Methane emissions in two drained peat agro-ecosystems with high and low agricultural intensity

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Abstract Methane (CH_4) emissions were compared for an intensively and extensively managed agricultural area on peat soils in the Netherlands to evaluate the effect of reduced management on the CH_4 balance. Chamber measurements (photoacoustic methods) for CH_4 were performed for a period of three years in the contributing landscape elements in the research sites. Various factors influencing CH_4 emissions were evaluated and temperature of water and soil was found to be the main driver in both sites. For upscaling of CH_4 fluxes to landscape scale, regression models were used which were specific for each of the contributing landforms. Ditches and bordering edges were emission hotspots and emitted together between 60% and 70% of the total terrestrial CH_4 emissions. Annual terrestrial CH_4 fluxes were estimated to be 203 (±48%), 162 (±60%) and 146 (±60%) kg CH_4 ha^{-1} and 157 (±63%), 180 (±54%) and 163 (±59%) kg CH_4 ha^{-1} in the intensively managed site and extensively managed site, for 2006, 2007 and 2008 respectively. About 70% of the CH_4 was emitted in the summer period. Farm based emissions caused per year an additional 257 kg CH_4 ha^{-1} and 172 kg CH_4 ha^{-1} for the intensively managed site and extensively managed site, respectively. To further evaluate the effect of agricultural activity on the CH_4 balance, the annual CH_4 fluxes of the two managed sites were also compared to the emissions of a natural peat site with no management and high ground water levels. By comparing the terrestrial and additional farm based emissions of the three sites, we finally concluded that transformation of intensively managed agricultural land to nature development will lead to an increase in terrestrial CH_4 emission, but will not by definition lead to a significant increase in CH_4 emission when farm based emissions are included.

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Introduction

The assessment of the contribution of the trace gas methane (CH_4) to the greenhouse gas effect and the related global warming is of great importance. Northern peatlands are significant sources of CH_4, and are estimated to emit between 20 and 50 Tg yr^{-1} (Mikaloff Fletcher et al. 2004a, b). In northern oligotrophic and eutrophic managed peatland systems, net uptake and emission rates of CH_4 have been found to depend on groundwater level, soil moisture content, temperature, and grassland management (Van den Pol-van Dasselaar et al. 1998a; Hargreaves and Fowler 1998; Christensen et al. 2003; Blodau and Moore 2003; Hendriks et al. 2007; Pelletier et al. 2007). CH_4 emissions are difficult to estimate because of their large spatial and temporal variability (e.g. Smemo and Yavitt 2006). Therefore there are two major challenges when upscaling of CH_4 fluxes from small scale to landscape scale: 1) selecting the correct ecosystem variables for stratification and 2) developing robust predictive relationships (Groffman et al. 2000).

The majority of fen meadow areas in Atlantic Europe are intensively managed. In the Netherlands, eutrophic peatlands have been drained for centuries and in the last 50 years peatlands have been drained even more deeply to make modern agriculture possible. These peatlands are therefore major carbon sources of CO_2 as a result of peat oxidation (Langeveld et al. 1997; Veenendaal et al. 2007). Burgerhart (2001) has suggested that peat oxidation can be reduced if agricultural peatlands are transformed into wetland nature by raising the water table and by reducing agricultural intensity. These measures alter the carbon cycle and probably turn carbon sources into carbon sinks. Large uncertainties exist, however, of such measures on the CH_4 balance. Hendriks et al. 2007 studied a nature restoration site with no agricultural practices since 1997. They found that a sink of 71 g CO_2-equiv $m^{-2}yr^{-1}$ had developed and they attributed this to a decrease in CO_2 emissions from fields and an increase in CH_4 emissions from ditches and water-logged soil after stopping agricultural activity. However, in this case the previous situation for CH_4 emission in the time that this area was used for intensive farming is unknown.

The objective of this study is 1) to find empirical relationships that describe the CH_4 emissions from the different landscape elements and to provide a spatially integrated flux for the intensively managed and extensively managed area and 2) to investigate the influence of agricultural activity on the CH_4 balance. Firstly, terrestrial methane fluxes were studied in an intensively managed area, where manure and fertiliser are applied and frequent mowing is practiced. These fluxes are compared to terrestrial CH_4 fluxes measured in an extensively managed area with reduced agricultural activity. Secondly, farm based methane fluxes were estimated using an emissions factor approach. Methane fluxes of the two managed sites were compared to methane fluxes in a former agricultural site which was converted to a nature reserve 11 years ago by stopping intensive dairy farming, raising the water table (>20 cm below field level for most of the year) (Hendriks et al. 2007).

Experimental sites and methodology

Experimental sites

The experimental areas Oukoop, an intensively managed dairy farm and Stein, an extensively managed area are located in a polder in the western part of the Netherlands 52°02′01″N″ 04°46″E″ and 52°01′07″N″ 04°46″E″, respectively (Fig. 1). The climate is temperate and humid, with mean annual precipitation of about 800 mm and an annual long-term mean temperature of 9.8°C. Nol et al. (2008) estimated that 21% of the polder is open water (ditches and small permanent pools), 6% is ditch edges (waterlogged land bordering the ditches) and 73% is drier land with a fluctuating water table. The soils consist of a clayey peat or peaty clay top layer of about 25 cm overlying 12 m eutrophic peat deposits. The polder is between 1.6 and 1.8 m below sea level. Perched water tables occur after heavy rains, when the soil impedes water infiltration. Both sites have been described in more detail by Veenendaal et al. (2007) and Schrier-Uijl et al. (accepted, AFM).

The Oukoop experimental area is situated on an intensively managed dairy farm. The management regime varies, but on average consisted of mowing three to four times a year, whereas applications of manure and/or fertiliser took place 5–6 times a year. *Lolium perenne* is the most dominant species and *Poa trivialis* is co-dominant with no plants in the drainage ditches. On average the water table is being kept at 50 cm below the surface with perching water tables

Fig. 1 The location of the managed experimental areas in the Netherlands (*right*) and a close up (*left*) of the intensively managed area (Oukoop) and the extensively managed area (Stein) which shows the characteristic parcellation of the polder landscape
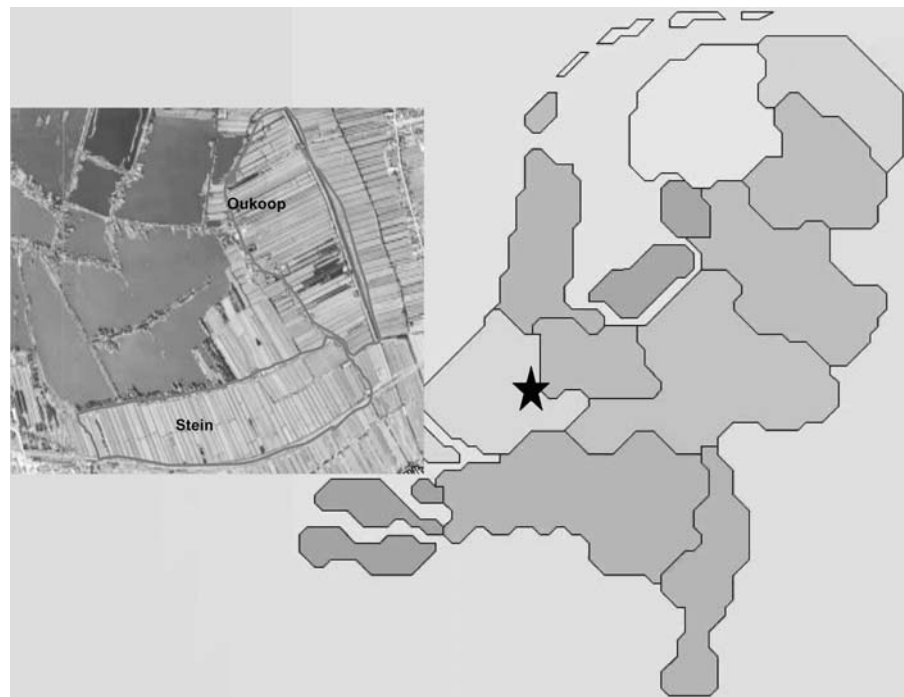
after heavy rain. Main characteristics of the Oukoop site are given in Table 1.

The management in Stein has been changed from intensive to extensive some 20 years ago and the area has been turned into a bird reserve. The research area was used as hayfield without application

of manure and fertiliser during the measurement period and was mown three times each year after June 15 (2006, 2007 and 2008). The water table was adjusted since 2006, with a high water table (15–20 cm below the surface) in winter and a low water table in summer (50 cm below the surface). In Stein,

Table 1 Main characteristics of the Oukoop and Stein site in the Netherlands

	Soil class, topography and landscape element	Human influence	Parent material	Drainage
Oukoop	Fibric rheic eutric Histosol	0–23 cm: anthropogenic topsoil	0–23 cm: anthropogenic	Poorly drained
	Flat, (alluvial) plain	Peat from ditches on edges	23–50 cm: clayey peat	Saturated for long periods during winter as a result of compaction
		Application of fertiliser: 370, 350 and 260 kg ha^{-1} in 2006, 2007 and 2008, resp. Application of cow manure: 55, 57 and 90 m^3 ha^{-1} in 2006, 2007 and 2008, resp	>50 cm: peat, 70% discernible remnants of wood and reed	Mean highest WT: ca. 35 cm Mean lowest WT: ca. 60 cm
Stein	Fibric rheic eutric Histosol	0–23 cm: anthropogenic topsoil	0–29 cm: anthropogenic	Poorly drained since 2005
	Flat, (alluvial) plain	Peat from ditches on edges	29–50 cm: clayey peat	Saturated for long periods every year
		No application of fertiliser or cow manure	>50 cm: peat, few recognizable plant remnants	Mean highest WT: ca. 25 cm Mean lowest WT: ca. 50 cm

Lolium perenne is also dominant, often with *Poa trivialis* co-dominant and no plants are present in the drainage ditches. Over time, *Holcus lanatus*, *Anthoxanthum odoratum* and *Rumex acetosa* have become more abundant. Characteristics of the Stein site are given in Table 1.

Methodology

Measurements

Terrestrial emissions of CH_4 were determined using a closed chamber method (Hutchinson and Mosier 1981). Methane concentrations were measured using a Photo Acoustic Field Gas Monitor (INNOVA 1412 sn, 710-113, ENMO services, Belgium) connected by Teflon tubes to a PVC chamber (e.g. van Huissteden et al. 2005). Samples were taken from the headspace of a closed cylindrical, dark chamber (30 cm diameter, 25 cm height) that was placed on a collar. A small fan was installed in the chamber to homogenize the inside air and a water lock was placed to control inside pressure. On land we used water between the chamber and the collar to seal the chamber from the ambient air during the measurement. For the ditches we used floaters and a lever system to gently lower the chamber onto the water surface, carefully avoiding the effect of pressure differences and the disturbance of the water surface. We used external silica gel and soda lime filters to minimize cross-interference of CO_2 and water vapour when CH_4 was measured at high CO_2 concentrations. The gas analyser was annually calibrated and tested for drift at the NMI (The Netherlands Institution of Standards, Delft, the Netherlands). In addition, the equipment was occasionally cross-checked for drift with a standard calibration gas. During the measurement period however, the equipment was not found to drift. All measurements were taken during the day, between 9am and 4pm. Each flux measurement consisted of five point-measurements taken at one-minute intervals from which dC/dt was calculated.

At the beginning of January 2005, 6 PVC collars (diameter 30 cm) were installed randomly in the footprint area of the eddy covariance systems at both experimental sites, so that gas emissions could be sampled. The measurements were carried out from January 2005 to November 2008 once a month up to twice a month or more during intensive field campaigns.

From February 2006 until November 2008, 19 additional sampling points, distributed over the experimental sites, were sampled every month at both research locations to study spatial variability. At both locations three landscape elements were distinguished with different soil/water temperatures and soil moisture conditions. They were: permanently water-filled ditches, ditch edges, and the field area with a fluctuating water table. Acreage of the landforms was determined by measurements in the field (Nol et al. 2008), the use of GIS maps and use of aerial photographs. In each of the two fields, four sample points were located on the water surface of the ditches, four points on the ditch edges and 11–14 sample points in the fields. In total over 1200 measurements were taken.

In addition to each flux measurement, soil or water temperature was measured at 5 cm depth and soil moisture content was determined in the top 5 cm of soil at the sample points, using a HH2 Delta-T device (Delta T Devices, Llandindrod Wells, USA) calibrated for the soil type. Soil and water temperatures were measured every half hour by sensors installed at a depth of 4 cm (Campbell scientific, USA and e+ sensor L-50, Eijkelkamp, the Netherlands, respectively). Water table depth was recorded hourly with pressure sensors installed in a steel frame to a depth of 70 cm into the soil at one or two places in the field (e+ sensor L-50, Eijkelkamp Agrisearch Equipment BV, Giesbeek, the Netherlands). In the ditch water of both experimental sites, electrical conductivity (*EC*) (Multi 350i, Fisher Scientific, the Netherlands) and *pH* (Cond340i-SET, Fisher Scientific, the Netherlands) was measured in 2008. In Stein, water tables were determined during each field CH_4 measurement in 2008 at the location of the measurement.

Wind speed, air temperature and water vapour pressure were measured with an eddy covariance system consisting of a Campbell Csat C3 Sonic anemometer (Campbell Scientific, Logan, Utah, USA) directed into the main wind direction and a Licor 7500 open path Infrared gas analyser (LI-COR Lincoln, NE, USA). The height of the mast was 305 cm and was located in the middle of the field sample points in both areas (Veenendaal et al. 2007; Schrier-Uijl et al., accepted AFM). For continuous measurements of CH_4 in the intensively managed site, we used the eddy covariance dataset of Kroon et al. (2007) where CH_4 concentrations were measured with a system consisting of a three-dimensional sonic anemometer and a QCL spectrom-

eter (model QCL-TILDAS-76, Aerodyne Research Inc., Billerica MA, USA).

Calculations and statistical analyses

Each flux measurement consisted of five points taken at one-minute intervals. The slope dC/dt of the gas concentration curve at time $t=0$ s was estimated using linear regression and the slope-intercept method as described by Kroon et al. (2008). The average flux values for CH_4 estimated by the slope intercept method were not significantly different from those estimated by the linear method and therefore, linear regression was used to calculate CH_4 fluxes. The short measurement period of 240 seconds, the rejection of the last point in the case of levelling, and additional measures taken to prevent leakage, mixing and temperature artefacts made it possible to use linear regression (Schrier-Uijl et al., accepted AFM). First, the data quality was assessed: outliers resulting from disturbances, chamber leakage or instrument failures were removed from the data set. Annual mean net CH_4 emissions were estimated by linear regression models of natural-logarithm transformed CH_4 data using T_{soil}/T_{water} as explanatory variables (model-based approach, e.g. Hargreaves and Fowler 1998). The reliability of this model based approach has been tested previously for the Oukoop experimental site by performing a comparison of the chamber method measurements with eddy covariance measurements of CH_4. The methods agreed well and the difference in cumulative emissions was 17% over a three months period (Schrier-Uijl et al. accepted AFM).

The statistical significance of differences between landscape elements within sites was calculated with one-way ANOVA. Analysis of covariance, with temperature as covariate, was used to ascertain the statistical significance of differences in the emissions from the landscape elements of the two sites. Correlations between natural-logarithm transformed CH_4 emissions and independent variables were calculated using step-wise multiple linear regression analysis (case-wise elimination of variables). Paired T-tests were used to calculate the statistical difference in emission between sites at the same day. Uncertainties per landscape element were estimated with a temperature dependent approach and were weighted for the proportion of each landscape ele-

ment in the total landscape. Statistical analyses were carried out with SPSS. For the calculations of the contribution of animals and manure in the total CH_4 balance, we used the method as described by Hensen et al. (2006) which uses simple emission factors for dairy cows, heifers, calves, manure and farmyard manure.

Results

Landscape elements

We compared the landscape elements for the period that measurements of emissions from all landscape elements ran parallel (January 2006–December 2008). The average water table depth, water temperature and soil temperature during this period are shown in Fig. 2. Because temperatures of the two experimental areas are similar (within 0.5°C) for most of the time, only Stein is shown.

At both sites, the CH_4 emissions from the ditches (21% of the area) and ditch edges (6% of the area) were significantly higher than those from the fields ($P<0.01$) and CH_4 emissions from ditches were significantly higher that those from edges ($P<0.01$). Ditches showed sometimes episodic, exceptionally high emission values. For example in 2006 on September 27 and 28 emissions were 366 ($n=6$) and 123 ($n=4$) mg m^{-2}hr^{-1} for the intensively managed and extensively managed areas, respectively versus 5 mg m^{-2}hr^{-1} averaged for the whole summer. During these extreme measurements wind velocity was high and turbulent water surface conditions were observed visually. Field fluxes in Stein were slightly
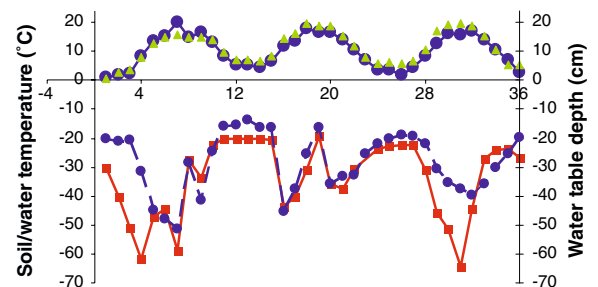

Fig. 2 Monthly averaged water temperatures (*green triangles*) and soil temperatures (*blue dots*) at 4 cm depth in Stein (upper graph) and water table depths (lower graph) for the intensively managed (*red squares*) and extensively managed (*blue dots*) areas from month 1 (January 2006) to month 36 (December 2008)

higher compared to field fluxes in Oukoop, with maximum values of 22 and 19 mg $m^{-2}hr^{-1}$, respectively. Field emission rates were highest in March, April, May and June in Oukoop and in May, June and July in Stein. Field fluxes were found to be increased by about 4% after manure application, which may cause the slightly higher emissions in March and April in Oukoop compared to Stein. Ditches and ditch edges together emit 60% and 68% of the total terrestrial emission in Stein and Oukoop, respectively (Fig. 3). Average flux values were not significantly different between Oukoop and Stein. In the ditch edges highest maximum values were observed in the spring period in Oukoop and in the summer period in Stein (365 and 118 mg $m^{-2}hr^{-1}$, respectively), the difference between the average edge fluxes of the sites was not significant. At both sites in 2006, 2007 and 2008 ditch emission rates were highest in June, July, August and September with average summer fluxes of 25 and 31 mg $m^{-2}hr^{-1}$ for Oukoop and Stein, respectively. Emission rates varied greatly depending on the time of the year and about 70% of the total annual CH_4 emissions were observed in summer. Plant cover, composition and biomass in both areas were mostly similar, and field fluxes appeared not influenced by differences in vegetation.

Driving variables

Methane emission was found to be correlated with several parameters (Table 2), with temperature being to be the most important driver for CH_4 emission in all three landscape elements for both Oukoop and Stein. When pooling water temperatures into classes, ln-transformed CH_4 emissions ($ln(CH_4)$) and water temperature in ditches showed a strong positive correlation in both sites ($r^2=0.996$; $P<0.01$; and $r^2=0.947$; $P<$
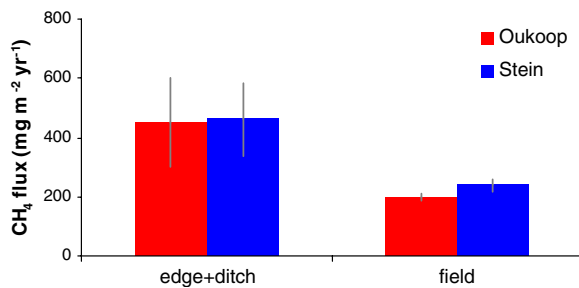

Fig. 3 CH_4 emissions from the different landforms for Oukoop (*red*) and Stein (*blue*) averaged over 2006, 2007 and 2008

Table 2 Matrix of Pearson correlations (*r*) of ln transformed methane emissions and related parameters for the different landscape elements in Oukoop (intensively managed) and Stein (extensively managed) measured by chambers (left) and eddy covariance (right)

	Tsoil	Tair	Moist.	WT	Twater	pH	EC	Tsoil	WT	U
Oukoop chamber measurements										
Field	0.265** (n=195)	0.545** (n=134)	-0.235* (n=119)	0.266[5] (n=40)						
Edge	0.397** (n=80)	0.350* (n=74)	-0.237* (n=73)							
Ditch		0.422** (n=90)			0.478** (n=97)	0.173[1] (n=30)	0.503***[3] (n=26)			
Oukoop EC measurements								0.481** (n=2540)	-0.081[5] (n=77)	0.063**[5] (n=2545)
Stein chamber measurements										
Field	0.474** (n=186)	0.279* (n=190)	-0.166* (n=146)	0.177[5] (n=36)						
Edge	0.500** (n=64)	0.473* (n=60)		0.05 (n=59)						
Ditch		0.424** (n=59)			0.496** (n=76)	0.035[2] (n=30)	-0.072[4] (n=30)			
Stein EC measurements								–	–	–

Tsoil: soil temperature; *Tair*: air temperature; *Moist*: soil moisture; *WT*: water table; *U*: wind velocity.

* or ** statistically significant at $P<0.05$ and $P<0.01$, respectively.

1. range 6.6–7.5; 2. range 6.6–7.4; 3. range 430–650; 4. range 140–346.
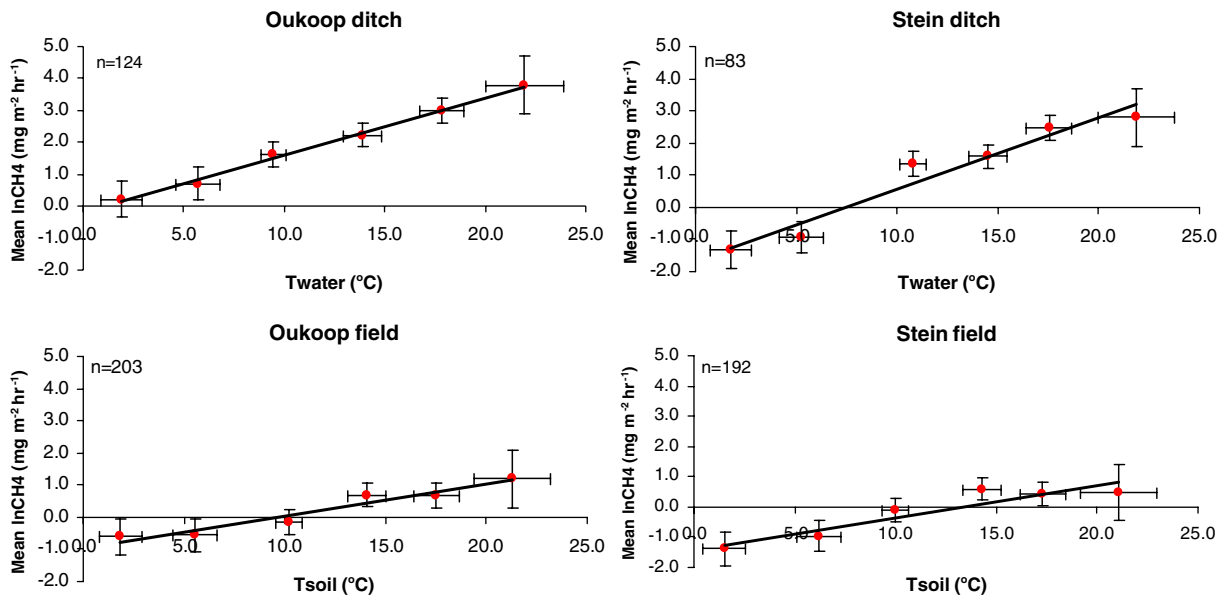
5. Corrected for temperature

Fig. 4 The dependency of ln transformed CH_4 fluxes (mg m^{-2}hr^{-1}) on temperature (°C) in ditches and fields in Oukoop (*left*) and Stein (*right*). Temperatures are pooled. The x-error bars represent the standard deviation of the temperature per class and the y-error bars represent the standard deviation of the ln(CH_4) flux

0.01 for Oukoop and Stein, respectively; Fig. 4). The ln (CH_4) emission in fields was strongly correlated with soil temperature (r^2=0.939; P<0.01; and r^2=0.865; P< 0.01, for Oukoop and Stein respectively; Fig. 4). For ditch edges the r^2 was 0.941 (P<0.01) and 0.861 (P< 0.01) for Oukoop and Stein, respectively.

Correlation of field CH_4 emissions with soil moisture were significant (P<0.05) in both the intensively and the extensively managed sites (Table 2), but when using non-linear multiple regression with temperature as explanatory variable, adding moisture did not significantly improve the predictive power of the regression equation. However, comparing monthly datasets revealed an exception for April in 2006 and 2007, when soil moisture was a stronger predictor than soil temperature for ln(CH_4) at both sites. The water table did not show a correlation with ln(CH_4) neither measured by eddy covariance in Oukoop nor measured by chambers in Stein (Table 2). Eddy covariance measurements show that after temperature correction variability in fluxes over the total area seem to be significantly correlated to wind velocity (Table 2). However, because fluxes measured by eddy covariance are integrated over a large area it is not clear if this dependence on turbulence appears in fields, edges, ditches or in a combination of these landscape elements. Ditch water temperature and electrical

conductivity (*EC*) in Oukoop were positively correlated with ln(CH_4) fluxes and *pH* was not (Table 2). Correlation statistics of chamber measurements (over three years) and eddy covariance measurements (over three months) are given in Table 2.

Water temperature was the main driving variable for CH_4 emission in ditches and soil temperature in soils and therefore, water and soil temperature based regressions were used to estimate annual CH_4 balances.

Annual terrestrial methane balances

To estimate annual terrestrial CH_4 balances over 2006–2008, we used non-linear regression with temperature as explanatory variable

$$F_{CH_4} = e^{a+bT} \qquad (1)$$

as described by Schrier et al. (accepted AFM) where F_{CH4} is the CH_4 flux (mg m^{-2}hr^{-1}) measured by the chamber, T is the temperature of soil or water (°C) and a and b are the coefficients which were derived for each landscape element using the measured temperatures and CH_4 fluxes. Uncertainties in the chamber based regressions were temperature dependent and were different for Oukoop and Stein and for each landform. Average daily uncertainty was about ±60%

of the average flux. To further evaluate the reliability of the use of day-time measurements for upscaling to 24-hour fluxes, diurnal variation of CH_4 fluxes was tested using an independent continuous eddy covariance dataset of Kroon et al. (2007). Residual fluxes $\ln(F_{Res})$ (in mg m^{-2} hr^{-1}) were determined after CH_4 fluxes as measured by eddy covariance $\ln(F_{EC})$ (in mg m^{-2} hr^{-1}) were corrected for temperature dependency using

$$\ln(F_{Res}) = \ln(F_{EC}) - (a + bT_{soil}) \qquad (2)$$

with $a = -1.8$, $b = 0.17$ and T_{soil} = soil temperature (°C). The residual ln-fluxes were normally distributed (data not shown) and did not differ significantly between day and night (Fig. 5).

Half hourly soil temperature and water temperature data and equation 1 were used to estimate half hourly CH_4 fluxes for Oukoop and Stein. Because fluxes were significantly different between the landforms, daily emissions were estimated per landscape element and multiplied by the area occupied by the landscape element, thus providing a spatially integrated daily flux (Fig. 6). Total terrestrial modelled fluxes ranged from 203 (±48%) to 146 (±60%) kg ha^{-1}yr^{-1} for Oukoop and from 180 (±54%) to 157 (±63%) kg CH_4 ha^{-1}yr^{-1} for Stein. Methane fluxes did not differ significantly between Oukoop and Stein and did not differ significantly between years. Estimates of cumulative fluxes per site and per year are given in Table 3.

Discussion and conclusions

The objective of this research was to investigate the influence of reduced agricultural activity on the CH_4 balance in two distinct areas. Therefore, the CH_4 emission from a drained, intensively managed peat area was compared to the CH_4 emission from a drained, extensively managed peat area.

First, the spatial and temporal variation of fluxes was investigated and a regression based approach was used to get spatially integrated annual CH_4 emissions. Both areas were stratified into fields, ditches and ditch edges and in both sites the permanently water-filled, 30–60 cm deep ditches and ditch edges turned out to be CH_4 hotspots that together emit 60% and 68% of the total terrestrial emission in Stein and Oukoop, respectively. Apparently, in the procedure of upscaling of the chamber based fluxes to landscape scale it is of great importance to determine the flux associated with each landscape element because they contribute significantly different to the CH_4 balance.

The edges of the ditches were saturated for most of the year, with soil moisture contents >60%. These conditions can give rise to a differently vegetation than in the drier fields and in some places *Iris pseudacorus* and *Typha angustifolia* are present. These aerenchymatic plants may cause additional emissions in the edges because CH_4 diffuses rapidly through their stems (e.g. Hendriks et al. 2007).

The CH_4 emission rates from all three landscape elements vary seasonally. In the extensively managed site, high CH_4 emissions were concentrated in the summer period, while in the intensively managed site they were concentrated in early spring and summer, partly associated with field applications of slurry. Van den Pol-van Dasselaar et al. (1999) also reported higher CH_4 emissions after manure application suggesting the combination of higher temperatures in
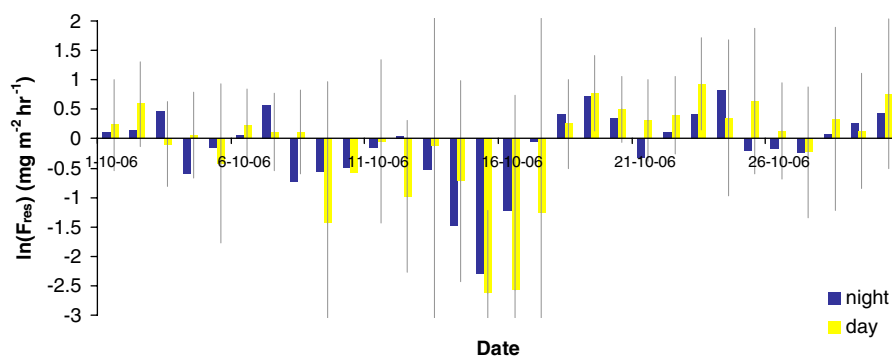

Fig. 5 Day/night dynamics of CH_4 fluxes represented by the residual fluxes $\ln(F_{Res})$ after correction for temperature by $\ln(F_{Res}) = \ln(F_{EC}) - (a + bT_{soil})$ for October 2006 based on eddy covariance flux measurements given in Kroon et al. (2007). Error bars show the uncertainty in the mean residual CH_4 flux given by $2\sigma_{\ln(F_{res})}/\sqrt{n}$ with σ the standard deviation
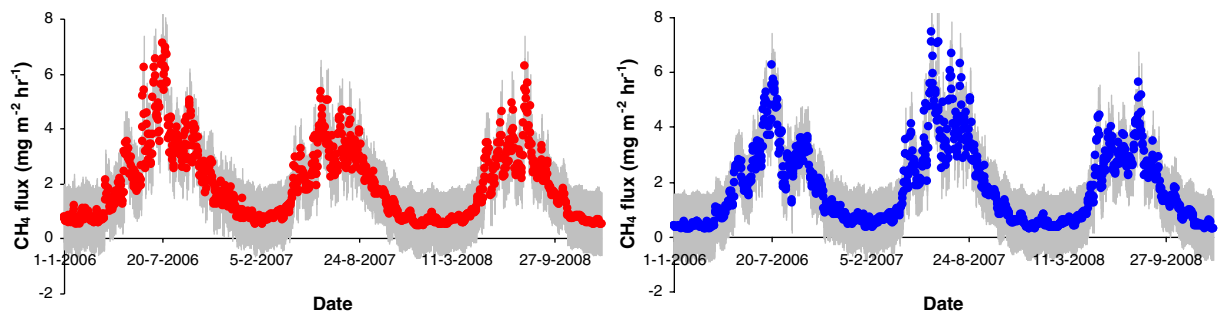
Fig. 6 Time series of upscaled daily spatially integrated CH_4 fluxes in Oukoop (*left*) and Stein (*right*) during the period 1 January 2006 to 31 December 2008. The temperature depen- dent uncertainty band around the dotted line represents plus and minus one standard error for mean prediction, based on the regression analyses, and calculated for each day

summer, wet soil, the application of easily decompos- able organic material and the anaerobic conditions in the slurry as the reason for enhanced CH_4 production. In both sites, over 70% of the total terrestrial CH_4 flux is emitted in summer. The exceptionally high emission peaks from ditches (up to 800 mg $m^{-2}hr^{-1}$ in the summer) may have resulted from ebullition events, during which CH_4 quickly passes through the top layer in the water column. These events mainly occurred when both the water temperature and the wind velocity were high. Ebullition can play an important role during turbulent conditions when bubbles are triggered to escape from the ditch bottom and also low air pressure can cause an increase in ebullition (Hendriks et al. 2008). Besides, during turbulent conditions the aquatic boundary layer thickness is decreased and the potential diffusion rate increases (Kremer et al. 2003; Minkkinen and Laine 2006).

Because an integration-based approach may lead to overestimation due to exceptionally high emissions eg. in the summer months, a regression based approach was used to calculate annual CH_4 fluxes (eg. Mikkelä et al. 1995; Chanton et al. 1995). Therefore, we aimed to find empirical relationships that describe the CH_4 emissions from the landscape elements of the two drained peat areas and we found temperature to be the main driver. Except for temper- ature, no other measured variables did contribute

significantly to the predictive power of the chamber based regression. Electrical conductivity was signifi- cantly correlated to CH_4 emission from ditches, but to less data was available to include this in the regression. The only month for which we found a strong significant correlation between volume fraction of water in the soil and CH_4 emission rates was April— the period when the field begins to dry out after being waterlogged in winter and when air temperature may rise rapidly from 10 to 25°C. Water table did not influence CH_4 emissions significantly, but the highest emissions occurred at intermediate and sometimes high water tables. In the study areas the water table fluctuated seasonally and within seasons also due to rainfall and polder level regulation by the Dutch water board with high (−15 cm) average water table depths in winter and low (−50 cm) in summer in Stein. In Oukoop water tables depths were low (−65 cm) in summer and high (−20 cm) in winter, and in the winter period perched water tables occurred after heavy rains. Most strong correlations between water table and CH_4 emission in other studies have been found at water tables between 0 and 20 cm below field level (eg. Furukawa et al. 2005; Hargreaves and Fowler 1998; Strack et al. 2004). The mostly lower water table (>20 cm below field level) in our site could be the cause for the lack of correlation between water table and CH_4 emission.

Table 3 Mean soil temper- atures, water temperatures (°C) and temperature based estimates of annual terrestrial methane emissions (kg CH_4 ha^{-1}) for the intensively (Oukoop) and extensively (Stein) managed areas

	2006	2007	2008
Tsoil	10.5	10.5	10.4
Twater	10.9	12.6	12.6
Terrestrial CH_4emission Oukoop	203 (±48%)	162 (±60%)	146 (±60%)
Terrestrial CH_4emission Stein	157 (±63%)	180 (±54%)	163 (±59%)

Table 4 Comparison between the CH_4 emission rates in this study and the CH_4 emission rates reported in other studies on peatland ecosystems. Mean CH_4 emission rates are in mg CH_4 $m^{-2}hr^{-1}$ and the three last columns represent the landscape elements

References	Ecosystem	Field	Edge/ saturated land	Ditch/pond
Minkkinen and Laine (2006)	Boreal fen	−0.04–0.04	–	15.72 up to 25 in summer
Hendriks et al. (2007)	Eutrophic fen abandoned agriculture	1.6	15.3	5.6
Bubier et al. (1993)	Boreal fen	0.0–1.0	–	5.8 up to 38.2 in summer
Bellisario et al. (1999)	Less eutrophic fen	1.0–10.0	–	–
Pelletier et al. (2007)	Boreal fen	0.1–0.9	1.2–8.2	–
Liblik et al. (1997)	Boreal fen	–	2.0–9.2	–
Van den Pol-van Dasselaar et al. (1998b)	Less eutrophic fen	0.9–2.3	11.8	–
Waddington and Day (2007)	Less eutrophic fen	–	–	2.9
Adrian et al. (1994)	Eutrophic aquifer	0.0–8.0	–	
Huttunen et al. (2003)	Boreal fen	–	–	up to 8.0
Hamilton et al. (1994)	Less eutrophic fen	–	–	4.6–7.5
Chanton et al. (1993)	Less eutrophic fen	–	5.3–12.4 (aerenchym plants)	–
Schrier et al. (this study)	Eutrophic fen (intensively managed)	0.7–0.8	4.8–6.0	4.5–7.0
Schrier et al. (this study)	Eutrophic fen (extensively managed)	0.8–0.9	2.7–4.4	4.5–5.3

Eddy covariance measurements showed that no significant differences in CH_4 flux occurred between day and night after correction for temperature. Thus, empirical relations based on temperature can be used to predict 24-hour fluxes of CH_4 per landscape element. The predictions of monthly to annual CH_4 emission have found to be in good agreement with values as measured by eddy covariance (Schrier et al, accepted AFM). However, considering the daily variability in CH_4 fluxes a better understanding of the influence of variables such as wind, precipitation, air pressure and application of manure and fertiliser on CH_4 emission is needed.

The measurements showed that both areas in this study are a net terrestrial source of CH_4 with annual regression-based means ranging from 146 to 203 kg ha^{-1} for Oukoop and from 156 to 180 kg ha^{-1} for Stein. These values are compared to emissions found in other managed and unmanaged peatland ecosystems (Table 4). Van den Pol-van Dasselaar et al. (1998a) studied CH_4 emissions in peat soils in a nature reserve elsewhere in the Netherlands and reported also a large spatial variability. Though the emission values in fields were quite similar to ours, the emission rates they found in saturated land were higher.

The field fluxes found in this study (water tables of 20–60 cm below field level) are lower compared to fluxes found in some other eutrophic systems with water tables between 0 and 20 cm below field level for most of the year (eg. Bellisario et al. 1999; Hendriks et al. 2007; Furukawa et al. 2005; Hargreaves and Fowler 1998; Strack et al. 2004). The extremely high emission rates from ditches found by Minkkinen and Laine (2006) and by Bubier et al. (1993) were similar to the extreme values we

Table 5 Estimates of annual terrestrial and annual total (terrestrial + farm based) methane emissions (kg ha^{-1}) for the intensively (Oukoop) and extensively (Stein) managed areas

	2006	2007	2008
Terrestrial CH_4emission Oukoop	203 (±48%)	162 (±60%)	146 (±60%)
Total CH_4emission Oukoop	460 (±48%)	419 (±60%)	403 (±60%)
Terrestrial CH_4emission Stein	157 (±63%)	180 (±54%)	163 (±59%)
Total CH_4emission Stein	329 (±63%)	352 (±54%)	335 (±59%)

found at turbulent water conditions in summer, but average summer fluxes of 18.72 mg m^2 hr^{-1} were higher.

The total ecosystem CH_4 emissions for both areas includes besides the terrestrial emissions also emissions from the farm itself. We estimated the total farm emissions (Q) for the farm located in the Oukoop area using a general accepted emission factor approach as described by Hensen et al. (2006) by

$$Q = N_{Dairy}E_d + N_{Heifer}E_y + N_{Calve}E_c$$
$$+ A_{manure}E_m + A_{farmyardmanure}E_f \qquad (3)$$

with N the number of animals and with emission factors for dairy cows (E_d), heifer (E_y), calves (E_c), manure (E_m) and farmyard manure (E_f): 274, 170, 48, 53 and 40 g CH_4 day^{-1} animal^{-1} or m^{-3} for farm yard manure, respectively (Sneath et al. 2006; van Amstel et al. 2003).

The Oukoop farm owned during the measurement period 50 ha land with 65 adult cows, 20 heifer, 10 calves and had a storage of 700 m^3 slurry and no other farm yard manure. The total farm emissions were estimated at 429 kg CH_4 ha $^{-1}$yr^{-1}. In addition, this farm used about 20 ha extra land in the Stein area for grass production. The grass is being removed to feed cows in the Oukoop area, and thus the estimated total farm emissions have to be distributed by approximately 0.4 and 0.6 over the extensively managed area and the intensively managed area, respectively. The mean total CH_4 emissions (terrestrial + farm based) for Oukoop and Stein are given in Table 5.

To investigate the influence of agricultural activity on the CH_4 balance, CH_4 fluxes of our two managed sites were also compared to a former agricultural peat site which was converted to a nature reserve 11 years ago by raising the water table (>20 cm below field level for most of the year) and cessation of any agricultural management (Hendriks et al. 2007). Without farm based emissions, the intensively managed area and extensively managed area are a net source of CH_4 ranging from 146 to 203 kg ha^{-1} and from 156 to 180 kg ha^{-1}, respectively and the natural site is a larger source of 417 kg ha^{-1}. When we took account of the farm-based emissions, the estimated total annual CH_4 flux was 427 kg ha^{-1} in the intensively managed site and 339 kg ha^{-1} in the extensively managed site averaged over the three years compared to 417 kg ha^{-1} in the natural site of Hendriks et al. (2007). This

suggests that transformation of intensively managed agricultural land to nature development will lead to an increase in terrestrial CH_4 emission, but not by definition lead to a significant increase in CH_4 emission when farm based emissions are included.

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