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D. M. D. Hendriks, J. van Huissteden, A. J. Dolman, M. K. van Der Molen. The full greenhouse gas balance of an abandoned peat meadow. *Biogeosciences Discussions*, 2007, 4 (1), pp.277-316. hal-00297865

**HAL Id: hal-00297865**

**<https://hal.science/hal-00297865>**

Submitted on 18 Jun 2008

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# The full greenhouse gas balance of an abandoned peat meadow

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Received: 20 December 2006 – Accepted: 26 January 2007 – Published: 31 January 2007

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## Abstract

Globally, peat lands are considered to be a sink of CO<sub>2</sub>, but a source when drained. Additionally, wet peat lands are thought to emit considerable amounts of CH<sub>4</sub> and N<sub>2</sub>O. Hitherto, reliable and integrated estimates of emissions and emission factors for this type of area have been lacking and the effects of wetland restoration on methane emissions have been poorly quantified. In this paper we estimate the full GHG balance of a restored natural peat land by determining the fluxes of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O through atmosphere and water, while accounting for the different GWP's.

This site is an abandoned agricultural peat meadow, which has been converted into a wetland nature reserve ten years ago by raising the water level. GHG fluxes were measured continuously with an eddy-correlation system (CO<sub>2</sub>) and flux chamber measurements (CH<sub>4</sub> and N<sub>2</sub>O). Meteorological and hydrological measurements were done as well. With growing seasons of respectively 192 and 155 days, the net annual CO<sub>2</sub> uptake was 276±61 g C m<sup>-2</sup> for 2004 and 311±58 g C m<sup>-2</sup> for 2005. Ecosystem respiration was estimated as 887±668 g C m<sup>-2</sup> for 2004 and 866±666 g C m<sup>-2</sup> for 2005. CH<sub>4</sub> fluxes from water, saturated land and relatively dry land varied: total annual CH<sub>4</sub> fluxes are 10.4±19.2 g C m<sup>-2</sup> yr<sup>-1</sup>, 101 g C m<sup>-2</sup> yr<sup>-1</sup>±30 and 37.3±10.9 g C m<sup>-2</sup> yr<sup>-1</sup>, respectively, and a annual weighed total CH<sub>4</sub> emission of 31.27±20.44 g C m<sup>-2</sup> yr<sup>-1</sup>. N<sub>2</sub>O fluxes were too low to be of significance. The carbon-balance consists for the largest part of CO<sub>2</sub> uptake, CO<sub>2</sub> respiration and CH<sub>4</sub> emission from wet land and water. CO<sub>2</sub> emission has decreased significantly as result of the raised water table, while CH<sub>4</sub> fluxes have increased. In global warming potentials the area is a very small sink of 71 g CO<sub>2</sub>-equiv m<sup>-2</sup> (over a 100-year period).

## 1 Introduction

Human activities have caused an increase in atmospheric concentrations of greenhouse gases since the pre-industrial era by 30% for CO<sub>2</sub>, by 150% for CH<sub>4</sub> and by

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17% for N<sub>2</sub>O (IPCC TAR, 2001). The European land surface is thought to be absorbing a significant amount of the current industrial CO<sub>2</sub> emissions (Janssens et al., 2003) and to be releasing over 40% of the European CH<sub>4</sub> and N<sub>2</sub>O emissions. However, reliable estimates of emissions and emission factors are still lacking.

5 Unlike industrial emissions, emissions related to land use are controlled by a combination of biological, climatological and management factors and show large spatial and temporal variability. To be able to understand the effects of the rising greenhouse gas concentrations in the atmosphere as well as the variability and vulnerability of the natural carbon cycle, knowledge of the emission and uptake of carbon by terrestrial  
10 surfaces is necessary.

Peat lands in Europe have formed one of the major sinks of atmospheric CO<sub>2</sub> since the last glacial maximum. This is the result of their ability to accumulate organic matter at a higher rate than decomposition takes place, mainly as a result of high water tables and therefore anaerobic conditions. Due to these generally wet and anaerobic  
15 conditions peat lands are also significant emitters of the greenhouse gas CH<sub>4</sub> and sometimes N<sub>2</sub>O (Christensen et al., 2007<sup>1</sup>). The Global Warming Potentials (GWP) of CH<sub>4</sub> (~23, over 100 years) and N<sub>2</sub>O (~300, over 100 years) are significantly higher than that of CO<sub>2</sub> (1 by definition).

Over the last 100 years many peat areas in Europe have been transformed into agricultural land with artificially low water tables. This resulted in an increase of peat  
20 oxidation and peat ecosystems have become a strong source of CO<sub>2</sub> (Langeveld et al., 1997). Peat oxidation can be reduced and peat areas can be turned into sinks of CO<sub>2</sub> if water levels are increased as suggested by a host of literature (e.g. Burgerhart, 2001; Van den Bos, 2003). In the western part of the Netherlands 10% of the land  
25 (160 000 ha) consists of peat soils (Fig. 1). Currently, most of these soils are managed and have artificially low water tables. Plans exist to reconvert these agricultural areas into wetland nature by raising the water tables and reducing management. This change

<sup>1</sup>Christensen, T. R., Friborg, T., Freibauer, A., et al.: Observations and status of peatland greenhouse gas emissions in Europe, in preparation, 2007.

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will probably turn the area from a CO<sub>2</sub>-source in a CO<sub>2</sub>-sink and alter the emissions of CH<sub>4</sub> and N<sub>2</sub>O.

To compile a full greenhouse gas balance of a peat land and to understand the mechanisms and processes that affect this balance, comprehensive and long term measurements are needed. All components of that balance should be studied, also the lateral and vertical transport of methane and of dissolved organic carbon and methane out of the system. Currently, only few year-round records of CO<sub>2</sub>-measurements in peat lands are available and for CH<sub>4</sub> and N<sub>2</sub>O no year round measurements exist at all. Besides, very few comprehensive integrated measurement campaigns have been carried out (Soussana, 2007<sup>2</sup>; Christensen et al., 2007<sup>1</sup>).

This paper describes the full spectrum of greenhouse gases in an abandoned peat meadow area in the western part of the Netherlands which has been transformed from an agricultural area into a wetland nature reserve by raising the water level. Our main goal is to quantify all sinks and sources of greenhouse gases in the area year round and to assess the full greenhouse gas balance. This implied, estimating not only the vertical losses and gains through atmosphere, but also vertical and lateral losses of dissolved gases through water and taking into account the different GWP's.

## 2 Site description

The Horstermeer site is located on former agricultural land in a drained natural lake in the central part of the Netherlands (52.144 N, 5.043 E, Fig. 1). The research site has been taken out of agricultural production more than 10 years ago, and has developed into semi-natural grassland. The two meter thick soil consists of peat, overlain with organic-rich lake deposits (Table 2) and is overlying eolian sands of Pleistocene age. After the site has been taken out of agricultural production, the ditch water table

<sup>2</sup>Soussana, J. F.: Towards a full accounting of the greenhouse gas balance of European grasslands, in preparation, 2007.

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has been raised to approximately 10 cm below the land surface. Large parts of the Horstermeer polder are subject to strong groundwater seepage from surrounding lake areas and Pleistocene ice pushed ridges. At the measurement location seepage is largely reduced and even infiltration occurs as a result of the high water table. The surface of the research area consists for 10% of ditches, for 20% of land that is saturated year-round (mostly alongside the ditches) and for 70% of relatively dry land with a fluctuating water table (between 0 to 40 cm below the soil surface) and an aerated top-layer. Management consists only of regulation of the ditch water table; no cattle grazing or harvesting takes place, the only removal of vegetation consists of sporadic grazing by roe deer. Vegetation consists of different types of grasses (dominant species *Holcus lanatus*, *Phalaris arundinacea*, *Glyceria fluitans*), horsetail (*Equisetum palustre*, *fluviatile*) reeds (*Phragmites australis*, *Typha latifolia*) and high forbs (*Urtica dioica*, *Cirsium arvense*, *palustre*). Main characteristics of the site are given in Table 1.

### 3 Methods and instrumentation

All measurements are carried out over the period 1 January 2004 till 31 December 2005, unless mentioned differently.

#### 3.1 Hydrological measurement techniques, acquisition and data processing

Hydrological measurements included water table recordings of the pressure heads using pressure sensors installed in access tubes in the clayey peat top layer at two locations and in the Pleistocene sand aquifer at one location. Also, the water level in the drainage ditch was measured with a pressure sensor in an access tube. Using the level of the ditch water relative to the height of the overflow weir, discharge could be calculated continuously (Van de Griend, 1989). Water levels were logged on an hourly basis and are all set to the same reference level before further analysis. Outliers and spikes are removed from the dataset. Finally gaps are filled with average values over

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the surrounding time period. No gaps larger than 24 h were encountered.

Water samples were taken from the pore water in the clayey peat, the groundwater from the sand aquifer and from the ditch water. Sampling was done using glass filters, installed in the soil or ditch water at 0.2 m depth intervals, and connected to the surface using small diameter teflon tubes. In the soil these filters were installed in a small diameter borehole, separated from each other by bentonite plugs. The soil filters were installed at three locations, the ditch filters at two locations. Samples were taken using a syringe for drawing up the water, after which the sampling tube was connected to a vacuum exetainer using a three-way stopcock. The samples were analyzed by gas chromatography of the gas-filled headspace of the exetainers. The total CH<sub>4</sub> concentration in the sampled volume was calculated using the gas-water solubility coefficient.

### 3.2 Meteorological measurement techniques, acquisition and data processing

Eddy-correlation measurements of CO<sub>2</sub> concentration, water vapour, wind speed and air temperature were performed with a Licor 7500 open path infrared gas analyser (LICOR Lincoln, NE, USA) and a Windmaster Pro 3 axis Ultrasonic Anemometer (GILL Instruments Limited, Hampshire, UK) directed into the main wind direction. Licor and Anemometer are installed at 4.3 m above the surface. Data were logged digitally on a handheld computer at a rate of 10 Hz (Van der Molen et al., 2006). The EUROFLUX methodology (Aubinet et al., 2000) was applied to the eddy covariance data to calculate the fluxes of momentum, sensible and latent heat and CO<sub>2</sub> on a thirty minute basis. The method of Nakai et al. (2006) was used to apply the angle of attack dependent calibration (Gash and Dolman, 2003; Van der Molen, 2004).

Additional micrometeorological measurements were executed at a tower close by the eddy-correlation set up. Air pressure was measured (SensorTechnics pressure transducers, model 144SC1216BARO) as well as wet and dry bulb temperatures (Fast response Chromel-Constantan thermocouple with an effective diameter of 0.2 mm, made at the Vrije Universiteit Amsterdam). Incoming and reflected shortwave radiation (Kipp & zonen, Delft, the Netherlands) and longwave radiation (Eppley Pyrgeometers,

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Eppley laboratory Inc., Model Precision Infrared Radiometers (PIR)) were measured. As backup of these radiation balance measurements the net radiation was measured (Campbell Scientific, Q10). All radiometers are installed at a height of 2.5 m (except incoming long wave radiation at 1.6 m height). Wind direction was monitored with a wind vane (Campbell Scientific Ltd, W200P) on top of the tower (4.6 m height) and wind speed with cup anemometers (Vector Instruments model A100M/A100ML) at 3.0 and 2.0 m height. Soil temperature was measured at various depths by thermistor probes (Campbell Scientific Ltd, model 107). The canopy skin temperature was measured using infrared thermometers (Everest, model 4000 BL). Precipitation was monitored with a tipping bucket rain gauge (Campbell Scientific Ltd, model ARG100), with a resolution of 0.2 mm, which was installed at 1.05 m above the ground. The instruments were sampled with a data logger (Campbell Scientific, model 23X) every 30 s (2 s for thermocouple) and the data stored as 30 min averages and standard deviations.

A quality check was performed during which all outliers and unrealistic values were removed from all eddy covariance data and meteorological data (see Table 3). Next, gap filling with  $u_*$  correction was done through methods that are similar to Falge et al. (2001), with consideration of both the co-variation of fluxes with meteorological variables and the temporal auto-correlation of the fluxes (Reichstein et al., 2005).

### 3.3 Soil flux measurement techniques, acquisition and data processing

Closed flux chamber measurements of  $\text{CH}_4$  and  $\text{N}_2\text{O}$  fluxes were performed using a Photo Acoustic Field Gas-Monitor (INNOVA 1312) connected with tubes to closed, dark chambers (non-transparent PVC, 45×45×12 or 30 cm). A fan was installed in the chambers to mix the air and increase the representativeness of the measurements. Since the gas monitor software does not compensate fully for cross-interference of  $\text{CO}_2$  and water vapour at high concentrations, the air was filtered before measurement with a Soda lime and a silica gel filter, which respectively remove  $\text{CO}_2$  and reduces water vapour concentrations. For each flux measurement five measurements were made at two-minute intervals. On land, at eight fixed locations stainless steel frames

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with a water-filled gutter were used to seal the chamber from the ambient air during measurement. To prevent vegetation disturbance, chambers with a height of 30 cm are used. Vegetation was not removed preceding the flux measurements, to prevent disturbance of CH<sub>4</sub> fluxes through plants and to maintain vegetation characteristics inside the chamber locations similar to those outside. In this way the representativeness of the chamber measurements for a larger area was maintained. During each measurement soil temperature and local water table were determined. On the ditch water surface measurements were done at three locations in 2005 and 2006. For this purpose a rectangular floater was used allowing the chamber to rest on the water.

The series of concentration measurements done with the flux chamber technique are calculated into fluxes by determining linear regression lines from the concentration changes over time. Air pressure and temperature from the moment of measuring are taken into account in the calculations. Data were checked for outliers that may result from instrument error or chamber leakage. Fluxes of N<sub>2</sub>O appeared to be negligible small with respect to the GHG balance and are therefore not considered in further analyses.

### 3.4 Vegetation and soil analyses

The vegetation was surveyed in 2005 and consisted of vegetation classification and air photo analysis. Biomass has been determined by harvesting in 40×40 cm squares and separating dead and living biomass.

Soil analysis has been performed on samples obtained by 5 cm<sup>3</sup> sample rings for undisturbed sampling. Permeability was determined with a permeameter using the falling head method. The organic matter content of these samples has been determined using thermogravimetry. Using an automatic oven (Leco TGA-601), samples were stepwise heated up to 1000°C in an oxygen atmosphere, with heating plateaus at 105°C and 500°C.

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## 4 Results

### 4.1 The water balance

Water enters the system either as precipitation or as groundwater seeping in the ditches. Losses consist of evaporation and runoff over a fixed weir as well as some infiltration of soil water to the Pleistocene sand aquifer underlying the clayey peat. Since the permeability of the peat layer is very low ( $0.027 \text{ m day}^{-1}$ ), we assume that a significant part of the vertical flow in the soil water is actually follows sub-horizontal flow paths. Using the precipitation data, water levels and evaporation data (observed by the eddy covariance) from 25 May 2005 to 25 May 2006 the storage of water per hectare in the soil of the Horstermeer over this year is calculated using the following water balance equation:

$$P - VFD - VFL - Q - E = \text{Storage} \quad (1)$$

Where:

$P$  = precipitation;

$VFD$  = vertical flow in ditches;

$VFL$  = vertical flow on land;

$Q$  = discharge;

$E$  = evaporation from land and water.

The precipitation of  $676 \pm 68 \text{ mm}$  over the year is nearly equalled by the transpiration ( $660 \pm 66 \text{ mm}$ ; Table 4), but is low compared to the average annual rainfall of 775–800 mm in the area (source: KNMI). Seepage is the dominant vertical flow in the ditches, while on land infiltration of soil water prevails. Taking into account the relative surface area of land and ditchwater, the net vertical flow (seepage) over the whole area is  $698 \pm 140 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ . The runoff from the research site consists only of discharge over the weir, which is  $1.730 \pm 173 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ . The maximum total uncertainty in the measurements is estimated at  $1.649 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ , which is large compared to the estimated storage of  $876 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ .

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## 4.2 Performance of the eddy-correlation set-up

Spectral analysis of the fluctuations of  $w$ ,  $T$  and  $\text{CO}_2$  in the atmosphere associated with turbulent transport provide a useful tool for assessing the reliability of flux measurements (Stull, 1988; Kaimal and Finnigen, 1994). We determined spectra of the wind, temperature and  $\text{CO}_2$ -concentration as well as co-spectra of temperature fluxes and  $\text{CO}_2$  fluxes using a Fast Fourier Transform (Fig. 2). 10 Hz eddy-correlation data of seven 30 min periods in springtime 2005 are used for this purpose. The power spectra and co-spectra are averaged and plotted over their frequency at log-log scale. Spectra for  $w$ ,  $T$  and  $\text{CO}_2$  have corresponding slopes showing a proportionality of  $-2/3$ , which is in agreement with the power law in the inertial sub-range (Eugster and Senn, 1994). Under ideal circumstances the shapes of the  $w'CO_2'$  and  $w'T'$  spectra should be similar. Here the co-spectra show comparable shapes and have corresponding slopes showing a proportionality of  $-2/3$ . The power spectrum of the  $\text{CO}_2$  time series, the co-spectrum of vertical wind and  $\text{CO}_2$  as well as the co-spectrum of vertical wind and air temperature indicate that the eddy covariance set-up records nearly all the fluctuations in  $\text{CO}_2$  associated with turbulent transport (Goulden et al., 1996), and that the measurements are taken in a well established surface layer.

In the energy balance, the ground heat flux ( $G$ ) in the clayey peat soil (Parmentier et al., 2007<sup>3</sup>) is relatively important compared to the latent and sensible heat fluxes ( $LE$  and  $H$ ) and amounts to over half of the energy in the net radiation (Fig. 3). The closure of the energy balance is good (Fig. 4), but the values of “ $LE+H+G$ ” are relatively high at sunny days around noon, resulting in a regression line with a slope of more than 1. The high values are mainly the result of very high ground heat fluxes. This may be caused by the fact that the ground heat flux is overestimated when the topsoil receives a lot of sunlight and becomes overheated. After removing the mid-day data points, the regression line has a slope of 0.996 and an  $R^2$  of 0.82. This implies that the quality of

<sup>3</sup>Parmentier, F. J. W., Hendriks, D. M. D., de Jeu, R. A. M., and van der Molen, M. K.: Evaporation and  $\text{CO}_2$  exchange of a peat bog independent of water table, in preparation, 2007.

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the data from the eddy covariance set-up is very good (Lloyd et al., 1996).

The uncertainty of NEE is based on the percentage of data gaps in the eddy covariance data after performing the quality check and  $u_*$ -correction. KNMI (Royal Dutch Meteorological Institute) data from De Bilt are used to support the gap filling method when necessary. (The distance between the site and the KNMI observation was 20 km.) Uncertainties resulting from the gap-filling procedure are directly proportional to the amount of gaps filled over the measurement period (Falge, 2001). We introduced the maximum error in NEE of  $0.675 \text{ g C m}^{-2}$  per percentage gap-filled per year. The total amount of data gaps was 36.72% for 2004 and 26.37% for 2005, resulting in a maximum error of  $25 \text{ g C m}^{-2} \text{ yr}^{-1}$  and  $18 \text{ g C m}^{-2} \text{ yr}^{-1}$ , respectively. According to Van der Molen et al. (2007)<sup>4</sup> the error introduced by the calculation routines is 13% of the total annual NEE.

### 4.3 Carbon dioxide

The net  $\text{CO}_2$  flux follows a daily pattern with periods of net  $\text{CO}_2$  uptake during daytime and respiration during night time (Fig. 3). In Fig. 6 the  $\text{CO}_2$  fluxes are shown as daily fluxes of  $\text{C-CO}_2$  per  $\text{m}^2$  as well as  $\text{C-CO}_2$  per  $\text{m}^2$  cumulated over a whole year. Over the period from 20 August to 1 October 2004, the quality of the eddy covariance data was insufficient. Over this period of 41 days, the cumulated NEE over the same period in 2005 is used to estimate the cumulated NEE in 2004. The growing season in 2004 (period where NEE is negative) lasts from 7 April to 14 October and has a net uptake of  $339 \text{ g C m}^{-2}$ . The NEE for 2004 was cumulated, resulting in a net annual  $\text{CO}_2$  uptake of  $276 \pm 61 \text{ g C m}^{-2}$ . The growing season in 2005 lasts from 7 April to 8 September and has a net uptake of  $331 \text{ g C m}^{-2}$ , while the annual NEE for 2005 amounts  $311 \pm 58 \text{ g C m}^{-2}$ .

<sup>4</sup>Van der Molen, M. K., Dolman, A. J., Marchesini, L. B., et al.: The carbon balance of the Boreal Eurasia consolidated with eddy covariance observations, Global Change Biology, in preparation, 2007.

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Net eco-system exchange (NEE) is determined directly from the eddy covariance CO<sub>2</sub> flux measurements and is considered to be the sum of the gross eco-system production (GEP) and ecosystem respiration ( $R_{\text{eco}}$ ). Ecosystem respiration (the sum of heterotrophic and autotrophic) can be expressed by its physical relation with soil temperature. Here, the respiration is determined using nightly NEE values ( $SW_{in} < 20 \text{ W m}^{-2}$ ) assuming photosynthesis is absent and the NEE consist only of  $R_{\text{eco}}$ . Next, the soil respiration is described as a function of the soil temperature by using the Arrhenius relation (Lloyd and Taylor, 1994):

$$R_{\text{eco}} = 0.0077 * e^{(0.1415 * T_{\text{soil}})} \quad (\text{error variance} = 0.77 \text{ and } R^2 = 0.5137) \quad (2)$$

This equation results in a partitioning of a annual NEE for 2004 of 276 g C m<sup>-2</sup> in a GEP of 1145±881 g C m<sup>-2</sup> yr and a Reco of 869±668 g C m<sup>-2</sup> yr. The annual NEE for 2005 of 311 g C m<sup>-2</sup> is partitioned in a GEP of 1177±905 g C m<sup>-2</sup> yr and a Reco of 866±666 g C m<sup>-2</sup> yr using the same method (see Fig. 5 and Table 5). Another attempt to partition the NEE fluxes of 2005 was made by using the model of Reichstein et al. (2005). This model uses air temperature to partition the data and results in a partitioning of 311 g C m<sup>-2</sup> yr NEE in a GEP of 1135 g C m<sup>-2</sup> yr and Reco of 823 g C m<sup>-2</sup> yr. The difference between the results of the two methods for flux partitioning is small. Since the first method (using nightly NEE) uses soil temperature instead of air temperature we consider this as a more physically based method as soil temperature is more closely related to  $R_{\text{eco}}$ .

The analyses of soil water, ground water and ditch water for total organic carbon (TOC) show that the highest concentrations of organic carbon are found in the soil water (158±9.5 g C m<sup>-3</sup>, see Table 7). The fluxes of organic carbon by water transport are calculated by multiplying the TOC concentrations in the water with the appropriate water volumes from the water balance. Over the year a net amount of 161±47.5 kg C ha<sup>-1</sup> is transported out of the research area by water fluxes. This transport mainly takes place by flow of soil water to the ditches and infiltration to the groundwater and by discharge of surface water (Hope, 2004; Worrall, 2004; Ding, 2004).

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## 4.4 Methane

On land a total of 200 closed flux chamber measurements were performed on the relatively dry part of the land in the central part of the site, 28 measurements on the saturated part of the land alongside the ditches and 28 measurements on the ditches.

5 Significantly different fluxes are measured at those three land elements and they are therefore considered separately in our further analyses and data processing.

In previous studies relations between soil temperature and CH<sub>4</sub> flux and between soil water level and CH<sub>4</sub> flux were found (Aerts and Toet, 1997; Fiedler and Sommer, 2000; Smith et al., 2004). Statistical analysis of the data shows that in our case the

10 temporal variation of the CH<sub>4</sub> fluxes is significantly correlated with soil temperature, but uncorrelated with water level (Table 6) while water level is significantly correlated with soil temperature. This phenomenon was encountered earlier by Wagner et al. (1999)

in a marshland. We assume that the lack of correlation between CH<sub>4</sub> flux and soil water level is caused by the soil characteristics at our research site. Peaty and clayey

15 soils often contain anaerobe areas above the water level. In those zones in the soil methanogenesis occurs and CH<sub>4</sub> fluxes at the surface can be higher than expected. As a consequence of the low correlation with CH<sub>4</sub> fluxes, soil water levels are not taken into account in the regression analyses of the CH<sub>4</sub> fluxes. The following exponential

20 regression equations describe the CH<sub>4</sub> flux (in mg CH<sub>4</sub>/m<sup>2</sup>/h) for the three land elements:

Dry land:

$$\text{CH}_4 \text{ flux} = e^{(-0.261+0.060 \cdot T_{\text{soil}})} \text{ (error variance} = 1.84 \text{ and } R^2 = 0.086) \quad (3)$$

Saturated land:

$$\text{CH}_4 \text{ flux} = e^{(2.205+0.045 \cdot T_{\text{soil}})} \text{ (error variance} = 0.29 \text{ and } R^2 = 0.243) \quad (4)$$

25 Ditches:

$$\text{CH}_4 \text{ flux} = e^{(0.767+0.079 \cdot T_{\text{soil}})} \text{ (error variance} = 0.29 \text{ and } R^2 = 0.457) \quad (5)$$

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Using these regression equations and continuous soil temperature data, the annual CH<sub>4</sub> flux for the three land elements could be determined. This resulted in annual CH<sub>4</sub> fluxes for 2005 of 10.4±19.2 g C m<sup>-2</sup> yr for the dry land, 101±30 g C m<sup>-2</sup> yr for the saturated land and 37.3±10.9 g C m<sup>-2</sup> yr for the ditches and a weighed total annual CH<sub>4</sub> emission of 31.3±20.4 g C m<sup>-2</sup> yr. The CH<sub>4</sub> fluxes of the dry land have a high variance error and are low compared to the fluxes from the ditches and the saturated land. The CH<sub>4</sub> fluxes of the saturated land are significantly highest and fluxes from all surface types show a clear seasonal trend over the year with the highest fluxes in late spring, summer and early autumn (Fig. 5).

The measurements of soil water, ground water and ditch water of dissolved CH<sub>4</sub> show that the soil water has a very high concentration of dissolved CH<sub>4</sub> (almost 88±11.4 g CH<sub>4</sub> m<sup>-3</sup>) while the ditchwater and groundwater contain relatively little dissolved CH<sub>4</sub> (Table 8) (Hope, 2004; Worrall, 2004; Ding, 2004). Theoretically, the maximum concentration of dissolved CH<sub>4</sub> in water under the conditions of the soil in the Horstermeerpolder is 35 g CH<sub>4</sub> m<sup>-3</sup> (10°C; 2 m deep). Higher concentrations of CH<sub>4</sub> in the soil water causes a gas pressure that is higher than the hydrostatic pressure and therefore gas bubbles will form in the soil (Obdam et al., 2001; Strack et al., 2006). In further calculations this maximum concentration of 35 g CH<sub>4</sub> m<sup>-3</sup> soil water is used. The fluxes of dissolved CH<sub>4</sub> by water transport are calculated by multiplying the dissolved CH<sub>4</sub> concentrations in the water with the appropriate water volumes from the water balance. Over the year a net amount of 16.8±4.7 kg C(CH<sub>4</sub>) per hectare is transported out of the research area by water fluxes. This transport mainly takes place by flow of soil water to the ditches and infiltration to the groundwater and by discharge of surface water.

#### 4.5 A full greenhouse gas balance

All incoming and outgoing carbon fluxes through air and water at the measurement site are taken into account and are upscaled to fluxes per hectare peat meadow per year.

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As mentioned before, the surface of the research area consists for 10% of ditches, for 20% of land that is saturated year-round and for 70% of land with a fluctuating water table and aerated top-layer. This ratio is taken into account while calculating the annual fluxes of CH<sub>4</sub> per hectare. Fluxes are considered in amounts of carbon and also converted to their Global Warming Potential.

The exchange of greenhouse gases through air has a direct effect on the greenhouse gas budget of the local atmosphere. The carbon fluxes with water as transport medium form sources and sinks as well, but when and where they will turn into gaseous state and affect the atmospheric greenhouse gas balance is unknown. Nevertheless the fluxes through water have an indirect effect on the carbon balance by transporting carbon from the system with the runoff and by transporting carbon into or out of the system via the underground, affecting the availability of carbon in the system for exchange with atmosphere. In order to make this distinction between direct and indirect effects on the carbon balance, the direct net carbon flux with atmosphere is therefore considered separately (Table 9), in addition to the total carbon balance where atmosphere and water are both taken into account.

From the total incoming carbon  $1177 \pm 905 \text{ g C m}^{-2} \text{ yr}^{-1}$  (99.4% of all CO<sub>2</sub>-equiv.) enters the system due to accumulation of plant material (GEP), while  $3.3 \pm 0.8 \text{ g C m}^{-2} \text{ yr}^{-1}$  (0.55% of all CO<sub>2</sub>-equivalents) enters the system with groundwater seepage. From the total emitted carbon  $866 \pm 666 \text{ g C m}^{-2} \text{ yr}^{-1}$  (74.4% of all CO<sub>2</sub>-equiv.) leaves the system through ecosystem respiration,  $31.3 \pm 20.4 \text{ g C m}^{-2} \text{ yr}^{-1}$  (22.5% of all CO<sub>2</sub>-equiv.) through emission of CH<sub>4</sub> gas,  $11.4 \pm 2.9 \text{ g C m}^{-2} \text{ yr}^{-1}$  (2.0% of all CO<sub>2</sub>-equivalents) through infiltration of soil- and ditchwater to deeper aquifers and  $9.6 \pm 1.4 \text{ g C m}^{-2} \text{ yr}^{-1}$  (1.2% of all CO<sub>2</sub>-equiv.) through discharging ditch water.

When concerning only fluxes with the atmosphere the area is a considerable carbon sink of  $279 \pm 78 \text{ g C m}^{-2} \text{ yr}^{-1}$ , while it is a smaller GHG sink of  $182 \text{ g CO}_2\text{-equiv. m}^{-2} \text{ yr}^{-1}$  (based on a 100-year time scale) due to the greater GWP of methane. When fluxes through water are added to the balance, the area is a carbon sink of  $262 \pm 84 \text{ g C m}^{-2} \text{ yr}^{-1}$ , and only a small GHG sink of  $71 \text{ g CO}_2\text{-equiv. m}^{-2} \text{ yr}^{-1}$  (see Table 9 and

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Fig. 8).

## 5 Discussion and conclusions

These results show that, with considerable experimental effort, it is possible to estimate a full greenhouse gas balance and its uncertainties for a specific area by measuring fluxes of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O simultaneously, while also paying attention to fluxes of organic carbon and dissolved methane through water and taking into account the different GWP's.

The eddy-correlation system performed well, as shown by the spectra and co-spectra as well as by the closure of the energy balance, and we can put confidence in those results. Using dark soil respiration flux chamber measurements with simultaneous recordings of the soil temperature appeared to be a useful method for determining ecosystem respiration. With growing seasons of, respectively, 192 and 155 days, the net annual CO<sub>2</sub> uptake was 276±61 g C m<sup>-2</sup> for 2004 and 311±58 g C m<sup>-2</sup> for 2005. Ecosystem respiration was estimated using the soil flux chamber measurements and soil temperature as 887±668 g C m<sup>-2</sup> for 2004 and 866±666 g C m<sup>-2</sup> for 2005. NEE of CO<sub>2</sub> at the Horstermeer site is high compared to the average NEE of European peat areas which ranges from 33 g C m<sup>-2</sup> (uptake) for undisturbed peat lands to -188 g C m<sup>-2</sup> (emission) for drained peat lands (Janssens et al., 2003). The high CO<sub>2</sub>-uptake at the site is the result of a combination of the temperate climate, the high water tables and the lack of management. All plant material formed during the long growing seasons (approximately 200 days) can grow to its full size, resulting in a high GEP and remains in situ after dying. The large amounts of respiring plants result in high  $R_{eco}$  during the summer period, while the anaerobic conditions caused by the high water table are unfavourable for oxidation of organic soils and dead plant material.

CH<sub>4</sub> emissions of the area are the net result of methanogenesis in the anaerobic parts of the soil and CH<sub>4</sub> oxidation in the aerated parts of the soil. A significant difference between CH<sub>4</sub> emissions from water, from saturated soils and from relatively

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dry soils was observed. Over 2005 the annual CH<sub>4</sub> fluxes are 10.4±19.2 g C m<sup>-2</sup> yr<sup>-1</sup>, 101±30 g C m<sup>-2</sup> yr<sup>-1</sup> and 37.3±10.9 g C m<sup>-2</sup> yr<sup>-1</sup>, respectively. Especially the CH<sub>4</sub> fluxes from the ditch water and from the saturated soil bordering the ditches are high. Here, anaerobic processes, including methanogenesis, prevail over aerobic processes as result of the water saturated conditions. These observations suggest even higher CH<sub>4</sub> emissions in the case of a further rise of the water table. Total observations result in a relatively high net CH<sub>4</sub> emission (31.3±20.4 g C m<sup>-2</sup> yr<sup>-1</sup>), even compared to the high average fluxes of 11.4 g C m<sup>-2</sup> yr<sup>-1</sup> from peat lands in Germany and the Netherlands mentioned by Christensen et al. (2007<sup>1</sup>). The emission of CH<sub>4</sub> in the Horstermeer polder accounts for 22.5% of the emitted CO<sub>2</sub>-equivalents from the peat meadow site. The uncertainty of the up scaling of CH<sub>4</sub> based only on soil temperature and water level is, however, high. Further research needs to be done to improve the understanding of methane fluxes.

The history of the Horstermeer site – a recently re-wetted highly productive peat meadow, with nutrients from fertilization still present in the soil – may have influenced the present high CH<sub>4</sub> emission. Nutrient addition may enhance CH<sub>4</sub> emission in peat soils (Aerts and Toet, 1997). The more nutrient-poor peat meadow sites of Van den Pol-Van Dasselaar et al. (1998, 1999), with otherwise comparable soils and water table also exhibit lower fluxes than the Horstermeer site. Fiedler and Sommer (2000) report fluxes of similar magnitude as those from the Horstermeer site, from peaty depressions with strong agricultural influence in southern Germany. At the site, the ditches and their margins produce the highest fluxes, contributing significantly to the greenhouse gas budget. The high methane fluxes from ditches also have been reported from other temperate wetland sites. In particular a nutrient-rich pond margin site produced high fluxes of up to 77.5 g C (CH<sub>4</sub>) m<sup>-2</sup> yr<sup>-1</sup> (Van den Pol van Dasselaar et al., 1998, 1999; Sundh et al., 2000), being a similar hotspot as the ditch margins at the site. Our results therefore also hint towards management options to reduce CH<sub>4</sub> emissions during wetland restoration.

N<sub>2</sub>O fluxes appeared to make negligible contribution to the GHG balance at the site.

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The formation of N<sub>2</sub>O on peat land is normally enhanced by an increase in available mineral nitrogen. Since the site has not been fertilised for 10 years, the enhancing effect has probably been diminished and the N<sub>2</sub>O emission is reduced to insignificant proportions.

Water, as transport medium of organic carbon and dissolved CH<sub>4</sub>, plays only a minor role in the balance of greenhouse gases in the area. Only 3.2% of the total CO<sub>2</sub>-equivalents are exchanged by transport of water. Although concentrations of dissolved CH<sub>4</sub> and organic carbon in the soil water are high, the impermeable soil prohibits the water to infiltrate quickly. The groundwater, on the other hand, contains relatively small amounts of dissolved CH<sub>4</sub> and organic carbon. Ditchwater and soil water are therefore barely fed with total organic carbon and CH<sub>4</sub> through seepaging water. Discharge in this controlled area is low compared to other, for example mountainous and uncontrolled areas, where the run off component forms a more important role of washing down of carbon from the system (Hope, 2004; Worrall, 2004; Ding, 2004).

Although the Horstermeer site apparently is a large sink for CO<sub>2</sub> (311 g C-CO<sub>2</sub> m<sup>-2</sup> yr<sup>-1</sup>) and is a considerable carbon sink of 262 g C m<sup>-2</sup> yr<sup>-1</sup> when CH<sub>4</sub> fluxes and transport by water are considered, the area is only a small net GHG sink in CO<sub>2</sub>-equivalents (71 g CO<sub>2</sub>-equiv ha<sup>-1</sup> yr<sup>-1</sup>). Similar results were found by Friberg et al. (2003) and by Whiting and Chanton (2001).

These results show that wetland restoration, for the purpose of restoring wetland habitats and biodiversity, may increase methane emission, but that restored wetlands can become a net sink of greenhouse gases. Additionally, our observations suggest higher CH<sub>4</sub> emissions in the case of a further rise of the water table. Hitherto, the effects of wetland restoration on methane emissions have been poorly quantified, but also other studies indicate an increase of methane emission (Tuittila et al., 2000; Van den Bos, 2003).

However, the effect of enhanced methane emission resulting from wetland restoration should be compared with the previous emission of drainage and agricultural use of the soil, with generally lower CO<sub>2</sub>-uptake, and extra CO<sub>2</sub> emission from peat decom-

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position (Van den Bos, 2003). Unfortunately we do not have quantitative data from the GHG emissions at the site before the water level was raised. At two similar but drained peat land sites nearby a net annual CO<sub>2</sub>-emission of 157 m<sup>-2</sup> and a net annual CO<sub>2</sub>-uptake of 62.4 g C m<sup>-2</sup> over 2005 were measured (Van Veenendaal et al., 2007<sup>5</sup>). We have also modelled the CO<sub>2</sub> and CH<sub>4</sub> emission at the site for a 20 cm lower water table than the present water table (approximately the water table position before re-wetting) using the PEATLAND model (Van Huissteden et al., 2006), after calibrating the model for the site using our measurement data of the dryer sites. This resulted in an increase of the CO<sub>2</sub> emission from peat degradation of 330 g C m<sup>-2</sup> yr<sup>-1</sup>, which is 2.36 times the peat decomposition for the present situation. The CH<sub>4</sub> emission from the land surface was reduced with 60% in the model results. The net GHG emission may have been 180% higher at a 20 cm lower water table, mainly by higher soil organic matter decomposition. In this result the effect of carbon export by harvest under agricultural land use in the past, and carbon uptake by vegetation in the present situation is not included. This suggests that although the area is presently only a small GHG sink, it may have been a considerably larger net source before rewetting. It should be noted also that the effects of higher N<sub>2</sub>O emission at agricultural land use (Langeveld, 1997; Schils et al., 2006) are not considered here.

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**Table 1.** Site description: elevation, roughness, length ( $z_0$ ), zero plane displacement ( $d$ ), mean biomass (living and dead), rain, mean annual temperature, reference height ( $z_{ref}$ ).

Site	Horstermeerpolder (NL-hor)
Location	52°11'44"N, 05°44'33"E
Elevation (m above NAP)	-2.2
$z_0$ (m)	0.04
$d$ (m)	0.5
height of vegetation (m)	0.2 - 2.5
Mean biomass (kg/m <sup>2</sup> ) in 2005	living = 0.434 dead = 0.998
Mean annual Rainfall (mm/year)	797 (average over longer period)
Mean annual Temperature (°C)	9.8 (average over longer period)
$z_{ref}$ (m)	4.3

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**Table 2.** Description of the soilprofile at the measurement site.

Depth (m)	Color	Material	Decomposition	Roots (kg/m <sup>3</sup> )	pH wet	KCl	Organic matter weight %	Permeability (cm/day)
0-20	7.5YR2/3	clayey peat	strong	many, 4.1	5.7	5	39.4	4.04
20-30	7.5YR2/2	clayey peat	strong	2	5.8	5.1	45.1	0.16
30-46	5Y2/2 black	gyttja	partly	2	5.5	5.2	32.5	
48-68	2.5Y3/1 greenish	clayey gyttja	slightly	few	6	5.6	36.4	
68-128	10YR2/3	peaty gyttja reworked		none	5.8	5.3	50.3	
128-178	2YR1.7/1	peat, clay			6.1	5.6	73.1	
178-210	10YR2/3	compact peat						
210-250		sand						

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**Table 3.** Ranges of values used in the quality check of the meteorological data.

variable	minimum value	maximum value
uw [ $\text{m}^2 \text{s}^{-2}$ ]	-0.10	0.10
T [ $^{\circ}\text{C}$ ]	-10	50
CO <sub>2</sub> concentration [ppm]	330	600
H <sub>2</sub> O concentration [ $\text{kg m}^{-3}$ ]	0.002	0.018
CO <sub>2</sub> flux [ $\mu\text{mol m}^{-2} \text{s}^{-1}$ ]	-40	30
LE [ $\text{W m}^{-2}$ ]	-400	1000
H [ $\text{W m}^{-2}$ ]	-100	300
LW <sub>in</sub> and LW <sub>out</sub> [ $\text{W m}^{-2}$ ]	50	700
SW <sub>in</sub> and SW <sub>out</sub> [ $\text{W m}^{-2}$ ]	-50	1200
P <sub>air</sub> [kPa]	70	130
T <sub>bole</sub> [ $^{\circ}\text{C}$ ]	-40	70

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**Table 4.** Water balance components total per year (right) and averaged per day (left).

waterbalance components	amount of water					
	per day (mm)	error	+/-' (mm)	total (m <sup>3</sup> /ha/year)	error	+/-' (m <sup>3</sup> )
Precipitation	1.85	10%	0.19	6756	10%	676
<i>Vertical Flow on Land</i>	-1.86			-6790		
<i>Vertical Flow at Ditches</i>	8.40			30650		
Net Vertical Flow	0.19	20%	0.04	698	20%	140
Discharge	-0.47	10%	0.05	-1730	10%	173
Evaporation (land and water)	-1.81	10%	0.18	-6600	10%	660
Storage	-0.24		0.45	-876		1649

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**Table 5.** Overview of net ecosystem exchange (NEE), gross eco-system production (GEP) and eco-system respiration (R) for growing and non-growing seasons of 2004 and 2005.

	Growing Season 2004	Non-Growing Season 2004	Year 2004	Growing Season 2005	Non-Growing Season 2005	Year 2005
Length of period	192	174	366	155	210	365
DOY of period	96 - 288	288 - 81	1 - 366	96 - 251	251 - 83	1 - 365
NEE (tonC-CO <sub>2</sub> /ha/yr)	-3.35	0.59	-2.76	-3.27	0.16	-3.11
GEP (tonC-CO <sub>2</sub> /ha/yr)	-10.06	-1.39	-11.45	-8.77	-3.00	-11.77
Reco (tonC-CO <sub>2</sub> /ha/yr)	6.71	2.16	8.87	5.50	3.16	8.66

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**Table 6.** Statistical analyses of the relation between CH<sub>4</sub> fluxes, soil temperature and water level for the three land elements (dry land, saturated land and ditches). From left to right the correlation coefficients, goodness-of-fit of the regression of the logarithm of the CH<sub>4</sub> flux and soil temperature ( $R^2$ ), F-test with significance (p-value) and variance error variance as well as the regression equation for CH<sub>4</sub> with soil temperature are shown.

	correlation coefficients			$R^2$	statistical parameters			Regression equation
	$\ln(\text{CH}_4)\text{-}T_{\text{soil}}$	$\ln(\text{CH}_4)\text{-soil wll}$	$T_{\text{soil}}\text{-soil wll}$		F-test	p-value	Error (variance)	
dry land	0.294	-0.132	-0.663	0.086	14.273	0.000	1.845	$\text{CH}_4 = \exp(-0.261 + 0.060 \cdot T_{\text{soil}})$
saturated land	0.493	-0.362	-0.671	0.243	3.210	0.103	0.292	$\text{CH}_4 = \exp(2.205 + 0.045 \cdot T_{\text{soil}})$
ditches	0.676	0.000	0.000	0.457	9.261	0.011	0.292	$\text{CH}_4 = \exp(0.767 + 0.079 \cdot T_{\text{soil}})$

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**Table 7.** Results of the water analyses for Total Organic Carbon (TOC) in the water, water fluxes over the year and total fluxes of dissolved CO<sub>2</sub> transported by water.

	TOC (gC/m <sup>3</sup> water)		water flux (m <sup>3</sup> /ha/year)		total TOC (gC/ha/yr)		
		error		error	<i>+/-</i> (gC/ha/yr)		
seepage in ditch	41.14	in ground water	6%	618.83	20%	25,458	6,619
infiltration in ditch	53.50	in ditch water	6%	-5.89	20%	-315	82
seepage on land	41.14	in ground water	6%	76.35	20%	3,141	817
infiltration on land	157.90	in soil water	6%	-619.76	20%	-97,860	25,444
discharge surface water	53.50	in ditch water	6%	-1,703.00	10%	-91,111	14,578
net yearly flux of TOC in water						-160,686	47,539

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**Table 8.** Results of the water analyses for dissolved CH<sub>4</sub> in the water, water fluxes over the year and total fluxes of dissolved CH<sub>4</sub> transported by water.

	CH <sub>4</sub> conc. (gCH <sub>4</sub> /m <sup>3</sup> water)		water flux (m <sup>3</sup> /ha/yr)		total CH <sub>4</sub> (gC/ha/yr) +/- (gC/ha/yr)	
		error		error		
seepage in ditch	8.62 in ground water	13%	618.83	20%	4,001.68	1,320.23
infiltration in ditch	3.91 in ditch water	13%	-5.89	20%	-17.27	5.70
seepage on land	8.62 in ground water	13%	76.35	20%	493.75	162.90
infiltration on land	35 (measured 88) in soil water	0%	-619.76	20%	-16,268.68	3,253.74
discharge surface water	0.027 in ditch water	13%	-1,703.00	10%	-4,995.67	7.93
net yearly flux of dissolved CH <sub>4</sub>					-16,786.18	4,750.50

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**Table 9.** Summary of all carbon fluxes in the research area over 2005. Fluxes are presented in tonC, tonCO<sub>2</sub>-equivalents as well as in percentages of CO<sub>2</sub>-equivalents.

	ton C/ha	+/- ton C/ha	CO <sub>2</sub> equivalents	
			ton/ha	percentage
1 GEP (CO <sub>2</sub> )	11.770	9.051	43.157	99.4%
2 dissolved CH <sub>4</sub> in seepage	0.004	0.001	0.138	0.3%
3 TOC in seepage	0.029	0.007	0.105	0.2%
<b>TOTAL INCOMING CARBON</b>	<b>11.803</b>	<b>9.059</b>	<b>43.399</b>	<b>100.0%</b>
4 R <sub>ecosystem</sub> (CO <sub>2</sub> )	-8.660	6.660	-31.753	74.4%
5 CH <sub>4</sub> emission from land	-0.073	0.134	-2.233	5.2%
6 CH <sub>4</sub> emission from saturated land	-0.203	0.059	-6.212	14.6%
7 CH <sub>4</sub> emission from water	-0.037	0.011	-1.144	2.7%
8 dissolved CH <sub>4</sub> in infiltration	-0.016	0.003	-0.499	1.2%
9 TOC in infiltration	-0.098	0.026	-0.360	0.8%
10 dissolved CH <sub>4</sub> in discharge	-0.005	0.000	-0.153	0.4%
11 TOC in discharge	-0.091	0.014	-0.334	0.8%
<b>TOTAL OUTGOING CARBON</b>	<b>-9.183</b>	<b>6.907</b>	<b>-42.688</b>	<b>100.0%</b>
<b>NET CARBON FLUX with ATMOSPHERE</b>	<b>2.797</b>	<b>0.784</b>	<b>1.815</b>	
<b>NET CARBON FLUX with ATMOSPHERE and WATEF</b>	<b>2.620</b>	<b>0.835</b>	<b>0.712</b>	
<b>NEE (CO<sub>2</sub>) = GPP(1) - R<sub>ecosystem</sub>(2)</b>	<b>3.110</b>	<b>0.580</b>	<b>11.403</b>	

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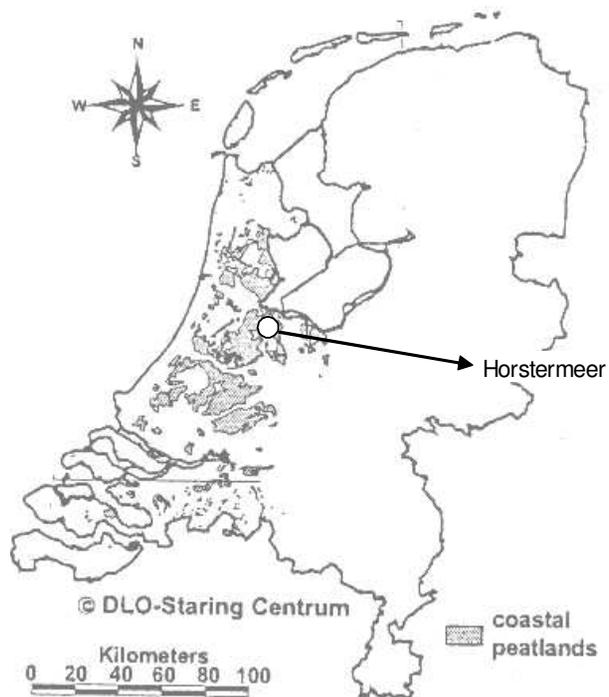
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**Fig. 1.** Current distribution of peat soils in the western part of the Netherlands (SC-DLO 1992) and location of Horstermeer research site.

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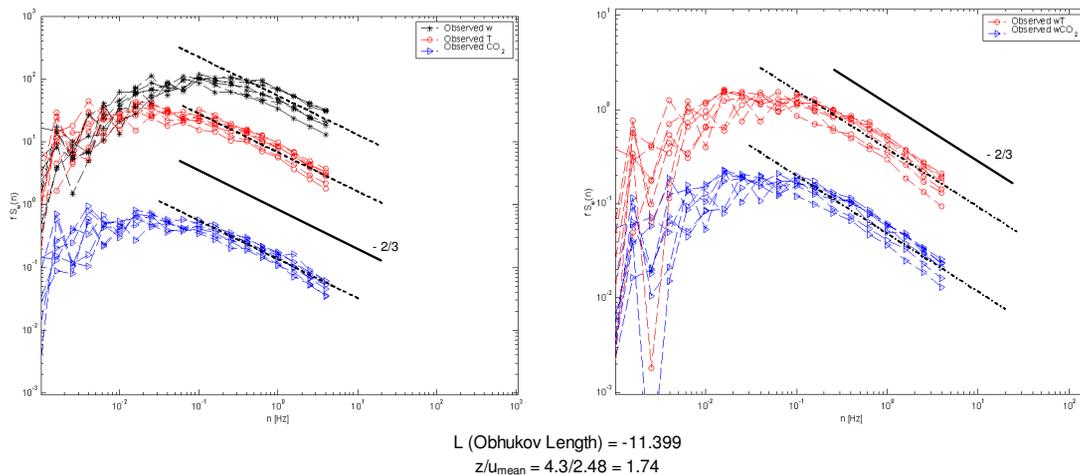
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**Fig. 2.** Spectra of  $w$ ,  $T$  and  $\text{CO}_2$ -concentration (left) and co-spectra of  $w'T'$  and  $w'CO_2'$  (right) for 10 Hz eddy-correlation data seven half hours in springtime (2005). Data are averaged per half hour.

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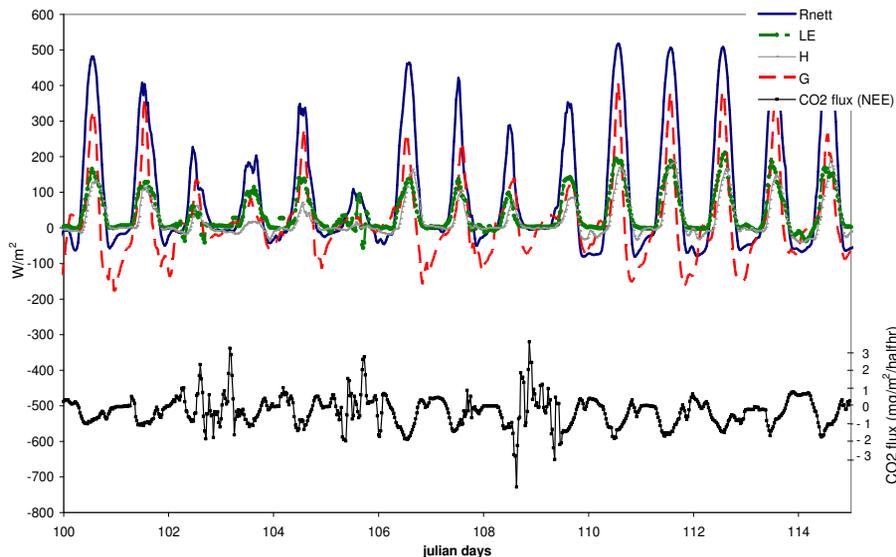
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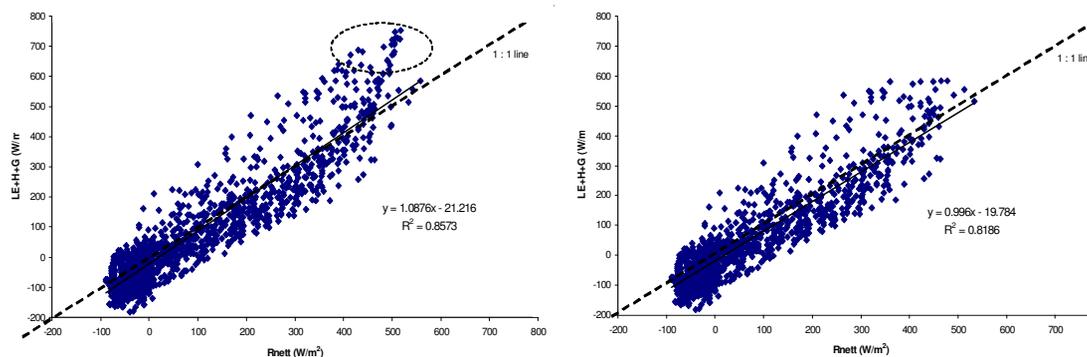


**Fig. 3.** Diurnal pattern of energy balance components net radiation, latent heat, sensible heat and ground heat flux and  $CO_2$  flux for seven days in the springtime of 2005.

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**Fig. 4.** Energy balance closure for daytime periods over a three week period during the spring of 2005 with 1:1 lines and linear relations. In the plot on the left, a circle is drawn around the outlying mid-day data points. In the plot on the right, mid-day measurements are removed.

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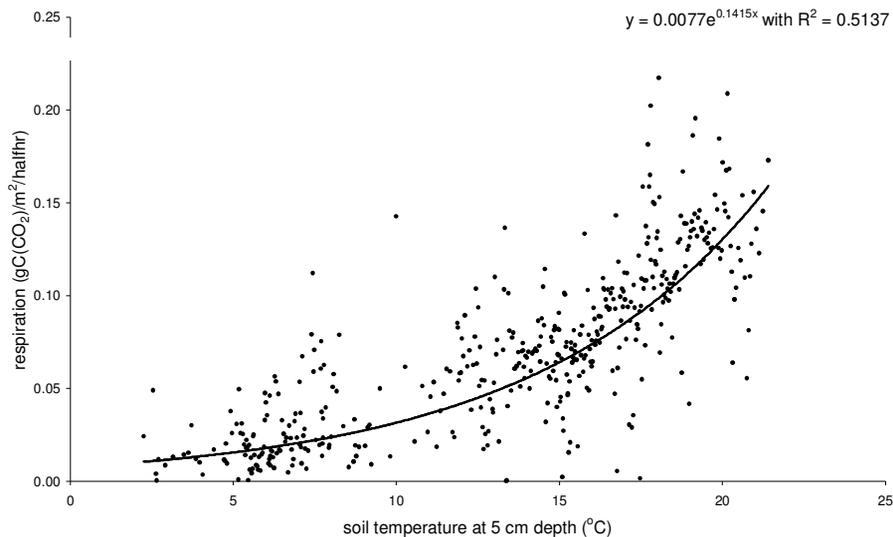
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**Fig. 5.** Relation between soil temperature and respiration using nightly eddy correlation CO<sub>2</sub> fluxes: best fit line with its equation and  $R^2$  value.

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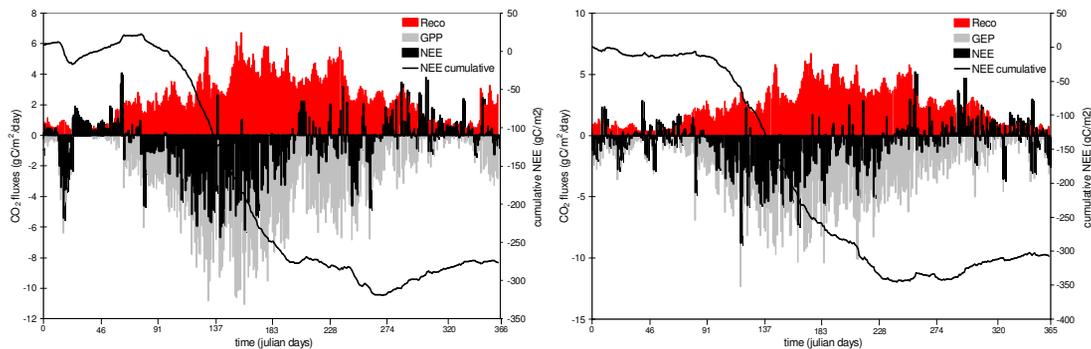


Fig. 6. NEE, GEP and Ecosystem Respiration for 2004 (left) and 2005 in  $g C/m^2/day$  and NEE ( $g C/m^2$ ) accumulated over the year.

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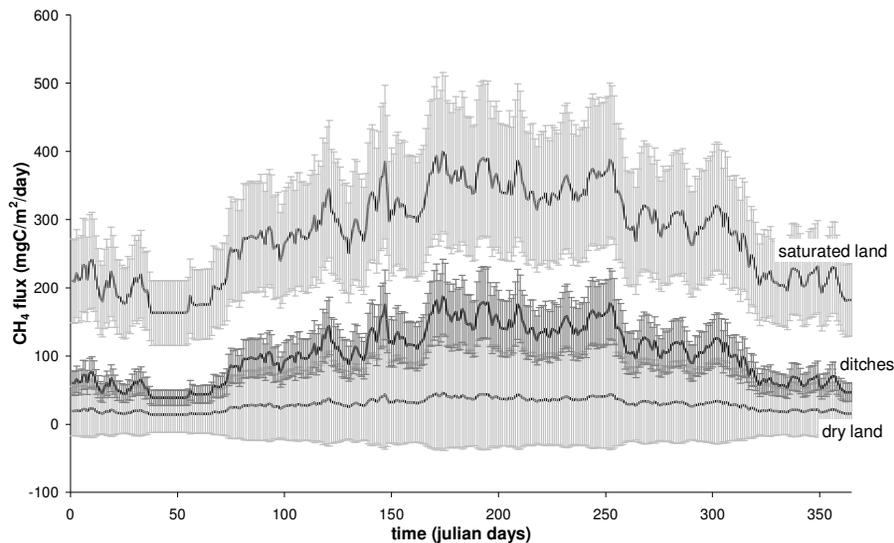
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**Fig. 7.** Modeled daily fluxes of CH<sub>4</sub> in g C/m<sup>2</sup>/day for dry land, saturated land and ditches over 2005. Error-bars indicate the variance from the regression analysis.

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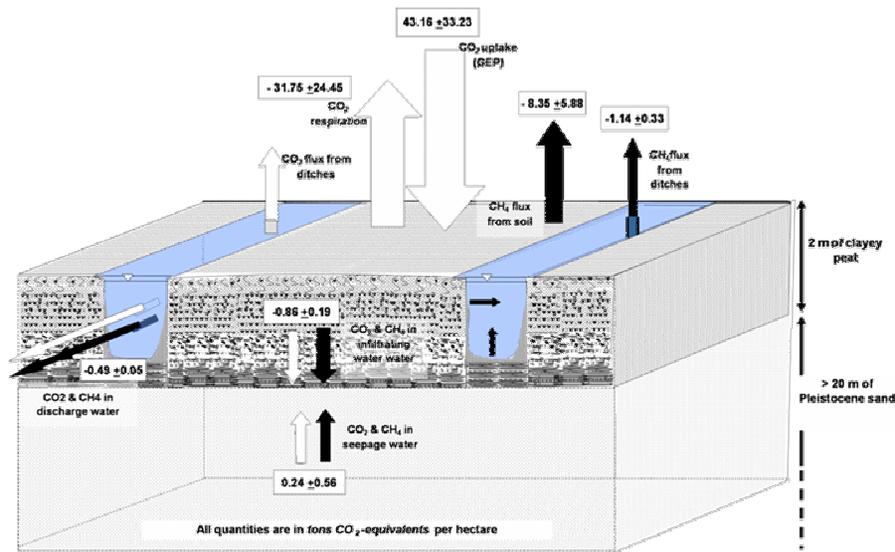


Fig. 8. Schematic cross section of the underground of the Horstermeer polder and yearly fluxes. Arrows indicate the respective fluxes of CO<sub>2</sub> (white) and CH<sub>4</sub> (black).

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