. USA). Each measurement cycle lasted for 30–40 min and a linearity check showed that linear interpolation of two points taken at the start and at the end of the closure gives a good approximation of the true flux (Zerva and Mencuccini 2005, unpublished data). Ambient air samples taken randomly at the height of chambers gave the initial concentration of CH_4. The amount of CH_4 in air samples was determined on a Hewlett Packard 5890 GC (Hewlett Packard Ltd, Altrincham, Cheshire, UK) Gas Chromatograph (GC) with a flame ionization detector (FID) and a digital integrator. External standards of 1, 3 and 10 µm mol^{-1} CH_4 were used for calibration.

Monitoring environmental factors

Soil temperatures at 1, 5 and 10 cm depths (from now on T_1, T_5 and T_{10}) were measured with a digital temperature probe (Fisher Scientific) adjacent to each chamber during all sampling dates. Soil moisture content (m^3 m^{-3}) was also measured in the upper 5 cm of the soil with a Theta probe (KT1-Basic, Delta-T Devices Ltd, Cambridge, UK) next to each collar and chamber. An effort was made to insert the probe in a similar position in order to minimise disturbance of the soil from its frequent insertion. The water table depth (cm from soil surface) was measured in dip wells established in the subplots (one for each subplot). Wells were established by removing a soil core (diameter 5 cm) to 80 cm depth.

PVC pipes (length 1 m, diameter 5 cm) with several small holes (diameter 0.5 cm) drilled laterally were inserted inside to act as liners. Dip wells were always sealed to prevent water entering them.

Soil pH was measured from a soil–water suspension (1:2.5v/v). The soil bulk density (g cm^{-3}) was calculated by dividing the weight of oven dried samples by their volume.

Soil carbon and nitrogen contents were estimated by flash combustion method in a Carlo Erba NA 2500 elemental analyser (ThermoQuest Italia, SpA, Milan, Italy).

Statistical analyses

All data were checked for normality and log-transformed when required. Analyses were carried out both on averaged monthly fluxes as well as on seasonal and yearly totals. The general linear model (GLM) used included the effects of three main factors (drainage, mounding and fertilisation) entered as fixed factors and plot entered as random factor nested within drainage. In case of monthly measurements, month was also entered as a repeated measures factor. The initial GLM included all possible second and third-order interactions. If interactions were not found to be significant, they were excluded and the model was run again without them to confirm the significance of the main factors. In case of significant interactions, the dataset was split and separate analyses were run for each combination. All analyses were run in Minitab 15 using GLM procedure. For all analyses, values from individual chambers were averaged within each subplot. For the mounded subplots, weighted averaging was done by weighing each flux by their respective area covered by mounds, hollows and undisturbed ground.

Results

Effect of site preparation on environmental parameters

Soil temperature

There was no significant difference in soil temperature at any depths among plots ($P > 0.05$). Soil temperature at all depths varied from month to month ($P < 0.0001$; Fig. 1a–c for T_5). Maximum temperatures were recorded in the summer and lowest temperatures in winter months. Overall, the mean daily soil temperature at all depths was significantly increased by drainage ($P < 0.0001$ for T_1, $P < 0.009$ for T_5 and $P < 0.02$ for T_{10}; Table 2), although in absolute terms the difference was 0.2 and 1.2°C. Soil temperature was also increased by mounding ($P < 0.0001$ for T_1 and $P < 0.005$ for T_5; Table 2). In absolute terms the difference in soil temperature between mounded and unmounded subplots was 0.2 and 1.3°C. Fertilisation did not affect soil temperature ($P > 0.05$).

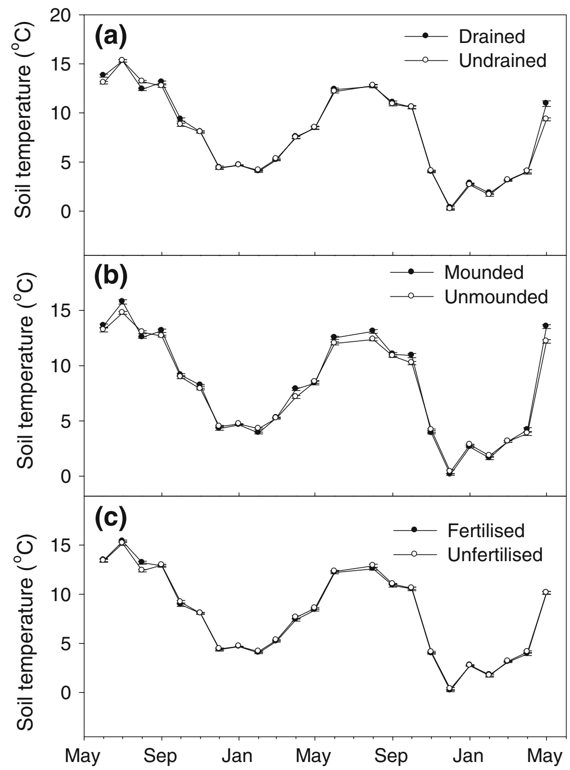

Fig. 1 Seasonal variations in soil temperature at 5 cm depth (T_5) in (**a**) the drained and undrained, (**b**) mounded and unmounded and (**c**) fertilised and unfertilised treatment. The *vertical bars* represent standard error of mean

Soil moisture content

There was no significant difference in soil moisture content among plots ($P > 0.05$). Soil moisture content in all treatments varied from month to month ($P < 0.0001$; Fig. 2b for drained and undrained plots). Overall, soil moisture content was significantly decreased by drainage ($P < 0.009$) and

Table 2 Mean annual (from June to end of May), soil temperature (°C) at 1 cm (T_1), 5 cm (T_5) and 10 cm (T_{10}) depths, soil moisture content (SM; $m^3\ m^{-3}$) and water table depth (WT; cm) by treatment and year

Treatment/Year	T_1	T_5	T_{10}	SM	WT
2006–2007					
Drained	9.9 ± 0.40	8.9 ± 0.33	8.6 ± 0.28	0.77 ± 0.01	−29.1 ± 1.93
Undrained	9.2 ± 0.36	8.8 ± 0.32	8.6 ± 0.29	0.81 ± 0.01	−18.6 ± 1.34
Mounded	9.8 ± 0.40	8.9 ± 0.34	8.7 ± 0.29	0.78 ± 0.01	−23.8 ± 1.71
Unmounded	9.5 ± 0.36	8.8 ± 0.31	8.5 ± 0.27	0.80 ± 0.01	−24.0 ± 1.73
Fertilised	9.6 ± 0.38	8.8 ± 0.33	8.6 ± 0.28	0.80 ± 0.01	−23.9 ± 1.72
Unfertilised	9.6 ± 0.38	8.8 ± 0.32	8.7 ± 0.28	0.79 ± 0.01	−23.8 ± 1.72
2007–2008					
Drained	7.7 ± 0.42	6.6 ± 0.39	6.3 ± 0.36	0.79 ± 0.01	−16.3 ± 1.84
Undrained	6.3 ± 0.38	6.2 ± 0.39	6.0 ± 0.37	0.92 ± 0.07	−6.5 ± 0.98
Mounded	7.2 ± 0.42	6.6 ± 0.41	6.2 ± 0.37	0.79 ± 0.01	−11.4 ± 1.53
Unmounded	6.7 ± 0.39	6.3 ± 0.38	6.1 ± 0.35	0.92 ± 0.07	−11.4 ± 1.54
Fertilised	7.0 ± 0.41	6.4 ± 0.39	6.1 ± 0.36	0.82 ± 0.01	−11.4 ± 1.55
Unfertilised	7.0 ± 0.40	6.5 ± 0.39	6.2 ± 0.37	0.90 ± 0.07	−11.4 ± 1.52
2006–2008					
Drained	8.9 ± 0.29	7.8 ± 0.26	7.5 ± 0.24	0.78 ± 0.01	−23.0 ± 1.39
Undrained	7.8 ± 0.28	7.6 ± 0.26	7.3 ± 0.24	0.87 ± 0.03	−12.8 ± 0.92
Mounded	8.5 ± 0.30	7.8 ± 0.27	7.5 ± 0.25	0.78 ± 0.01	−17.9 ± 1.21
Unmounded	8.2 ± 0.28	7.6 ± 0.25	7.4 ± 0.23	0.86 ± 0.03	−17.9 ± 1.22
Fertilised	8.3 ± 0.29	7.6 ± 0.26	7.4 ± 0.24	0.81 ± 0.01	−17.99 ± 1.22
Unfertilised	8.4 ± 0.29	7.6 ± 0.27	7.4 ± 0.26	0.84 ± 0.03	−17.9 ± 1.21

The "±" indicate the standard error of mean

mounding ($P < 0.0001$). Fertilisation did not affect soil moisture content ($P > 0.05$).

Water table depth

There was no significant difference in the water table depth between plots ($P > 0.05$). The month to month variability in water table depth was highly significant ($P < 0.0001$; Fig. 2a for drained and undrained plots). The water table depth was significantly lowered by drainage ($P < 0.0001$; Table 2). Mounding or fertilisation did not affect the water table depth.

Effect of site preparation on soil CH_4 emissions

Methane flux rates were affected by all three practises (Table 3). Plots differed significantly in CH_4 flux rate throughout the measurement period ($P < 0.0001$), with largest average emissions of 4.82 mg $CH_4\ m^{-2}\ day^{-1}$ observed in the undrained plots. There were no significant interactions between practises, except when the factors month and plot were also included ($P > 0.05$; Table 4).

Effect of drainage on soil CH_4 emissions

Over the whole study period, soil CH_4 fluxes were significantly decreased by drainage ($P < 0.005$; Table 4). Methane fluxes from drained and undrained plots varied from month to month ($P < 0.0001$; Fig. 3a; Table 4). Averaged monthly CH_4 fluxes ranged from −0.31 to 5.17 mg $CH_4\ m^{-2}\ day^{-1}$ in the drained plots and 1.66–11.06 mg $CH_4\ m^{-2}\ day^{-1}$ in their undrained counterparts. Methane fluxes were significantly decreased by drainage in the first and second year of study (all $P < 0.007$; Table 3). The 2 years of study differed significantly ($P < 0.0001$) with more CH_4 emitted in the first than the second year of study.

Seasonal values of CH_4 fluxes from the summer of 2006 to the spring of 2008 showed that they were significantly decreased by drainage in the summer of 2006 ($P < 0.035$) but not in 2007 ($P > 0.05$; Table 5). The two summer seasons differed significantly ($P < 0.0001$), with more CH_4 emitted in the summer of 2006 than in 2007. Drainage significantly decreased CH_4 fluxes in the autumn of 2006 ($P < 0.031$) and 2007 ($P < 0.006$). The two autumn seasons differed significantly ($P < 0.0001$) with more

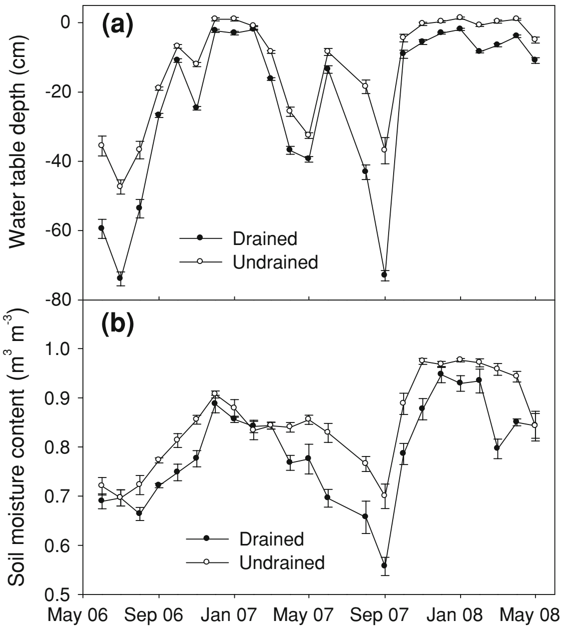

Fig. 2 Seasonal variations in: **a** water table depth, **b** soil moisture content in the drained and undrained plots. The *vertical bars* represent standard error of mean

CH_4 emitted in the autumn of 2006 than the corresponding period in 2007. Drainage significantly decreased CH_4 fluxes in the winter of 2006 and 2007 (all $P < 0.01$). The two winter seasons did not differ in CH_4 flux rate ($P > 0.05$). Drainage also decreased CH_4 fluxes in the spring of 2007 ($P < 0.003$) and 2008 ($P < 0.013$), respectively. The spring seasons differed significantly in CH_4 fluxes ($P < 0.0001$) with more CH_4 emitted in the spring of 2007 than in 2008.

Table 3 Mean daily CH_4 flux rates (mg m^{-2} day^{-1}) averaged over the year

Treatment/Year	mg CH_4 m^{-2} day^{-1}	% Change in CH_4
2006–2007		
Drained	**2.48 ± 0.15a**	
Undrained	**5.80 ± 0.36b**	−57
Mounded	**4.74 ± 0.34a**	
Unmounded	**3.55 ± 0.26b**	34
Fertilised	**5.08 ± 0.34a**	
Unfertilised	**3.20 ± 0.24b**	59
2007–2008		
Drained	**0.89 ± 0.12a**	
Undrained	**3.75 ± 0.16b**	−76
Mounded	**2.85 ± 0.27a**	
Unmounded	**1.79 ± 0.19b**	59
Fertilised	2.53 ± 0.15a	
Unfertilised	2.11 ± 0.11a	20
2006–2008		
Drained	**1.72 ± 0.11a**	
Undrained	**4.82 ± 0.23b**	−64
Mounded	**3.84 ± 0.23a**	
Unmounded	**2.71 ± 0.17b**	41
Fertilised	**3.86 ± 0.23a**	
Unfertilised	**2.68 ± 0.16b**	44

Values followed by different letters indicate a significant difference between treated and untreated plots ($P < 0.05$). Values in bold are statistically significant ($P < 0.05$). Negative values of the % change in flux indicate a decrease in CH_4 fluxes as a result of treatment. The "±" indicate the standard error of the mean

Effect of mounding on CH_4 emission rates

Mounding significantly increased CH_4 fluxes throughout the measurement period ($P < 0.0001$; Table 3). Averaged monthly fluxes in the mounded and unmounded subplots ranged from 0.64 to 8.95 CH_4 m^{-2} day^{-1} and from 0.47 to 7.28 mg CH_4 m^{-2} day^{-1}, respectively (Fig. 3b). Methane fluxes in the mounded and unmounded subplots varied from month to month ($P < 0.0001$). Averaged daily CH_4 fluxes were significantly higher in the mounded subplots than their unmounded counterparts in the first ($P < 0.0001$) and second ($P < 0.005$) year of study. The two sampling years differed significantly ($P < 0.0001$) with more CH_4 emitted in the first year than second year of study.

Seasonal CH_4 emissions were not affected by mounding in the summer of 2006 and 2007 ($P > 0.05$; Table 5), respectively. However, more CH_4 was emitted in the summer of 2006 than the corresponding period in 2007 ($P < 0.0001$). Mounding increased CH_4 emissions in the autumn of 2006 ($P < 0.0001$) and 2007 ($P < 0.031$). The two autumn seasons differed significantly ($P < 0.0001$) with more CH_4 emitted in the autumn of 2006 than the corresponding period in 2007. Mounding increased CH_4 fluxes in the winter of 2006 ($P < 0.024$) but not in 2007 ($P > 0.05$). Mounding also increased CH_4 fluxes in the spring of 2008 ($P < 0.0001$) but not in 2007 ($P > 0.05$).

Averaged CH_4 emissions from different subsites (mounds, hollows and undisturbed ground) in the

Table 4 Effects of site preparation (drainage, mounding fertilisation) and sampling interval (month) on CH_4 fluxes

Source of variation	*df*	*F*	*P*
Drainage	1	31.37	**0.005**
Plot	4	7.53	**<0.0001**
Drainage × fertilisation	1	3.13	0.151
Drainage × mounding	1	3.69	0.127
Drainage × month	22	3.23	0.129
Drainage × fertilisation × mounding	1	0.00	0.949
Drainage × mounding × month	22	2.45	**0.002**
Drainage × fertilisation × month	22	1.30	0.191
Drainage × fertilisation × mounding × month	22	1.26	0.224
Fertilisation	1	29.98	**<0.0001**
Fertilisation × mounding	1	0.07	0.800
Fertilisation × mounding × plot	4	5.74	**<0.0001**
Fertilisation × month	22	3.41	**<0.0001**
Fertilisation × mounding × month	22	2.20	**0.005**
Fertilisation × month × plot	88	0.90	0.692
Mounding	1	22.30	**<0.0001**
Mounding × month	22	3.23	**<0.0001**
Mounding × plot	4	0.69	0.637
Mounding × month × plot	88	1.01	0.472
Month	22	14.29	**<0.0001**
Month × plot	88	3.41	**<0.0001**

P values in bold are statistically significant ($P < 0.05$)

mounded subplots are shown in Fig. 4. Averaged monthly CH_4 emitted from mounds ranged from 0.15 to 2.52 mg m^{-2} day^{-1}, while CH_4 uptake ranging from −0.82 to −0.16 mg m^{-2} day^{-1} occurred in June 2006 and 2007, July 2007 and March 2008. Averaged monthly CH_4 emissions from hollows ranged from 1.67 to 40.87 mg m^{-2} day^{-1}. Mean monthly CH_4 emitted from undisturbed ground ranged from 0.09 to 10.75 mg m^{-2} day^{-1}, and CH_4 uptake of −0.40 mg m^{-2} day^{-1} occurred in June 2007. Methane emitted from hollows exhibited large spatial variability, as can be seen from large standard error of mean in Fig. 4. This is compatible with enhanced CH_4 production and emission in anaerobic conditions of such water-covered hollows.

Effect of fertilisation on CH_4 emissions

Fertilisation significantly increased CH_4 fluxes over the 2 years of study ($P < 0.0001$; Table 3). Methane fluxes in the fertilised and unfertilised subplots varied from month to month ($P < 0.0001$; Fig. 3c). Averaged monthly CH_4 fluxes in the fertilised and unfertilised subplots ranged from 0.23 to 9.67 mg CH_4 m^{-2} day^{-1} and from 1.12 to 6.56 mg CH_4 m^{-2} day^{-1}, respectively. The mean daily CH_4 flux rate was significantly increased by fertilisation in the first ($P < 0.0001$) but not in the second year of study ($P > 0.05$). The 2 years of study differed significantly ($P < 0.0001$) with more CH_4 emitted in the first than second year (Table 3).

Methane emissions were significantly increased by fertilisation in the summer of 2006 ($P < 0.0001$) but not in 2007 ($P > 0.05$; Table 5). The summer seasons differed significantly ($P < 0.0001$) with more CH_4 emitted in the summer of 2006 than in 2007. Fertilisation significantly increased CH_4 emissions in the autumn of 2006 ($P < 0.0001$) and in 2007 ($P < 0.025$). More CH_4 emissions were observed in the autumn of 2006 than in 2007 ($P < 0.0001$). Methane fluxes were not affected by fertilisation in the winter and spring seasons ($P > 0.05$).

Relationships between CH_4 fluxes and environmental factors

Over the whole study period, linear regression analysis showed that the CH_4 flux rate in the

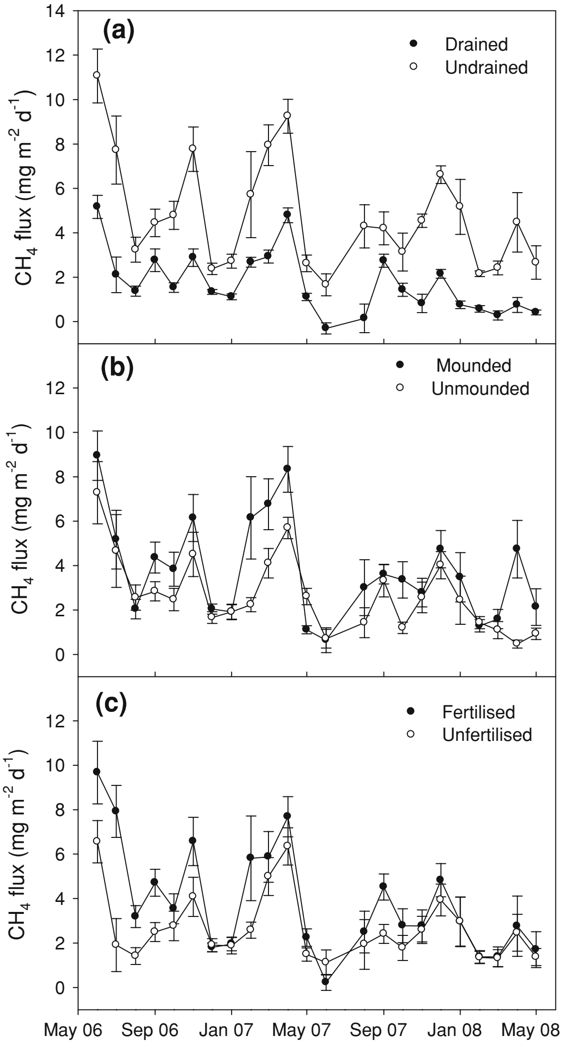

Fig. 3 Seasonal variation in CH_4 fluxes **a** drained and undrained, **b** mounded and unmounded and **c** fertilised and unfertilised treatment. *Dots* represent means of all chambers at each sampling date and the *vertical bars* represent standard error of the mean

drained plots was significantly correlated with water table depth ($R^2 = 0.19$; $P < 0.04$). Linear regression, using temperature (T_1, T_5 and T_{10}) as the independent variable showed a weak ($R^2 = 0.04$ to 0.07) and nonsignificant relationship with CH_4 emissions in the drained plots. Similarly, the relationship between soil moisture content and CH_4 fluxes was weak and not significant. Applying a forward stepwise multiple regression analysis of all variables showed that water table depth and soil moisture content were the most important variables controlling CH_4 fluxes in the drained plots. Soil water table depth alone accounted for 19% of the variation, which increased to 26% when soil moisture was included. In the undrained plots, linear regression analysis detected a weak ($R^2 = 0.14$; $P = 0.08$) and insignificant relationship between water table depth and CH_4 fluxes. The linear relationship between soil temperature (T_1, T_5 and T_{10}; $R^2 = 0.02$ to 0.09) and soil moisture ($R^2 = 0.05$) in undrained plots was weak and not significant. A forward stepwise multiple regression analysis of all variables detected an interaction between water table depth and soil temperature (T_1 and T_{10}). Water table depth accounted for 14% of the variation, which increased to 21 and 31%, respectively when soil temperature (T_1 and T_{10}) was included in the model.

Linear regression analysis showed a significant linear relationship ($P < 0.008$) between water table depth and CH_4 fluxes in the fertilised subplots. A weak ($R^2 = 0.10$; $P = 0.09$) and nonsignificant relationship was also detected between soil temperature (T_1) and CH_4 fluxes. Soil temperature (T_5 and T_{10}) and soil moisture also showed a weak and nonsignificant linear relationship with CH_4 fluxes in the fertilised subplots (all $R^2 = 0.09$). Applying a forward stepwise multiple linear regression analysis of all measured variables showed that water table depth and soil moisture were the most important factors influencing CH_4 fluxes. Soil water table explained 29% of the variation, which increased to 32% when soil moisture was included. Linear regression analysis and a forward stepwise multiple regression analysis did not found a relationship between CH_4 fluxes and all variables in the mounded and unfertilised subplots.

Linear regression analysis, using soil water table depth as an independent variable, detected significant relationship with CH_4 fluxes in the unmounded subplots ($P < 0.005$). The relationship between soil temperature (T_1, T_5 and T_{10}; $R^2 = 0.07$ to 0.10) and soil moisture ($R^2 = 0.02$) was weak and not significant. A forward stepwise multiple regression analysis of all variables showed that water table depth and soil temperature (T_{10}) were the most important variables. Water table depth alone accounted for 32% of the variation; which increased to 42% when soil temperature (T_{10}) was included.

Table 5 Seasonal CH_4 fluxes (mg m^{-2} day^{-1}) by treatment and season

Treatment	CH_4 flux (mg m^{-2} day^{-1})			
	June–August	September–November	December–February	March–May
2006–2007	Summer	Autumn	Winter	Spring
Drained	**2.88 ± 0.42a**	**2.39 ± 0.24a**	**1.71 ± 0.15a**	**2.94 ± 0.30a**
Undrained	**7.34 ± 0.85b**	**5.66 ± 0.50a**	**3.60 ± 0.69b**	**6.60 ± 0.63b**
Mounded	5.39 ± 0.75a	**4.78 ± 0.51a**	**3.37 ± 0.70a**	5.40 ± 0.72a
Unmounded	4.83 ± 0.79a	**3.27 ± 0.42b**	**1.94 ± 0.18b**	4.14 ± 0.36a
Fertilised	**6.93 ± 0.77a**	**4.94 ± 0.50a**	3.19 ± 0.70a	5.27 ± 0.62a
Unfertilised	**3.29 ± 0.64b**	**3.11 ± 0.40b**	2.12 ± 0.20a	4.28 ± 0.53a
2007–2008				
Drained	−0.08 ± 0.48a	**1.66 ± 0.23a**	**1.16 ± 0.15a**	**0.48 ± 0.14a**
Undrained	2.98 ± 0.85a	**3.96 ± 0.39b**	**4.45 ± 0.53b**	**3.18 ± 0.53a**
Mounded	1.82 ± 1.01a	**3.25 ± 0.37a**	3.17 ± 0.52a	**2.82 ± 0.57a**
Unmounded	1.07 ± 0.56a	**2.37 ± 0.37b**	2.26 ± 0.45a	**0.84 ± 0.17b**
Fertilised	1.36 ± 0.77a	**3.36 ± 0.41a**	3.05 ± 0.50a	1.95 ± 0.54a
Unfertilised	1.53 ± 0.87a	**2.26 ± 0.31b**	2.75 ± 0.47a	1.71 ± 0.33a

Values followed by different letters indicate a significant difference between treated and untreated plots ($P < 0.05$)

Values in bold are statistically significant ($P < 0.05$)

The "±" indicate standard error of the mean

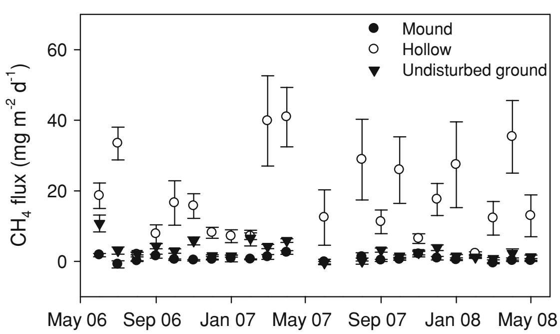

Fig. 4 Mean monthly CH_4 flux rates from subsites in the mounded treatment (undisturbed ground, mounds and hollows). The *vertical bars* indicate the standard error of the mean

Contribution of CH_4 emissions to the greenhouse effect and global warming potential

All treatments emitted more CH_4 in the first than second year of study (Table 6). The global warming potential (GWP) of CH_4 was calculated over the 2 years of study. GWP measures the potential of CH_4 to heat up the atmosphere and is given relative to CO_2, the most important gas which has GWP of 1. The emission of 1 kg of CH_4 is 21 times more effective than 1 kg of CO_2 (IPCC 2007). Our results show that drainage decreased the GWP in the first and second year of study, while mounding and fertilisation increased the GWP (Table 7).

Discussion

Effects of site preparation on environmental factors

Soil temperature (T_1, T_5 and T_{10}) in the present study was increased by drainage because well-drained soils warm faster than wet soils. In general drainage improves aeration and alters the soil surface thermal properties and energy near the soil surface. In absolute values, the difference in soil temperature between drained and undrained plots varied between 0.2 and 1.2°C at all depths. These results are consistent with results of drainage studies conducted in peatland sites which found that peat temperature increased after drainage (e.g., Lieffers and Rothwell 1987; Lieffers 1988; Macdonald and Lieffers 1990; Van Cleve et al. 1990; Prevost et al. 1997). For example, Prevost et al. (1997) found that seasonal maximum temperature at 10 cm depth increased by 3.5°C after drainage (5 m away from ditches) and by 1.5°C (at distances greater than 5 m). Soil

Table 6 Annual contribution of soil CH_4 emissions (kg ha^{-1} $year^{-1}$) from all practises to the greenhouse effect

Year	Treatment					
	Drained	Undrained	Mounded	Unmounded	Fertilised	Unfertilised
2006–2007	9.06 ± 0.55	21.18 ± 1.30	17.29 ± 1.25	12.95 ± 0.94	18.55 ± 1.25	11.68 ± 0.88
2007–2008	3.23 ± 0.43	13.53 ± 0.92	10.24 ± 0.95	6.52 ± 0.70	9.22 ± 0.94	7.54 ± 0.73
All years (2006–2008)	6.27 ± 0.39	17.52 ± 0.84	13.92 ± 0.82	9.87 ± 0.62	14.09 ± 0.84	9.70 ± 0.59

The "±" indicate standard error of the mean

temperature measured at 1 and 5 cm depths (T_1 and T_5) was significantly increased by mounding in the present study because mounding exposes the mineral soil on top of mounds which absorb more heat that the soil covered with litter or vegetation and hence raises daytime soil temperature. In absolute values, the difference in soil temperature between mounded and unmounded subplots varied between 0.2 and 1.3°C. This result is consistent with results from mounding experiments, which collectively found that mounding increased day time soil temperature (Sutton 1993; DeLong et al. 1997; Saari et al. 2004).

Soil moisture was decreased by drainage between May and October. This occurred because drainage improves aeration and increases soil temperature and evapotranspiration resulting in drier surface soils. Mounding also decreased the soil moisture content between May and October, which is likely to have been caused by improvement in aeration and increased soil temperature after mounding. This would have dried the soil on top of mounds to a depth of 5 cm, where soil moisture content was measured. Saari et al. (2004) also found that soil moisture content in the mounded plots was significantly lower compared to undisturbed soil.

Drainage markedly caused a decrease in water table depth, with the deepest depth recorded in July 2006 and September 2007. Over the two years of this study, the average water table depth was 23.0 cm below the soil surface in the drained plots and 13.8 cm in their undrained counterparts. Similar results have been reported for drainage studies conducted in peatlands sites in the boreal and temperate region (e.g., Laine et al. 1995b; Martikainen et al. 1995; Regina et al. 1996; Minkkinen and Laine 1998; Nykänen et al. 1998). As expected, the water table depth was not affected by mounding or fertilisation.

Effects of drainage on fluxes of CH_4

The drained and undrained plots emitted CH_4 on all sampling dates from 2006 to 2008, with more CH_4 emitted from undrained than drained plots. The mean daily CH_4 flux rate from our drained plots was higher than the mean daily CH_4 flux rate (0.27–0.55 mg CH_4 m^{-2} day^{-1}) reported for a drained upland blanket bog in Scotland (MacDonald et al. 1997). Ball et al. (2007) found that the mean daily CH_4 flux rate on an unplanted grassland adjacent to a coniferous stand at Harwood Forest, not far from the present study site ranged from 0.33 to 0.71 mg CH_4 m^{-2} day^{-1}. Higher CH_4 emissions observed in the drained plots in the present study could probably be attributed to high substrate availability and moist soil than in sites where the other two studies were conducted. The mean daily CH_4 flux rate in this study was at the lower range of 0.3–30 mg m^{-2} day^{-1} reported for wet forest soils in Canada (Castro et al. 1993; Yavitt et al. 1995) and very much lower than 7.9–204 g CH_4 m^{-2} day^{-1} reported for wet fertilised grasslands on peaty soils in the Netherlands (Van den Pol-van Dasselaar et al. 1999). Peaty gley soils at our study site are seasonally waterlogged, with the water table depth dropping significantly in the summer than in areas where these other studies were conducted. This could explain lower CH_4 fluxes observed in this study. The lower emission fluxes from the present study could also be attributed to low substrate availability and lower summer temperatures in the UK than in areas where these other studies were conducted.

Overall, lowering the water table by drainage decreased CH_4 emissions by 57–76% indicating that both methanotrophs and methanogens were present in the soil microbial community at our study site. Drainage decreased soil moisture and increased soil

Table 7 Comparison of the annual (2006–2007 and 2007–2008) GWP of soil CH_4–CO_2 equivalent emissions (kg ha^{-1} $year^{-1}$) for all practises and the change (%) caused by each practise

Year	Treatment								
	Drained	Undrained	Change (%)	Mounded	Unmounded	Change (%)	Fertilised	Unfertilised	Change (%)
2006–2007	190.20 ± 11.62	444.76 ± 27.32	−57.2	363.07 ± 26.19	271.89 ± 19.83	33.5	389.59 ± 26.29	245.37 ± 18.55	58.8
2007–2008	67.90 ± 9.02	284.16 ± 19.27	−76.1	215.12 ± 19.88	136.94 ± 14.60	57.1	193.72 ± 19.74	158.34 ± 15.39	22.3
All years (2006–2008)	131.71 ± 8.29	367.95 ± 17.62	−64.2	292.31 ± 17.20	207.35 ± 13.11	41.0	295.91 ± 17.64	203.75 ± 12.42	45.2

The "±" indicate standard error of the mean. Negative values indicate a decrease in GWP

temperature both of which influence microbial processes and their location in peaty soils (e.g., Nykänen et al. 1998). The production of CH_4 by methanogenic bacteria occurs in water-saturated peat profiles where the fresh organic substrate from vegetation is subjected to anaerobic decomposition; whereas after drainage the organic substrate in peaty soils is oxidised in aerobic layers before reaching water saturated profiles, thus decreasing the amount of organic substrate available for CH_4 production (Nykänen et al. 1998). Similar reductions in CH_4 emissions observed after drainage at our study site have been reported for drainage experiments conducted in boreal and temperate peatland sites (e.g., Freeman et al. 1993; Roulet et al. 1993; Martikainen et al. 1995; Nykänen et al. 1998; Sundh et al. 2000; Minkkinen et al. 2002). For example, Minkkinen et al. (2002) found that CH_4 fluxes from drained peatland sites were 50% lower compared to undrained sites because lowering the groundwater table increase oxygenation which increases CH_4 consumption. Freeman et al. (1993) collected intact cores from a Welsh peatland to study the potential effect of climate change on CH_4 flux rate. They manipulated the water table depth within intact monoliths in the laboratory thereby simulating water table lowering caused by climate change and found that the treatment decreased CH_4 fluxes by up to 80%. Drainage decreases CH_4 fluxes from peatland soils initially because of increased CH_4 oxidation in the enlarged aerobic part of the peat profile and subsequently through the decreased CH_4 production in the lower "inert" layer of the peat (e.g., Minkkinen et al. 2008). Part of the CH_4 diffusing upwards in drained peaty soils is oxidised in the uppermost aerobic upper part of peat layers (e.g., Crill et al. 1994) and converted to CO_2. Although drainage decreased CH_4 emissions at our study site, CO_2 emissions were 22.6 and 32.6% higher in the drained than undrained plots in the first and second year study (Mojeremane 2009 unpublished data).

In the present study, CH_4 fluxes in the drained and undrained plots decreased by 64 and 35% in the second year, and this may have been related to slightly higher summer soil temperatures which were observed in the first year of study. It is also possible that the decrease was caused by lack of variation in CH_4 flux rate or infrequent measurements in the second year. In the second year of study, CH_4 fluxes were measured 11 times at approximately monthly interval, compared to 20 times in the first year. Episodic CH_4 fluxes caused by periodic rainfall (e.g., Kettunen et al. 1996) or rapid fluctuation in water table depth and soil temperature (e.g., Windsor et al. 1992; Romanowicz et al. 1993; Mikkelä et al. 1995; Kettunen et al. 1996) may have been missed due to infrequent sampling in the second year.

Effects of mounding on emission of CH_4

Mounding buries the litter and organic layers beneath the mineral soil layers (Smolander et al. 2000; Saari et al. 2004) and this may alter environmental variables controlling soil CH_4 fluxes. However, few studies have attempted to evaluate the effect of mounding on soil CH_4 fluxes. In the present study, mounding increased CH_4 emissions by 34–59%. Saari et al. (2004) measured CH_4 emissions from mounds and undisturbed soil in a clearfelled Norway spruce stand in south-eastern Finland. They found that CH_4 fluxes from mounds were 33% lower than from undisturbed soil in the first year of study, but increased in subsequent years. They suggested that the initial decrease in CH_4 fluxes soon after mounding occurred as a result of CH_4 oxidation in the mineral soil on top of mounds. They also suggested that the double organic horizons may have reduced diffusion of atmospheric CH_4 into the mineral soil beneath mounds and inhibited CH_4 consumption in that layer in subsequent years.

In this study, watered-covered hollows in the mounded subplots emitted more CH_4 than mounds and undisturbed soil. Large CH_4 emissions measured from hollows can be attributed to abundant supply of substrate for methanogenic bacteria because the stagnant water inside hollows was consistently inhabited by green algae (e.g., Schiller and Hastie 1996). Large CH_4 fluxes have also been reported for ditches in peatland sites drained for forestry (e.g., Roulet and Moore 1995; Schiller and Hastie 1996; Minkkinen et al. 1997; Von Arnold et al. 2005; Minkkinen and Laine 2006) because ditch bottoms are often colonised by vegetation which decreases the movement of water, especially in bogs (Minkkinen et al. 2008). Mounding increased peat bulk density at our experimental site (Mojeremane 2009 unpublished data) due to compaction caused by excavator, which probably also reduced CH_4 oxidation (e.g., Hansen et al. 1993; Flessa et al. 2002) and enhanced CH_4 fluxes (e.g., Ruser et al. 1998; Smith et al. 2000).

Net CH_4 uptake occurred occasionally on top of mounds. Mounding decreased soil moisture content and increased soil temperature, and caused aerobic conditions on top of mounds where oxidation of atmospheric CH_4 (e.g., Melling et al. 2005) exceeded production in anaerobic layers beneath mounds. Methane uptake also occurred on undisturbed ground in June 2007. The explanation could be that at the end of spring to midsummer the water table depth in this site dropped due to high evapotranspiration resulting in drier surface soils where CH_4 was consumed before being released into the atmosphere (e.g., Crill et al. 1994; Nykänen et al. 1998; Van den Pol-van Dasselaar et al. 1998). This is consistent with results of previous studies which found that well-drained temperate grassland soils consume 0–1 mg CH_4 m^{-2} day^{-1} (Mosier et al. 1991; Kruse and Iversen 1995; Dobbie et al. 1996).

Effect of fertilisation on CH_4 fluxes

Fertilised and unfertilised subplots emitted CH_4 on all sampling occasions from 2006 to 2008. Fertilisation increased CH_4 fluxes by 20–59%. Fertilisation stimulated CH_4 emissions in the first year of study. Increase in CH_4 emissions in fertilised soils has been attributed to inhibition of methanotrophy by NH_4^+ based fertilisers (Gulledge et al. 1997; Van den Pol-van Dasselaar et al. 1999). The inhibition of CH_4 oxidation by NH_4^+ based fertilisers has been demonstrated in experiments conducted in various ecosystems (e.g., Steudler et al. 1989; Castro et al. 1994; Sitaula et al. 1995; King and Schnell 1998; Wang and Ineson 2003; Suwanwaree and Robertson 2005), with no effects reported in some experiments (e.g., Dunfield et al. 1995; Delgado and Mosier 1996). Increased CH_4 emissions observed in the fertilised subplots in our study may also have been caused by the soil environment which was suitable for CH_4 production and emission soon after fertilisation. Suwanwaree and Robertson (2005) applied N fertiliser at a rate of 100 kg ha^{-1} in a forest site and observed that CH_4 fluxes increased by 60%. Steudler et al. (1989) reported that adding 120 kg N ha^{-1} $year^{-1}$ as NH_4NO_3 increased CH_4 fluxes by 33% in temperate forest soils. Sitaula et al (1995) also found that adding 90 kg N ha^{-1} $year^{-1}$ to a Scots pine Forest in Norway over 2 years increased CH_4 flux rates by 38%. The mechanism responsible for increased CH_4 fluxes from N fertilised soils is not well understood. It has been suggested that N increases soil CH_4 fluxes by inhibiting CH_4 oxidising microorganisms (e.g., Van den Pol-van Dasselaar et al. 1999) or by changing the composition and size of the microbial community (e.g., Saari et al. 1997; Van den Pol-van Dasselaar et al. 1999; Kähkönen et al. 2002).

In the second year of study, CH_4 fluxes from fertilised subplots were not significantly different from their unfertilised counterparts. The decline in CH_4 fluxes from the fertilised subplots may indicate that N uptake by plants, losses through leaching and as gaseous N_2O probably depleted the pool of N applied in this site in the second year of study.

Effects of environmental factors on fluxes of CH_4

Soil water table was the major factor determining methane fluxes in this study, similar to wetlands (e.g., Moore and Dalva 1993; Liblik et al. 1997; Nykänen et al. 1998; Hughes et al. 1999). For example, Liblik et al. (1997) observed that water table depth explained 62% of variation in CH_4 fluxes from wetlands in Canada, Moore and Dalva (1993) observed strong relationships between water table depth and CH_4 emissions in peat cores. Water table depth in our study affected soil CH_4 emissions from drained, undrained, fertilised and unmounded treatment. Drainage initially increased CH_4 fluxes for a very short period, which was followed by a reduction relative to undrained plots throughout the study. A similar pattern has been observed in peatlands sites (e.g., Windsor et al. 1992; Moore and Roulet 1993; Liblik et al. 1997; Hughes et al. 1999). This has been attributed to increased gas diffusivity and a disturbance effect of a falling water table which releases CH_4 entrapped in the peat and porewater (e.g., Hughes et al. 1999). Romanowicz et al. (1995) also suggested that water table lowering can also release CH_4 trapped in deep peat.

Soil moisture content is often a significant factor controlling CH_4 fluxes in soils (Bowden et al. 1998; McNamara et al. 2008). In our study the linear relationship between soil moisture and CH_4 flux was weak and not significant when soil moisture was treated as independent variable. Similar results were reported for a mature and a clear-felled forest stand at Harwood Forest (Zerva and Mencuccini 2005a). It is possible that CH_4 production in our study occurred at depth lower than 5 cm, where soil moisture content was measured, and that methanotroph community were not sensitive to these levels of soil moisture content (e.g., Sjögersten and Wookey 2002). For example, McNamara et al. (2008) found that CH_4 fluxes under oak and grassland were correlated with soil moisture at 10–15 cm depth. Soil moisture in this site was neither too high to limit diffusion of CH_4 or O_2 transport nor too low to stress methanotrophs. Using a forward stepwise multiple linear regression demonstrated that soil moisture interacted with soil water table depth to influence CH_4 emissions in the drained plots and fertilised subplots. It seems, therefore that the effect of soil moisture on CH_4 fluxes in this site was dependent on the position of the soil water table.

Methane production has a strong temperature response (e.g., Crill et al. 1994; Schnell and King 1995) and therefore an increase in soil temperature will increase CH_4 fluxes (Nykänen et al. 1998). Linear regression analysis showed that the relationship between soil temperature (T_1, T_5 and T_{10}) and CH_4 fluxes in this site was weak and insignificant. Work in a spruce-fir forest soil in Maine, USA also found no significant relationship between CH_4 fluxes and soil temperature (Rustad and Fernandez 1998). This may indicate that CH_4 fluxes at our site were probably more dependent on substrate availability, rather than temperature. However, a stepwise multiple linear regression analysis showed that soil temperature (T_1 and T_{10}) interacted with soil water table depth in the undrained plots to influence CH_4 fluxes. Soil temperature (T_{10}) also interacted with water table in the unmounded subplots. Nykänen et al. (1998) also observed that water table depth interacted with soil temperature to influence CH_4 fluxes in natural and drained peatland sites.

Contribution of CH_4 emissions to greenhouse effect and GWP

The results of the present study showed that drained and undrained plots contributed 6.27 ± 0.39 and 17.52 ± 0.84 kg CH_4 ha^{-1} to the atmosphere. Mounded and unmounded subplots released 13.92 ± 0.82 and 9.87 ± 0.62 CH_4 kg ha^{-1}, whereas fertilised and unfertilised subplots emitted 14.09 ± 0.84 and 9.70 ± 0.59 CH_4 kg ha^{-1} over the whole measurement period. All treatments emitted more CH_4 to the atmosphere in the first than second year of study.

According to the results of the present study, drainage decreased CH_4–CO_2 equivalent emissions by 64.2%. Drained plots emitted less CH_4–CO_2 equivalent emissions in the second year than in the first year. Mounding and fertilisation increased CH_4–CO_2 equivalent emissions by 41 and 45.2%, respectively. More CH_4–CO_2 equivalent emissions were released from mounded subplots in the second year compared to first year of study, whereas the effect of fertilisation on CH_4–CO_2 equivalent emissions was more pronounced in the first than second year of study.

Conclusion

Results from this study indicate that lowering the water table depth and mounding increased soil temperature. The two practises also decreased soil moisture content. Methane emissions were initially very briefly increased by drainage, which was followed by a reduction relative to undrained plots throughout the study. Lowering the water table depth by drainage increases oxygenation and soil temperature, and thus increases the mineralisation of organic matter in aerobic upper peat layers, which reduces the supply of organic substrate for CH_4 production in anaerobic layers beneath the peat surface. Mounding increased CH_4 fluxes because low emissions from mounds and undisturbed ground were counteracted by large fluxes emitted from hollows which were consistently covered with stagnant water inhabited by green algae. Mounding decreased soil moisture content and increased soil temperature causing aerobic conditions on top of mounds where CH_4 uptake occurred occasionally. Methane emissions in the fertilised subplots were significantly higher than in their unfertilised counterparts in the first year of study, but declined in the second year because N uptake by plants, losses through leaching and as gaseous N_2O depleted the pool of N applied in this site in the second year. Soil water table depth was the major factor controlling CH_4 fluxes at our study site. The relationships of CH_4 fluxes with soil temperature and soil moisture content were weak and not significant. However, soil moisture content and soil temperature interacted with water table depth to influence CH_4 emissions, indicating that the effect of these variables was dependent on the position of the groundwater table. Longer-term studies are needed to understand relationships between CH_4 fluxes, soil temperature and soil moisture.

Acknowledgments Witness Mojeremane was supported by Botswana College of Agriculture (BCA) Scholarship. We thank the Forestry Commission for providing the study site. We also thank Professor Keith Smith for providing static chambers and Mr Robert Howard for his assistance in the gas analyses.

References

Ball T, Smith KA, Moncrief JB (2007) Effect of stand age on greenhouse gas fluxes from a Sitka spruce [*Picea sitchensis* (Bong.) Carr.] chronosequence on a peaty gley. Glob Change Biol 13:2128–2142. doi:10.1111/j.1365-2486.2007.01427.x

Bellisario LM, Bubier JL, Moore TR, Chanton JP (1999) Controls on CH_4 emissions from a northern peatland. Glob Biogeochem Cycle 13:81–91. doi:10.1029/1998GB900021

Bodelier PLE, Laanbroek HJ (2004) Nitrogen as a regulatory factor of methane oxidation in soils and sediments. FEMS Microbiol Ecol 47:265–277. doi:10.1016/S0168-6496(03)00304-0

Bossio DA, Horwath WR, Mutters RG, van Kessel C (1999) Methane pool and flux dynamics in a rice field following straw incorporation. Biol Biochem 31:1313–1322. doi:10.1016/S0038-0717(99)00050-4

Bowden RD, Newkirk KM, Rullo GM (1998) Carbon dioxide and methane fluxes by a forest soil under laboratory-controlled moisture and temperature conditions. Soil Biol Biochem 30:1591–1597. doi:10.1016/S0038-0717(97)00228-9

Butterbach-Bahl K, Gasche R, Huber C, Kreutzer K, Papen H (1998) Impact of N-input by wet deposition on N-trace gas fluxes and CH_4-oxidation in spruce forest ecosystems of the temperate zone in Europe. Atmos Environ 32:559–564. doi:10.1016/S1352-2310(97)00234-3

Cannell MGR, Dewar RC, Pyatt DG (1993) Conifer plantations on drained peatlands in Britain: a net gain or loss of carbon? Forestry 66:353–369. doi:10.1093/forestry/66.4.353

Castaldi S, Ermice A, Strumia S (2006) Fluxes of N_2O and CH_4 from soils of savannas and seasonally-dry ecosystems. J Biogeogr 33:401–415. doi:10.1111/j.1365-2699.2005.01447.x

Castro MS, Steudler PA, Melillo JM, Aber JD, Millham S (1993) Exchange of N_2O and CH_4 between the atmosphere and soils in spruce-fir forests in the northeastern United States. Biogeochemistry 18:119–135. doi:10.1007/BF00003273

Castro MS, Peterjohn WT, Melillo JM, Steudler PA, Gholz HL, Lewis D (1994) Effects of nitrogen fertilization on the fluxes of N_2O, CH_4, and CO_2 from soils in a Florida slash pine plantation. Can J For Res 24:9–13. doi:10.1139/x94-002

Chan ASK, Parkin TB (2001) Methane oxidation and production activity in soils from natural and agricultural ecosystems. J Environ Qual 30:1896–1903

Chen H, Wu N, Gao Y, Wang Y, Luo P, Tian J (2009) Spatial variations on methane emissions from Zoige alpine wetlands of Southwest China. Sci Total Environ 407:1097–1104. doi:10.1016/j.scitotenv.2008.10.038

Crill PM, Martikainen PJ, Nykänen H, Silvola J (1994) Temperature and N fertilization effects on methane oxidation in a drained peatland soil. Soil Biol Biochem 26:1331–1339. doi:10.1016/0038-0717(94)90214-3

Crutzen PJ (1991) Methane's sinks and sources. Nature 350:380–381. doi:10.1038/350380a0

Dalal RC, Allen DE (2008) TURNER REVIEW No. 18. Greenhouse gas fluxes from natural ecosystems. Aust J Bot 56:369–407. doi:10.1071/BT07128

Daulat WE, Clymo RS (1998) Effects of temperature and watertable on the efflux of methane from peatland surface cores. Atmos Environ 32:3207–3218. doi:10.1016/S1352-2310(98)00078-8

Davidson EA, Belk E, Boone RD (1998) Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest. Glob Change Biol 4:217–227. doi:10.1046/j.1365-2486.1998.00128.x

Delgado JA, Mosier AR (1996) Mitigation alternatives to decrease nitrous oxide emissions and urea–nitrogen loss and their effect on methane flux. J Environ Qual 25:1105–1111

DeLong HB, Lieffers VJ, Blenis PV (1997) Microsite effects on first-year establishment and over winter survival of white spruce in aspen-dominated boreal mixed woods. Can J For Res 27:1452–1457. doi:10.1139/cjfr-27-9-1452

Ding W-X, Cai Z-C (2007) Methane emission from natural wetlands in China: summary of years 1995–2004 studies. Pedosphere 17:475–486. doi:10.1016/S1002-0160(07)60057-5

Ding W, Cai Z, Tsuruta H, Li X (2003) Key factors affecting spatial variation of methane emissions from freshwater marshes. Chemosphere 51:167–173. doi:10.1016/S0045-6535(02)00804-4

Dobbie KE, Smith KA, Priemé A, Christensen S, Degórska A, Orlanski P (1996) Effect of land use on the rate of methane uptake by surface soils in northern Europe. Atmos Environ 30:1005–1011. doi:10.1016/1352-2310(95)00416-5

Dunfield PF, Topp E, Archambault C, Knowles R (1995) Effect of nitrogen fertilizers and moisture content on CH_4 and N_2O fluxes in a humisol: Measurements in the field and intact soil cores. Biogeochemistry 29:199–222. doi:10.1007/BF02186048

Dutaur L, Verchot V (2007) A global inventory of the soil CH_4 sink. Glob Biogeochem Cycle 21:GB4013. doi:10.1029/2006GB002734

Flessa H, Ruser R, Schilling R, Loftfield N, Munch JC, Kaiser EA, Beese F (2002) N_2O and CH_4 fluxes in potato fields: automated measurement, management effects and temporal variation. Geoderma 105:307–325. doi:10.1016/S0016-7061(01)00110-0

Freeman C, Lock MA, Reynolds B (1993) Fluxes of CO_2, CH_4 and N_2O from a welsh peatland following simulation of water table draw-down: potential feedback to climatic change. Biogeochemistry 19:51–60. doi:10.1007/BF00000574

Frenzel P, Karofeld E (2000) CH_4 emission from a hollow-ridge complex in a raised bog: the role of CH_4 production and oxidation. Biogeochemistry 51:91–112. doi:10.1023/A:1006351118347

Frenzel P, Rudolph J (1998) Methane emission from a wetland plant: the role of CH_4 oxidation in Eriophorum. Plant Soil 202:27–32. doi:10.1023/A:1004348929219

Gulledge J, Doyle AP, Schimel JP (1997) Different NH_4^+-inhibition patterns of soil CH_4 consumption: a result of distinct CH_4-oxidizer populations across sites? Soil Biol Biochem 29:13–21. doi:10.1016/S0038-0717(96)00265-9

Hansen S, Maehlum JE, Bakken LR (1993) N_2O and CH_4 fluxes in soil influenced by fertilisation and tractor traffic. Soil Biol Biochem 25:621–630. doi:10.1016/0038-0717(93)90202-M

Hargreaves KJ, Fowler D (1998) Quantifying the effects of water table and soil temperature on the emission of methane from peat wetland at the field scale. Atmos Environ 32:3275–3282. doi:10.1016/S1352-2310(98)00082-X

Hilger HA, Wollum AG, Barlaz MA (2000) Landfill methane oxidation response to vegetation, fertilisation, and liming. J Environ Qual 29:324–334

Hillman GR (1992) Some hydrological effects of peatland drainage in Alberta's boreal forest. Can J For Res 22:1588–1596. doi:10.1139/x92-211

Hou AX, Chen GX, Wang ZP, Van Cleemput O, Patrick WH Jr (2000) Methane and nitrous oxide emissions from a rice field in relation to soil redox and microbiological processes. Soil Sci Soc Am J 64:2180–2186

Hughes S, Dowrick DJ, Freeman C, Hudson JA, Reynolds B (1999) Methane emissions from a gully mire in mid-Wales U.K. under consecutive summer water table drawdown. Environ Sci Technol 33:362–365. doi:10.1021/es980563z

Hütsch BW (1998) Methane oxidation in arable soil as inhibited by ammonium, nitrite, and organic manure with respect to soil pH. Biol Fertil Soils 28:27–35. doi:10.1007/s003740050459

Hütsch BW (2001) Methane oxidation in non-flooded soils as affected by crop production. Eur J Agron 14:237–260. doi:10.1016/S1161-0301(01)00110-1

Huttunen JT, Nykänen H, Turunen J, Martikainen PJ (2003) Methane emissions from natural peatlands in northern boreal zone in Finland, Fennoscandia. Atmos Environ 37:147–151. doi:10.1016/S1352-2310(02)00771-9

Inter-government Panel on Climate Change (IPCC) (2007) Mitigation. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds) Contribution of working group III to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Jäckel U, Schnell S, Conrad R (2004) Microbial ethylene production and inhibition of methanotrophic activity in a

deciduous forest soil. Soil Biol Biochem 36:835–840. doi: 10.1016/j.soilbio.2004.01.013
Joabsson A, Christensen TR (2001) Methane emissions from wetlands and their relationship with vascular plants: an Arctic example. Glob Change Biol 7:919–932. doi: 10.1046/j.1354-1013.2001.00044.x
Joabsson A, Christensen TR, Wallén B (1999) Vascular plant controls on methane emissions from northern peatforming wetlands. Trends Ecol Evol 14:385–388. doi:10.1016/S0169-5347(99)01649-3
Kähkönen MA, Wittmann C, Ilvesniemi H, Westman CJ, Salkinoja-Salonen MS (2002) Mineralization of detritus and oxidation of methane in acid boreal coniferous forest soils: seasonal and vertical distribution and effects of clear-cut. Soil Biol Biochem 34:1191–1200. doi: 10.1016/S0038-0717(02)00056-1
Kettunen A, Kaitala V, Alm J, Silvola J, Nykänen H, Martikainen PJ (1996) Cross- correlation analysis of the dynamics of methane emissions from a boreal peatland. Glob Biogeochem Cycle 10:457–471. doi:10.1029/96GB01609
King GM, Schnell S (1998) Effects of ammonium and non-ammonium salt additions on methane oxidation by *Methylosinus trichosporium* OB3b and Maine forest soils. Appl Environ Microbiol 64:253–257
Kirschbaum MUF (1995) The temperature dependence of soil organic matter decomposition, and the effect of global warming on soil organic C storage. Soil Biol Biochem 27:753–760. doi:10.1016/0038-0717(94)00242-S
Knief C, Lipsku A, Dunfield PF (2003) Diversity and activity of methanotrophic bacteria in different upland soils. Appl Environ Microbiol 69:6703–6714. doi:10.1128/AEM.69.11.6703-6714.2003
Kruse CW, Iversen N (1995) Effect of plant succession, ploughing, and fertilization on the microbiological oxidation of atmospheric methane in a heathland soil. FEMS Microbiol Ecol 18:121–128. doi:10.1111/j.1574-6941.1995.tb00169.x
Laine J, Vasander H, Sallantaus T (1995a) Ecological effects of peatland drainage for forestry. Environ Rev 3:286–303
Laine J, Vasander H, Laiho R (1995b) Long-term effects of water level drawdown on the vegetation of drained pine mires in southern Finland. J Appl Ecol 32:785–802. doi: 10.2307/2404818
Laine A, Wilson D, Kiely G, Byrne KA (2007) Methane flux dynamics in an Irish lowland blanket bog. Plant Soil 299:181–193. doi:10.1007/s11104-007-9374-6
Le Mer J, Roger P (2001) Production, oxidation, emission and consumption of methane by soils: a review. Eur J Soil Biol 37:25–50. doi:10.1016/S1164-5563(01)01067-6
Lelieveld J, Crutzen PJ, Dentener FJ (1998) Changing concentration, lifetime and climate forcing of atmospheric methane. Tellus B Chem Phys Meterol 50:128–150. doi: 10.1034/j.1600-0889.1998.t01-1-00002.x
Liblik C, Moore TR, Burier JL, Robinson SD (1997) Methane emissions from wetlands in the zone of discontinuous permafrost: fort Simpson, Northwest Territories, Canada. Glob Biogeochem Cycle 11:485–494. doi:10.1029/97GB01935
Lieffers VJ (1988) Sphagnum and cellulose decomposition in drained and natural areas of an Alberta peatland. Can J Soil Sci 68:755–761
Lieffers VJ, Rothwell RL (1987) Effects of drainage on substrate temperature and phenology of some trees and shrubs in an Alberta peatland. Can J For Res 17:97–104. doi: 10.1139/x87-019
Lloyd D, Thomas KL, Benstead J, Davies KL, Lloyd SH, Arah JRM, Stephen KD (1998) Methanogenesis and CO_2 exchange in an ombrotrophic peat bog. Atmos Environ 32:3229–3238. doi:10.1016/S1352-2310(97)00481-0
Macdonald SE, Lieffers VJ (1990) Photosynthesis, water relations, and foliar nitrogen of *Picea mariana* and *Larix laricina* from drained and undrained peatlands. Can J For Res 20:995–1000. doi:10.1139/x90-133
MacDonald JA, Skiba U, Shepard LJ, Ball B, Roberts JD, Smith K, Fowler D (1997) The effect of nitrogen deposition and seasonal variability on methane oxidation and nitrous oxide emission rates in an upland spruce plantation and moorland. Atmos Environ 31:3693–3706. doi: 10.1016/S1352-2310(97)00265-3
Maljanen M, Hytönen J, Martikainen PJ (2001) Fluxes of N_2O, CH_4 and CO_2 on afforested boreal agricultural soils. Plant Soil 231:113–121. doi:10.1023/A:1010372914805
Martikainen PJ, Martikainen PJ, Nykänen H, Alm J, Silvola J (1995) Change in fluxes of carbon dioxide, methane and nitrous oxide due to forest drainage of mire sites of different trophy. Plant Soil 168/169:571–577. doi:10.1007/BF00029370
McNamara NP, Black HIJ, Piearce TG, Reay DS, Ineson P (2008) The influence of afforestation and tree species on soil methane fluxes from shallow organic soils at the UK gisburn forest experiment. Soil Use Manage 24:1–7. doi: 10.1111/j.1475-2743.2008.00147.x
Melling L, Hatano R, Goh KJ (2005) Methane fluxes from three ecosystems in tropical peatland of Sarawak, Malaysia. Soil Biol Biochem 37:1445–1453. doi:10.1016/j.soilbio.2005.01.001
Merino A, Perez-Batallón P, Macias F (2004) Responses of soil organic matter and greenhouse gas fluxes to soil management and land use changes in a humid temperate region of southern Europe. Soil Biol Biochem 36:917–925. doi:10.1016/j.soilbio.2004.02.006
Mikkelä C, Sundh I, Svensson BH, Nilsson M (1995) Diurnal variation in methane emission in relation to the water table, soil temperature, climate and vegetation cover in a Swedish acid mire. Biogeochemistry 28:93–114. doi: 10.1007/BF02180679
Minkkinen K, Laine J (1998) Long-term effect of forest drainage on the peat carbon stores of pine mires in Finland. Can J For Res 28:1267–1275. doi:10.1139/cjfr-28-9-1267
Minkkinen K, Laine J (2006) Vegetation heterogeneity and ditches create spatial variability in methane fluxes from peatlands drained for forestry. Plant Soil 285:289–304. doi:10.1007/s11104-006-9016-4
Minkkinen K, Laine J, Nykänen H, Martikainen PJ (1997) Importance of drainage ditches in emissions of methane from mires drained for forestry. Can J For Res 27:949–952. doi:10.1139/cjfr-27-6-949
Minkkinen K, Korhonen R, Savolainen I, Laine J (2002) Carbon balance and radiative forcing of Finnish peatlands 1900–2100-impact of drainage for forestry. Glob Change Biol 8:785–799. doi:10.1046/j.1365-2486.2002.00504.x

Minkkinen K, Byrne KA, Trettin C (2008) Climate impacts of peatland forestry. In: Strack M (ed) Peatlands and climate change. International Peat Society, Jyväskyla. Finland, pp 98–122

Miura Y, Watanabe A, Murase J, Kimura M (1992) Methane production and its fate in paddy fields II. Oxidation of methane and its coupled ferric oxide reduction in subsoil. Soil Sci Plant Nutr 38:673–679

Moore TR, Dalva M (1993) The influence of temperature and water table position on carbon dioxide and methane emissions from laboratory columns of peatland soils. Eur J Soil Sci 44:651–664. doi:10.1111/j.1365-2389.1993.tb02330.x

Moore TR, Roulet NT (1993) Methane flux: water table relations in northern wetlands. Geophys Res Lett 20:587–590. doi:10.1029/93GL00208

Mosier A, Schimel D, Valentine D, Bronson K, Parton W (1991) Methane and nitrous oxide fluxes in native, fertilized and cultivated grasslands. Nature 350:330–332. doi:10.1038/350330a0

Nykänen H, Alm J, Silvola J, Tolonen K, Martikainen PJ (1998) Methane fluxes on boreal peatlands of different fertility and the effect of long-term experimental lowering table on flux rates. Glob Biogeochem Cycle 12:53–69. doi:10.1029/97GB02732

Prevost M, Belleau P, Plamondon AP (1997) Substrate conditions in a treed peatland: responses to drainage. Ecoscience 4:543–554

Priemé A, Christensen S, Dobbie KE, Smith KA (1997) Slow increase in rate of methane oxidation in soils with time following land use change from arable agriculture to woodland. Soil Biol Biochem 29:1269–1273. doi:10.1016/S0038-0717(97)00017-5

Reay DS, Nedwell DB (2004) Methane oxidation in temperate soils: effects of inorganic N. Soil Biol Biochem 36:2059–2065. doi:10.1016/j.soilbio.2004.06.002

Regina K, Nykänen H, Silvola J, Martikainen PJ (1996) Fluxes of nitrous oxide from boreal peatlands as affected by peatland type, water table level and nitrification capacity. Biogeochemistry 35:401–418. doi:10.1007/BF02183033

Romanowicz EA, Siegel DI, Glaser PH (1993) Hydraulic reversals and episodic methane emissions during drought cycles in mires. Geology 21:231–234. doi:10.1130/0091-7613(1993)021<;0231:HRAEME>;2.3.CO;2

Romanowicz EA, Siegel DI, Chanton JP, Glaser PH (1995) Temporal variations in dissolved methane deep in the Lake Agassiz Peatlands, Minnesota. Glob Biogeochem Cycle 9:197–212. doi:10.1029/95GB00634

Roulet NT, Moore TR (1995) The effect of forestry drainage practices on the emission of methane from northern peatlands. Can J For Res 25:491–499. doi:10.1139/x95-055

Roulet NT, Ash R, Quinton W, Moore T (1993) Methane flux from drained northern peatlands: effect of a persistent water table lowering on flux. Glob Biogeochem Cycle 7:749–769. doi:10.1029/93GB01931

Roura-Carol M, Freeman C (1999) Methane release from peat soils: effects of *Sphagnum* and *Juncus*. Soil Biol Biochem 31:323–325. doi:10.1016/S0038-0717(98)00125-4

Rusch H, Rennenberg H (1998) Black alder (*Alnus glutinosa* (L.) Gaertn.) trees mediate methane and nitrous oxide emission from the soil to the atmosphere. Plant Soil 201:1–7. doi:10.1023/A:1004331521059

Ruser R, Schilling R, Steindl H, Flessa H, Beese F (1998) Soil compaction and fertilization effects on nitrous oxide and methane fluxes in potato fields. Soil Sci Soc Am J 62:1587–1595

Rustad LE, Fernandez IJ (1998) Experimental soil warming effects on CO_2 and CH_4 flux from a low elevation spruce–fir forest soil in Maine, USA. Glob Change Biol 4:597–605. doi:10.1046/j.1365-2486.1998.00169.x

Saari A, Martikainen PJ, Ferm A, Ruuskanen J, De Boer W, Troelstra SR, Laanbroek HJ (1997) Methane oxidation in soil profiles of Dutch and Finnish coniferous forests with different soil texture and atmospheric nitrogen deposition. Soil Biol Biochem 29:1625–1632. doi:10.1016/S0038-0717(97)00085-0

Saari A, Smolander A, Martikainen PJ (2004) Methane consumption in a frequently nitrogen-fertilized and limed spruce forest soil after clear-cutting. Soil Use Manage 20:65–73. doi:10.1079/SUM2004224

Saarnio S, Alm J, Martikainen PJ, Silvola J (1998) Effects of raised CO_2 on potential CH_4 production and oxidation in, and CH_4 emission from, a boreal mire. J Ecol 86:261–268. doi:10.1046/j.1365-2745.1998.00248.x

Schiller CL, Hastie DR (1996) Nitrous oxide and methane fluxes from perturbed and unperturbed boreal forest sites in northern Ontario. J Geophys Res 101:22. doi:10.1029/96JD01620 767–22,774

Schimel J (2000) Rice, microbes and methane. Nature 403:375–377. doi:10.1038/35000325

Schimel JP, Gulledge J (1998) Microbial community structure and global trace gases. Glob Change Biol 4:745–758. doi:10.1046/j.1365-2486.1998.00195.x

Schnell S, King GM (1995) Stability of methane oxidation capacity to variations in methane and nutrient concentrations. FEMS Microbiol Ecol 17:285–294. doi:10.1111/j.1574-6941.1995.tb00153.x

Seghers D, Top EM, Reheul D, Bulcke R, Boeckx P, Verstraete W, Sicilliano SD (2003) Long-term effects of mineral versus organic fertilizers on activity and structure of the methanotrophic community in agricultural soils. Environ Microbiol 5:867–877. doi:10.1046/j.1462-2920.2003.00477.x

Singh S, Singh JS, Kashyap AK (1999) Methane flux from irrigated rice fields in relation to crop growth and N-fertilization. Soil Biol Biochem 31:1219–1228. doi:10.1016/S0038-0717(99)00027-9

Sitaula BK, Bakken LR, Abrahamsen G (1995) CH_4 uptake by temperate forest soil: effect of N input and soil acidification. Soil Biol Biochem 27:871–880. doi:10.1016/0038-0717(95)00017-9

Sjögersten S, Wookey P (2002) Spatio-temporal variability and environmental controls of methane fluxes at the forest-tundra ecotone in the Fennoscandian mountains. Glob Change Biol 8:885–894. doi:10.1046/j.1365-2486.2002.00522.x

Sjögersten S, Melander E, Wookey PA (2007) Depth distribution of net methanotrophic activity at a mountain Birch Forest–tundra heath ecotone, Northern Sweden. Antar Alp Res 39:477–480. doi:10.1657/1523-0430(06-009)[SJOGERSTEN]2.0.CO;2

Smith KA (2005) The impact of agriculture and other land uses on emissions of methane and nitrous oxide and nitric oxides. Environ Sci 2:101–108. doi:10.1080/15693430500370423

Smith KA, Clayton H, McTaggart IP, Thomson PE, Arah JRM, Scott A (1995) The measurement of nitrous oxide emissions from soil by using chambers. Phil Trans Roy Soc London Ser A 351:327–338

Smith KA, Dobbie KE, Ball BC, Bakken LR, Sitaula BK, Hansen S, Brumme R, Borken W, Christensen S, Priemé A, Fowler D, Macdonald JA, Skiba U, Klemedtsson L, Kasimir-Klemedtsson A, Degórska A, Orlanski P (2000) Oxidation of atmospheric methane in Northern European soils, comparison with other ecosystems, and uncertainties in the global terrestrial sink. Glob Change Biol 6:791–803. doi:10.1046/j.1365-2486.2000.00356.x

Smith KA, Ball T, Conen F, Dobbie KE, Massheder J, Rey A (2003) Exchange of greenhouse gases between soil and atmosphere: interactions of soil physical factors and biological processes. Eur J Soil Sci 54:779–791. doi:10.1046/j.1351-0754.2003.0567.x

Smolander A, Paavolainen L, Mälkönen E (2000) C and N transformations in forest soil after mounding for regeneration. For Ecol Man 134:17–28. doi:10.1016/S0378-1127(99)00242-X

Steudler PA, Bowden RD, Melillo JM, Aber JD (1989) Influence of nitrogen fertilization on methane uptake in temperate forest soils. Nature 341:314–316. doi:10.1038/341314a0

Ström L, Ekberg A, Mastepanov M, Christensen TR (2003) The effect of vascular plants on carbon turnover and methane emissions from a tundra wetland. Glob Change Biol 9:1185–1192. doi:10.1046/j.1365-2486.2003.00655.x

Sundh I, Nilsson M, Mikkelä C, Granberg G, Svensson BH (2000) Fluxes of methane and carbon dioxide on peat-mining areas in Sweden. Ambio 29:499–503

Sutton RF (1993) Mounding site preparation: a review of European and North-American experience. New For 7:151–192. doi:10.1007/BF00034198

Suwanwaree P, Robertson GP (2005) Methane oxidation in forest, successional, and no-till agricultural ecosystems: effects of nitrogen and soil disturbance. Soil Sci Soc Am J 69:1722–1729. doi:10.2136/sssaj2004.0223

Tate KR, Ross DJ, Saggar S, Hedley CB, Dando J, Singh BK, Lambie SM (2007) Methane uptake in soils from *Pinus radiata* plantations, a reverting shrubland and adjacent pastures: effects of land-use change, and soil texture, water and mineral nitrogen. Soil Biol Biochem 39:1437–1449. doi:10.1016/j.soilbio.2007.01.005

Taylor CMA (1991) Forest fertilisation in Britain. Forestry commission bulletin, vol 95. HMSO, London, p 45

Terazawa K, Ishizuka S, Sakata T, Yamada K, Takahashi M (2007) Methane emissions from stems of *Fraxinus mandshurica* var. japonica trees in a floodplain forest. Soil Biol Biochem 39:2689–2692. doi:10.1016/j.soilbio.2007.05.013

Tlustos P, Willison TW, Baker JC, Murphy DV, Pavlikova D, Goulding KWT, Powlson DS (1998) Short-term effects of nitrogen on methane oxidation in soils. Biol Fertil Soils 28:64–70. doi:10.1007/s003740050464

Tuittila ES, Komulainen VM, Vasander H, Nykänen H, Martikainen PJ, Laine J (2000) Methane dynamics of a restored cut-away peatland. Glob Change Biol 6:569–581. doi:10.1046/j.1365-2486.2000.00341.x

Van Cleve K, Oechel WC, Hom JL (1990) Response of black spruce (*Picea mariana*) ecosystems to soil temperature modification in interior Alaska. Can J For Res 20:1530–1535. doi:10.1139/x90-203

Van den Pol-van Dasselaar A, van Beusichem ML, Oenema O (1998) Effects of soil moisture content and temperature on methane uptake by grasslands on sandy soils. Plant Soil 204:213–222

Van den Pol-van Dasselaar A, van Beusichem ML, Oenema O (1999) Effects of nitrogen input and grazing on methane fluxes of extensively and intensively managed grasslands in the Netherlands. Biol Fert Soils 29:24–30

Von Arnold K, Weslien P, Nilsson M, Svensson BH, Klemedtsson L (2005) Fluxes of CO_2, CH_4 and N_2O from drained coniferous forests on organic soils. For Ecol Manage 210:239–254. doi:10.1016/j.foreco.2005.02.031

Wang ZP, Ineson P (2003) Methane oxidation in a temperate coniferous forest soil: effects of inorganic N. Soil Biol Biochem 35:427–433. doi:10.1016/S0038-0717(02)00294-8

Windsor J, Moore TR, Roulet NT (1992) Episodic fluxes of methane from subarctic fens. Can J Soil Sci 72:441–452

Yang W, Song C, Zhang J (2006) Dynamics of methane emissions from a freshwater marsh of northeast China. Sci Total Environ 371:286–292. doi:10.1016/j.scitotenv.2006.08.034

Yavitt JB, Williams CJ (2000) Controls on microbial production methane and carbon dioxide in three *Sphagnum*-dominated peatland ecosystems as revealed by a reciprocal field peat transplant experiment. Geomicrobiol J 17:61–88. doi:10.1080/014904500270503

Yavitt JB, Fahey TJ, Simmons JA (1995) Methane and carbon dioxide dynamics in a northern hardwood ecosystem. Soil Sci Soc Am J 59:796–804

Zerva A, Mencuccini M (2005a) Short-term effects of clearfelling on soil CO_2, CH_4, and N_2O fluxes in Sitka spruce plantation. Soil Biol Biochem 37:2025–2036. doi:10.1016/j.soilbio.2005.03.004

Zerva A, Mencuccini M (2005b) Carbon stocks in a peaty gley soil profile after afforestation with Sitka spruce (*Picea sitchensis*). Ann For Sci 62:873–880. doi:10.1051/forest:2005078

Zerva A, Ball T, Smith KA, Mencuccini M (2005) Soil carbon dynamics in a Sitka spruce (*Picea sitchensis* (Bong.) Carr.) chronosequence on a peaty gley. For Ecol Manage 205:227–240. doi:10.1016/j.foreco.2004.10.035