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Methane emissions from wet grasslands on peat soil in a nature preserve

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Abstract. The area of wet grasslands on peat soil in the Netherlands is slowly increasing at the expense of drained, agriculturally used grasslands. This study aimed (i) to assess the contribution of wet grasslands on peat soil to methane (CH_4) emissions, and (ii) to explain differences among sites and between years in order to improve our understanding of controlling factors. For these purposes, a field study was conducted in the period 1994–1996 in the nature preserve "Nieuwkoopse Plassen", which is a former peat mining and agricultural area. Net CH_4 emissions were measured weekly to monthly with vented closed flux chambers at three representative sites, and at ditches near these sites. Three-years average of CH_4 emissions was 7.9 g CH_4 m^{-2} yr^{-1} for Drie Berken Zudde, 13.3 for Koole, and 20.4 for Brampjesgat. Ditches near the sites emitted 4.2–22.5 g CH_4 m^{-2} yr^{-1}. The time-course of CH_4 emissions for all experimental sites and years was fit with a multiple linear regression model with ground water level and soil temperature as independent variables. Lowering or raising the ground water level by 5 cm could decrease or increase CH_4 emissions by 30–50%. Therefore, ground water level management of these grasslands should be done with care.

Introduction

Methane (CH_4) is one of the most important greenhouse gases. Methanogenesis occurs wherever organic matter is decomposed under anaerobic conditions, in the absence of electron acceptors other than CO_2. Under aerobic conditions CH_4 can be oxidised by methanotrophs. Net CH_4 exchanges between the soil and the atmosphere are the result of the biogeochemical processes: CH_4 production and CH_4 consumption, and CH_4 transport. Transport can take place via diffusion, ebullition, and via the vascular system of plants. Important environmental factors determining CH_4 emissions from soils are vegetation, temperature and ground water level (e.g. Bartlett & Harriss 1993; Bubier et al. 1995; Kettunen et al. 1996; Whiting & Chanton 1993). Vegetation may serve as a conduit for CH_4 and O_2 transport,

and as a substrate for methanogens. Soil temperature affects the kinetics of both microbial CH_4 production and consumption. Ground water level acts as a border between anaerobic and aerobic layers in the soil.

Wetlands are mainly situated on peat soil (Bartlett & Harriss 1993). They have the potential of emitting large amounts of CH_4, since they are mainly anaerobic. On a global scale, wetlands contribute between 10 and 28% to total CH_4 sources (IPCC 1995). Approximately half of the total surface area of the Netherlands has been wetland for some time during the last 3000 years. Especially during the last few centuries the area of wetlands has decreased drastically. Most of it has been transformed into agricultural land. At present, less than 1% of the total surface area is wetland. However, this area is increasing, due to the policy of the government of the Netherlands to withdraw intensively managed, drained grasslands from agriculture and turn them into wet grasslands. Thus far, CH_4 emissions from wet grasslands in the Netherlands had not been quantified.

The aim of our study was (i) to assess the contribution of wet grasslands on peat soil to CH_4 emissions, and (ii) to explain differences among sites and between years in order to improve our understanding of possible controlling factors. For these purposes, a three-year field study was conducted at wet grasslands in the nature preserve "Nieuwkoopse Plassen". Net CH_4 emissions, CH_4 concentrations in the soil profile, ground water levels and soil temperatures were measured. We hypothesised (i) that the wet grasslands would emit considerable amounts of CH_4, and (ii) that differences in CH_4 emissions among sites and between years would mainly depend on differences in ground water level and soil temperature.

Materials and methods

Site description

"Nieuwkoopse Plassen" is a nature preserve located in the major peat area of the western part of the Netherlands (52°08′ N, 4°48′ E). During several centuries, the "Nieuwkoopse Plassen" area has been used for peat mining and agriculture. Since some decades, it is a nature preserve with narrow (30–80 m wide) grassland and reed fields, surrounded by ditches. Ground water level is kept near the surface via water level of the ditches. The area can be characterised as a fen, i.e. a minerotrophic peat soil, due to the influence of surface water. Measurements were done at three grassland sites spread over the area, which could only be reached by boat: Drie Berken Zudde, Koole and Brampjesgat (Table 1), and at ditches near these sites.

Table 1. Mean ground water level (GWL) and ranges in the years 1994–1996, soil characteristics of the 0–20 cm layer, and vegetation types of the sites Drie Berken Zudde (DBZ), Koole and Brampjesgat.

		DBZ	Koole	Brampjesgat
GWL, cm,	Mean	−18	−9	−11
	Ranges	−36 to −7	−35 to 3	−25 to −1
Loss-on-ignition (%)		94	78	69
Total nitrogen (g kg^{-1})		15	16	16
Total phosphorus (g kg^{-1})		0.6	0.9	1.5
pH-H_2O		3.5	4.9	5.3
Vegetation type, in % of total DM above 5 cm, average of harvest 1994 and 1995				
Grasses		55	8	23
Mosses		31	57	21
Rushes		4	17	17
Sedges		2	16	11
Reed		3	0	24
Remainder		5	2	4

The sites form a good representative of the wet, nutrient-poor grassland sites in the area. They were chosen to cover a range of ground water levels and vegetation types. Drie Berken Zudde and Koole have not been fertilised for more than 20 years. Brampjesgat still receives every second year farm yard manure (about 5 ton DM ha^{-1}). The sites are high in organic matter and low in nitrogen and phosphorus. The pH is low, especially at Drie Berken Zudde. The vegetation of the sites is dominated by grasses (mainly *Agrostis canina* L., *Anthoxanthum odoratum* L. and *Molinia caerulea* (L.) Moench), mosses (*Sphagnum* spp., *Polytrichum* spp.), rushes (*Juncus* spp.), sedges (*Carex* spp.), and reed (*Phragmites australis* (Cav.) Trin. ex Steudel). Rushes, sedges and reed may transport CH_4 directly from anaerobic layers to the atmosphere via their aerenchymatous tissues. The sites are mown once or twice every year in the period July to September. Typical yields are 3–5 ton DM ha^{-1} yr^{-1}.

Monitoring net CH_4 emissions, ground water levels and soil temperatures

Net CH_4 emissions were measured weekly to monthly from January 1994 to October 1996 with six vented closed flux chambers (Hutchinson & Mosier 1981; Mosier 1989) per site. To prevent artificially induced fluxes due to the very soft top soil, wooden boardwalks were installed. Circular, steel frames

(I.D. 25 cm, height 30 cm) were permanently installed into the soil to a depth of about 25 cm. During measurements, circular, PVC flux chambers (I.D. 25 cm, height 25 to 77 cm depending on the height of the vegetation) were placed on top of the frames. Preliminary measurements showed that size of the flux chambers did not affect calculated CH_4 emissions. Flux chambers were closed by a PVC lid and covered with insulating sheets to prevent temperature changes within the chamber.

Net CH_4 emissions from ditches near the sites were measured biweekly to monthly from October 1994 to November 1995 with three to six flux chambers, i.e. one or two per ditch. These circular, PVC flux chambers were connected to a floating tray and carefully placed on the water. Measurements could only be carried out when there was not much wind.

To examine diurnal variability, CH_4 emissions were measured several times during 31 October 1994 and 24 July 1995. On 28 September and 3 October 1996, CH_4 emissions were measured in the coldest and warmest period of the day (just before sunrise between 4.30 and 6.30, and between 13.00 and 15.00).

At each site and at each measurement, ground water level was recorded from water level readings in perforated pipes (I.D. 4 cm) with the peat surface as reference point. Ambient temperature and soil temperatures at 0, 2, 5, 10, 20, 30, 40, and 50 cm depth were also recorded.

CH_4 concentrations in flux chambers are expected to follow a linear increase or decrease and finally level off (Mosier 1989). We measured in the linear phase. Four gas samples were taken with glass syringes at regular time intervals (10 to 20 minutes) from the headspace of the chambers. Gas samples were analysed for CH_4 within 24 h by gas chromatography using a flame ionisation detector (coefficient of variation: 0.08%). A standard CH_4 concentration of 2.0 μL L^{-1} ($\pm$5%) was used for calibration. Net CH_4 emissions were calculated from linear regression of the time-course of CH_4 concentration in the headspace of the chambers. Mean annual CH_4 emissions, ground water levels and soil temperatures were estimated by trapezoidal integration over time. Data for November and December 1996 were taken from the average of the corresponding periods in 1994 and 1995. CH_4 emissions followed a skewed distribution and were transformed to a near-normal distribution by ln-transforming the data. Simple and multiple linear regression analyses were performed with ln-transformed CH_4 emissions as dependent variable, and ground water level and soil temperatures at several depths as independent variables.

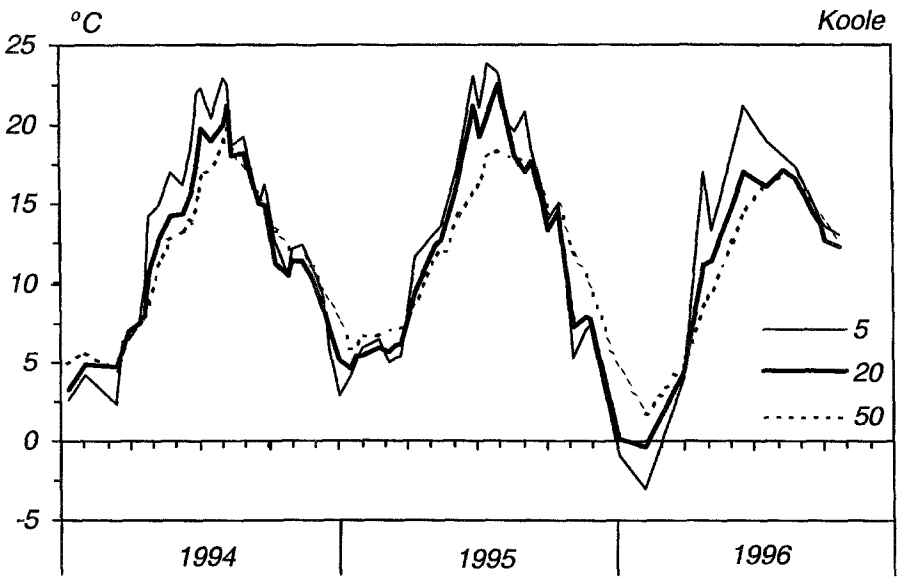

Figure 1. Time-course of soil temperatures (°C) at 5, 20, and 50 cm depth at the site Koole.

Monitoring CH_4 concentrations in the soil profile

CH_4 concentrations in the soil profile were measured weekly to monthly at Drie Berken Zudde from January to July 1995 and at Koole from September 1994 to November 1995. Perforated PVC pipes (I.D. 5 cm) were permanently installed in the soil in an area of about 0.1 m^2 about three months before the start of the measurements. The end of each pipe consisted of a small perforated compartment of 10 cm height. Pipes of different lengths with compartments at 0–10, 20–30, 30–40, and 40–50 cm at Drie Berken Zudde, and at 0–10, 10–20, 20–30, 30–40, and 95–105 cm at Koole were used. The holes in the compartments allowed water and air from the surrounding soil to enter. CH_4 concentrations in the compartments were assumed to be in equilibrium with CH_4 concentrations in the surrounding soil. Each compartment had two polythene tubes going from the compartment to the soil surface. Gas samples were taken via the tubes with glass syringes, and analysed for CH_4 by gas chromatography. Whenever ground water level reached a certain compartment of the pipe, water samples were taken and injected into incubation bottles. The bottles were shaken vigorously to degas the water. Sub samples from the headspace of the bottles were taken through rubber septa and analysed for CH_4. As the solubility of CH_4 in water is low, amount of dissolved CH_4 in the water was neglected. CH_4 concentrations in the soil profile were converted to mg m^{-3} using an average peat porosity of 0.95,

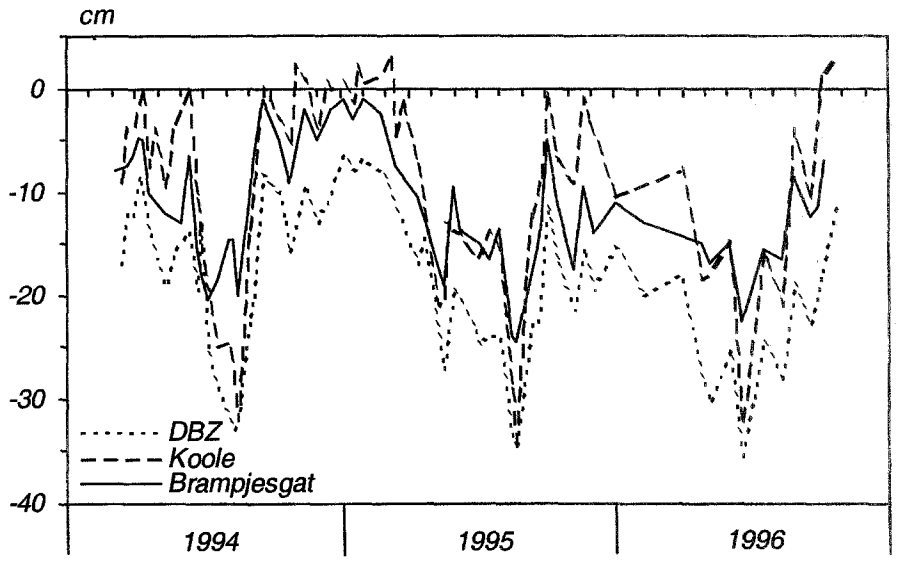

Figure 2. Time-course of ground water level (cm below the surface) at the sites Drie Berken Zudde (DBZ), Koole, and Brampjesgat.

as found by Liblik et al. (1997). CH_4 storage (mg m^{-2}) was determined by integrating CH_4 concentrations of the upper 40 cm of the peat profile.

Results

Weather and ground water level

Average air temperature was 10.6 °C in 1994, 10.4 in 1995 and 8.6 in 1996 (long-term average is 9.4 °C). Annual precipitation was 903 mm in 1994, 739 in 1995 and 597 in 1996 (long-term average is 792 mm). Figure 1 shows the time-course of soil temperatures at 5, 20, and 50 cm depth at the site Koole. The time-course of soil temperatures at Drie Berken Zudde and Brampjesgat was similar (not shown). Drie Berken Zudde had the lowest ground water level (Figure 2). Ground water levels generally decreased in summer.

Net CH_4 emissions

All three sites were sources of CH_4 (Figure 3). Differences among sites and between years were quite large. Mean net CH_4 emissions from ditches near the sites were highest in summer (Figure 4).

Results on diurnal variability are based on few observations. On 28 September and 3 October 1996, day-time net CH_4 emissions were 52 and

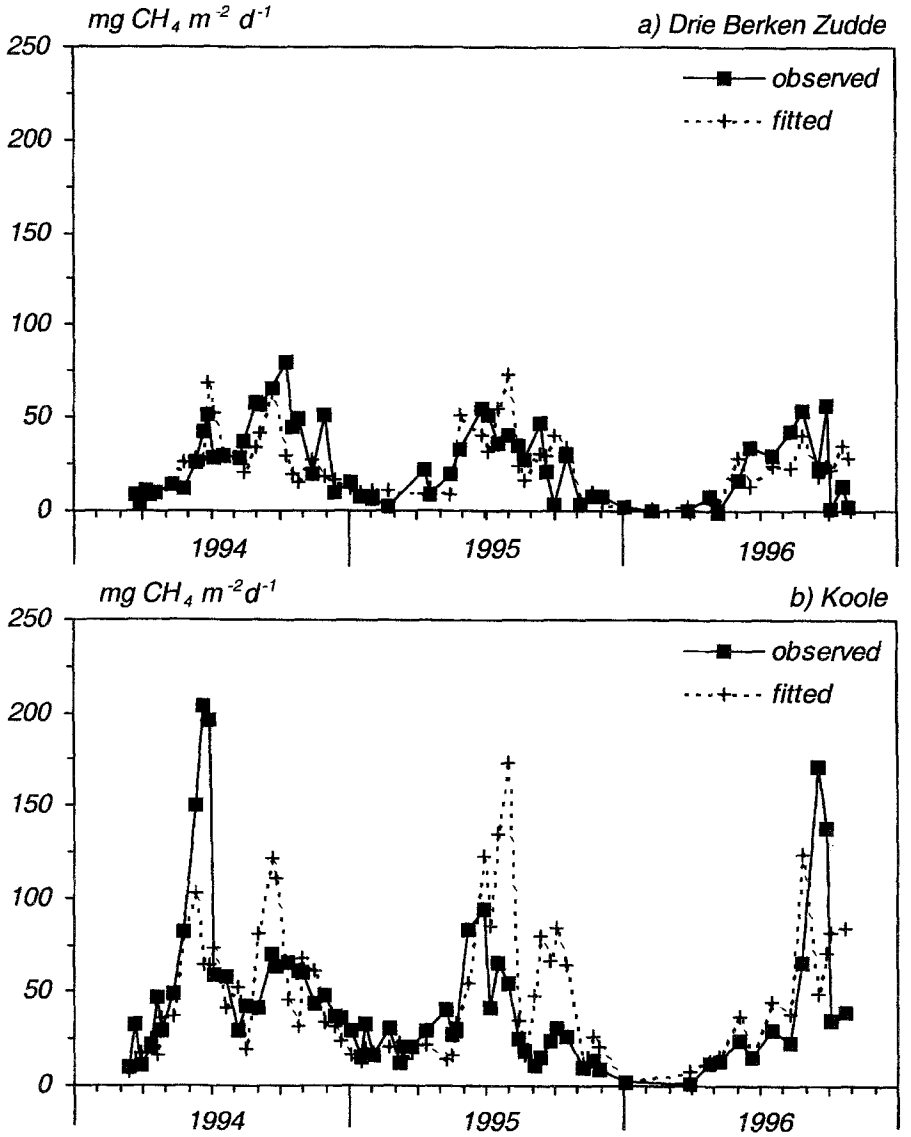

Figure 3. Time-course of observed and fitted (Equation 1) mean net CH_4 emissions (mg CH_4 m^{-2} d^{-1}) from the sites (*a*) Drie Berken Zudde, (*b*) Koole, and (*c*) Brampjesgat. Each data point represents the average of six measurements.

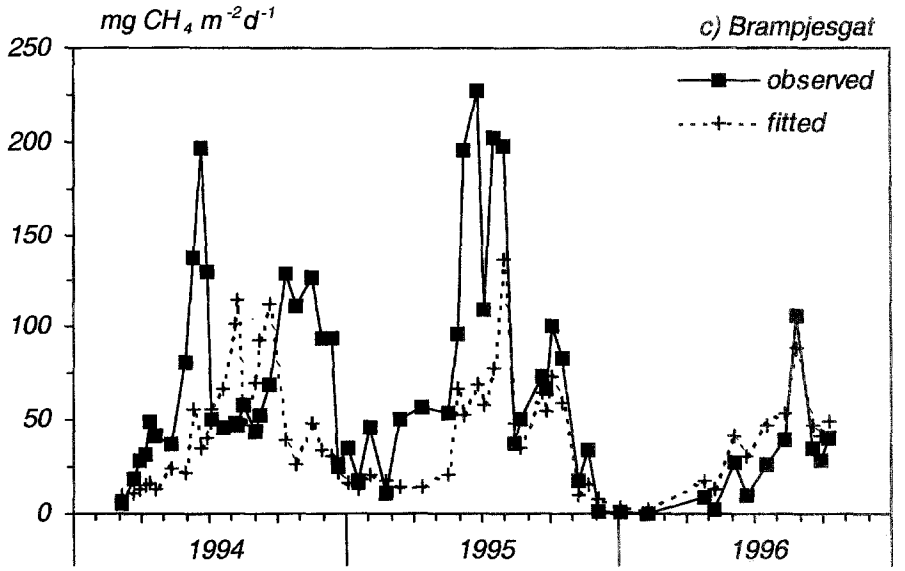

Figure 3. Continued.

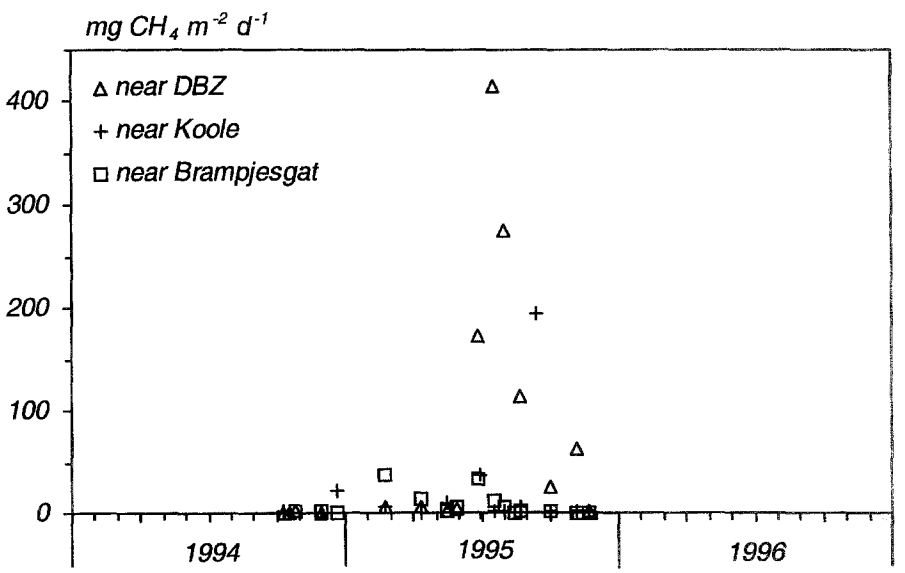

Figure 4. Time-course of mean net CH_4 emissions (mg CH_4 m^{-2} d^{-1}) from ditches near Drie Berken Zudde (DBZ), Koole and Brampjesgat. Each data point represents one or two measurements.

Table 2. Mean annual net CH_4 emissions (g CH_4 m^{-2} yr^{-1}, ±SD) of six flux chambers at Drie Berken Zudde (DBZ), Koole and Brampjesgat, and for ditches near the sites. Mean annual ground water level (cm below the surface) is given in brackets.

	DBZ	Koole	Brampjesgat
1994	9.6 ± 9.1 (16 cm)	18.2 ± 12.2 (7 cm)	22.4 ± 10.7 (9 cm)
1995	8.3 ± 9.8 (18 cm)	11.1 ± 11.1 (10 cm)	27.8 ± 22.0 (12 cm)
1996	6.0 ± 6.8 (21 cm)	10.7 ± 11.0 (11 cm)	11.1 ± 5.1 (13 cm)
Average 1994–1996	7.9 ± 8.8 (18 cm)	13.3 ± 12.0 (9 cm)	20.4 ± 16.0 (11 cm)
Ditches	22.5	7.3	4.2

59% of night-time net CH_4 emissions. On 31 October 1994 and 24 July 1995, no clear pattern of CH_4 emissions was found during the day.

Annual net CH_4 emissions

At Drie Berken Zudde and Koole, mean annual net CH_4 emissions were highest in 1994, and at Brampjesgat in 1995 (Table 2). At all three sites, CH_4 emissions were low in 1996. The relatively high standard deviations indicate a high spatial variability of CH_4 emissions within sites. Drie Berken Zudde showed the lowest mean annual net CH_4 emissions and Brampjesgat the highest. CH_4 emissions from ditches however were lowest near Brampjesgat and highest near Drie Berken Zudde (Table 2). Emissions from ditches were never measured in situations of disturbances like heavy wind or passing boats, in which mixing of ditch water and release of CH_4 from CH_4-rich bottom water may occur. Emissions were thus underestimated. Underestimation may have been smallest at the ditch near Drie Berken Zudde, which was best protected against wind and is located in a rather remote area where no boats pass.

CH_4 emissions in relation to ground water level and soil temperatures

Simple linear regression analyses of each of the individual data from the three sites showed that ln-transformed mean net CH_4 emissions were related to soil temperatures (r^2 of 0.27–0.33; n = 183). The relation with only ground water level was poor (r^2 of 0.01; n = 183). The best model obtained with multiple linear regression analyses included both soil temperature and ground water level (r^2 of 0.54; n = 183) (Figure 3):

$$\ln(Y_t) = 1.75 + 0.20 * T_{20,t} - 0.075 * GWL_t \quad (1)$$

t = time, day;
Y_t = net CH_4 emissions at time t, mg CH_4 m^{-2} d^{-1};
$T_{20,t}$ = soil temperature at 20 cm depth at time t, °C;
GWL_t = ground water level at time t, cm below the surface.

Linear regression analyses were also carried out with ln-transformed mean annual net CH_4 emissions as dependent variable, i.e. for each year and for each site, and mean annual ground water level and soil temperatures as independent variables. The best model included ground water level (r^2 of 0.57; n = 9):

$$\ln(Y_t) = 3.57 - 0.08 * GWL_t \quad (2)$$

t = time, year;
Y_t = annual net CH_4 emissions at time t, g CH_4 m^{-2} yr^{-1};
GWL_t = annual ground water level at time t, cm below the surface.

CH_4 concentrations in the soil profile

CH_4 concentrations in the soil increased from ambient at the surface to about 3000 mg m^{-3} in deeper layers. Ground water level influenced the CH_4 concentration profile (Figure 5). CH_4 concentrations in soil layers above the ground water table were near ambient. A considerable increase was found immediately below the ground water level. This indicates a net flux of CH_4 from the saturated peat into the unsaturated zone. Calculated CH_4 storage is dependent on the depth to which CH_4 concentrations are integrated. CH_4 storage (±SD) in the upper 40 cm of the soil profile was 120±155 mg m^{-2} at Drie Berken Zudde and 209±124 mg m^{-2} at Koole. At Drie Berken Zudde, CH_4 storage was on average 258 mg m^{-2} in winter and 11 in summer. At Koole, however, there was no clear seasonal pattern, probably due to the relatively high ground water level throughout the year (Figure 2). Turnover time of CH_4, i.e. storage to emission ratio, was on average 5–6 days for both sites.

Discussion

CH_4 emissions

In a review, Bartlett & Harriss (1993) arrive for wetlands in the latitudes 45°–60° N at a mean estimate of 87 mg CH_4 m^{-2} d^{-1} during the emission period (standard error of mean: 18, range: 0–664), this is equivalent to 13 g CH_4

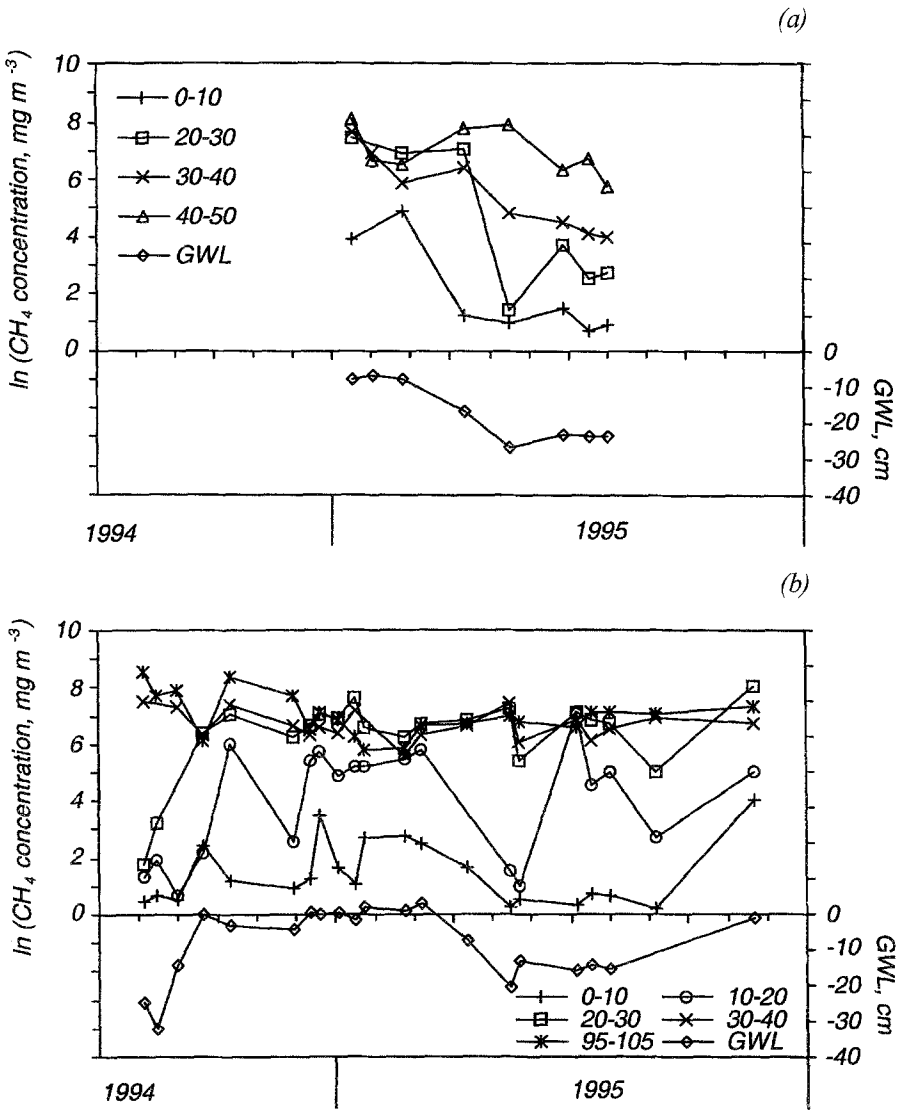

Figure 5. Time-course of ln-transformed CH_4 concentration (mg m^{-3}) in different soil layers (cm below the surface) at (*a*) Drie Berken Zudde (DBZ), and (*b*) Koole, and ground water level (cm below the surface).

m^{-2} yr^{-1} (winter fluxes were assumed to be zero). More recent studies (e.g. Bubier et al. 1993; Martikainen et al. 1995; Suyker et al. 1996) yielded similar CH_4 emissions. CH_4 emissions from our grasslands were in the same range (6–28 g CH_4 m^{-2} yr^{-1}, Table 2). Differences among the three sites could largely be attributed to ground water level differences. However, Brampjesgat

showed higher CH_4 emissions than Koole whilst the annual mean ground water level was almost similar. This might be explained by other differences among the sites, for example in vegetation and in pH (Table 1) (Van den Pol-van Dasselaar et al. 1998).

In the "Nieuwkoopse Plassen" area, fields are surrounded by ditches. CH_4 emissions from these ditches ranged from 0–425 mg CH_4 m^{-2} d^{-1}, which is similar to the CH_4 emissions from ditches of drained bogs and fens in Ontario, Canada (5–400 mg CH_4 m^{-2} d^{-1}) as found by Roulet and Moore (1995). Emissions from ditches seemed to be related to temperature with the highest emissions occurring in summer (Figure 4). We expect that the major CH_4 transport mechanism in ditches was diffusion and convection for low emissions and ebullition for high emissions. This was supported by an often occurring non-linear increase in CH_4 concentration in the headspace of the chamber in summer, indicating the escape of CH_4 bubbles to the headspace between two measurements. Further on, bubbles were frequently seen in summer.

Temporal variability of CH_4 emissions

Interannual variability

Interannual variability of CH_4 emissions (Table 2) was related to differences in ground water level (Equation 2). Moore and Roulet (1993) and Liblik et al. (1997) found a strong relationship between the logarithm of the average seasonal CH_4 flux and average seasonal water table depth for wetland sites in Canada. Our results support this relationship. Also, our results confirm that the relationship between CH_4 emissions and ground water level is not only present in summer, but during the whole year. The latter is important in estimating annual emissions. The existence of large differences between years implies that monitoring of CH_4 emissions should be done for at least several years to obtain a reliable estimate of emissions from a particular area. If extrapolation of measurements is needed, special attention should be paid to ground water level and soil temperature. This is especially important during the growth period, as the highest CH_4 emission rates may occur in that period.

Seasonal variability

We found a strong seasonal variability with high emissions in summer and low emissions in winter (Figure 3). We hypothesised that differences in CH_4 emissions would mainly depend on differences in ground water level and soil temperature. This was true (Equation 1, r^2 of 0.54; n = 183), but still a large part of the temporal variability of CH_4 emissions could not be explained. Although this is found often (e.g. Frolking & Crill 1994; Rouse et al. 1995), in some studies a larger part of the variability could be explained (e.g. Dise et

al. 1993; Suyker et al. 1996). However, our regression model fitted the time-course of CH_4 emissions for all three sites and all three years (Figure 3), even though there were relatively large differences among sites and between years. Therefore, we conclude that both ground water level and soil temperature have a large influence on CH_4 emissions.

Temperature may affect the microbial CH_4 producing and consuming processes instantaneously, while ground water level may have both short- and long-term effects controlling methanogenic and methanotrophic populations within a site. A decrease of CH_4 production due to a decrease of ground water level may be caused by an increase of electron acceptors, such as oxygen, nitrate and sulphate (Freeman et al. 1994), by a decrease of available methanogenic substrates, as well as by a reduction in the population of methanogenic bacteria (Shannon & White 1994). Often, there appears to be a hysteresis effect, i.e. CH_4 emissions are greater on the falling than rising water table limbs, for a set water table depth (e.g. Moore & Dalva 1993). For our sites, a hysteresis effect could not be detected. According to Shannon and White (1994), a substantial drop of the water table may cause lower CH_4 emissions for at least a year following the return of saturated conditions. This would suggest that the relatively dry conditions of 1995 and 1996 might affect CH_4 emissions of coming years.

Diurnal variability

Our CH_4 emission estimates (Figures 3 and 4, Table 2) are based on measurements during the day. However, CH_4 emissions may fluctuate within a time scale of hours. This may be caused by changes in e.g. temperature, which may affect both methanogenesis and methanotrophy and radiation, which may affect plant-mediated CH_4 transport and substrate availability for methanogens through affecting plant photosynthesis and subsequent carbon translocation to roots (Mikkelä et al. 1995). The magnitude of diurnal variability of CH_4 emissions from wetlands is inconsistent. For example, Suyker et al. (1996) showed that CH_4 emissions from a fen were higher during daytime than during night-time. Klinger et al. (1994) could not detect diurnal variability of CH_4 emissions from peatlands. Mikkelä et al. (1995) found no significant differences between CH_4 emissions during day and night for sites with high ground water levels. For sites with low ground water levels however (5–30 cm below the surface), they found higher emissions during the night than during the day. They speculate that this may be caused by diurnal variability of CH_4 oxidation due to temperature changes in the top layer, and hardly any diurnal variability of CH_4 production, occurring in the deeper layers. Our few data on variability of CH_4 emissions during the day suggest that we might have underestimated CH_4 emissions, as CH_4 emis-

sions were higher during night-time than during day-time. However, this is based on too little information to draw any firm conclusions. Possible effects of measurement time during the day may be excluded, as the measurement chronology was changed at every measurement date.

Effect of climate and land use changes on CH_4 emissions

In the Netherlands, about 3% of the peat area is similar to the "Nieuwkoopse Plassen" area (Table 2). The greater part of peat soils is drained and agriculturally utilised. Intensively managed and drained grasslands on these peat soils are a small sink of CH_4 with an annual consumption of 0.01 to 0.03 g atmospheric CH_4 m^{-2} yr^{-1} (Van den Pol-van Dasselaar et al. 1997). The government of the Netherlands intends to convert part of the intensively managed grasslands on peat soil from agriculture into more natural ecosystems. The ground water level of these grasslands will than be raised again, and both fertilisation and dry matter yield will be reduced. Eventually, these grasslands will be comparable to grasslands in the "Nieuwkoopse Plassen" area with estimated mean annual net CH_4 emissions of 6–28 g CH_4 m^{-2} yr^{-1}. Therefore, this policy may lead to increased CH_4 emissions.

Both soil temperature and ground water level have a large influence on CH_4 emissions. If, as a consequence of increased greenhouse gas emissions, temperatures on earth will increase, then CH_4 emissions will also increase, unless, as a consequence of a warmer climate, ground water level will drop simultaneously. According to Equation 1, the effect of changes in soil temperature might be considerable: an increase of soil temperature at 20 cm depth by 2 °C would cause CH_4 emissions to increase by 50%, assuming that all other factors remain constant.

In the nature preserve "Nieuwkoopse Plassen", ground water level is maintained on a higher level than in the surrounding agriculturally used areas. It is possible to manage the ground water level via the water level in the ditches. Changes in ground water level management will affect CH_4 emissions. If, for example, ground water level is maintained 5 cm above the present level, then CH_4 emissions may increase by 45–50% (according to Equation 1 and 2). If however, ground water level drops 5 cm, CH_4 emissions may decrease by 30%. The largest impact will be achieved in summer, when CH_4 emissions are high. As the impact of ground water level on CH_4 emissions may be considerable, ground water level management of wet grasslands should be done with care.

Acknowledgements

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