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The full greenhouse gas balance of an abandoned peat meadow

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Abstract

Globally, peat lands are considered to be a sink of CO_2, but a source when drained. Additionally, wet peat lands are thought to emit considerable amounts of CH_4 and N_2O. 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_2, CH_4 and N_2O 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_2) and flux chamber measurements (CH_4 and N_2O). Meteorological and hydrological measurements were done as well. With growing seasons of respectively 192 and 155 days, the net annual CO_2 uptake was 276±61 g C m^{-2} for 2004 and 311±58 g C m^{-2} for 2005. Ecosystem respiration was estimated as 887±668 g C m^{-2} for 2004 and 866±666 g C m^{-2} for 2005. CH_4 fluxes from water, saturated land and relatively dry land varied: total annual CH_4 fluxes are 10.4±19.2 g C m^{-2} yr^{-1}, 101 g C m^{-2} yr^{-1}±30 and 37.3±10.9 g C m^{-2} yr^{-1}, respectively, and a annual weighed total CH_4 emission of 31.27±20.44 g C m^{-2} yr^{-1}. N_2O fluxes were too low to be of significance. The carbon-balance consists for the largest part of CO_2 uptake, CO_2 respiration and CH_4 emission from wet land and water. CO_2 emission has decreased significantly as result of the raised water table, while CH_4 fluxes have increased. In global warming potentials the area is a very small sink of 71 g CO_2-equiv m^{-2} (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_2, by 150% for CH_4 and by

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17% for N2O (IPCC TAR, 2001). The European land surface is thought to be absorbing a significant amount of the current industrial CO_2 emissions (Janssens et al., 2003) and to be releasing over 40% of the European CH_4 and N_2O emissions. However, reliable estimates of emissions and emission factors are still lacking.

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 surfaces is necessary.

Peat lands in Europe have formed one of the major sinks of atmospheric CO_2 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 conditions peat lands are also significant emitters of the greenhouse gas CH_4 and sometimes N_2O (Christensen et al., 2007[1]). The Global Warming Potentials (GWP) of CH_4 (~23, over 100 years) and N_2O (~300, over 100 years) are significantly higher than that of CO_2 (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 oxidation and peat ecosystems have become a strong source of CO_2 (Langeveld et al., 1997). Peat oxidation can be reduced and peat areas can be turned into sinks of CO_2 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 (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

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

will probably turn the area from a CO_2-source in a CO_2-sink and alter the emissions of CH_4 and N_2O.

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_2-measurements in peat lands are available and for CH_4 and N_2O no year round measurements exist at all. Besides, very few comprehensive integrated measurement campaigns have been carried out (Soussana, 2007[2]; Christensen et al., 2007[1]).

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

[2]Soussana, J. F.: Towards a full accounting of the greenhouse gas balance of European grasslands, in preparation, 2007.

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 diocia, 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

the surrounding time period. No gaps larger then 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_4 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_2 concentration, water vapour, wind speed and air temperature were performed with a Licor 7500 open path infrared gas analyser (LI-COR 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_2 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,

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 CH_4 and N_2O 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 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 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

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_4 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_2O 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^3 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.

4 Results

4.1 The water balance

Water enters the system either as precipitation or as groundwater seepaging 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 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±68 mm over the year is nearly equalled by the transpiration (660±66 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±140 $m^3\ ha^{-1}\ yr^{-1}$. The runoff from the research site consists only of discharge over the weir, which is 1.730±173 $m^3\ ha^{-1}\ year^{-1}$. The maximum total uncertainty in the measurements is estimated at 1.649 $m^3\ ha^{-1}\ year^{-1}$, which is large compared to the estimated storage of 876 $m^3\ ha^{-1}\ year^{-1}$.

4.2 Performance of the eddy-correlation set-up

Spectral analysis of the fluctuations of w, T and 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 CO_2-concentration as well as co-spectra of temperature fluxes and 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 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 CO_2 time series, the co-spectrum of vertical wind and 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 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[3]) 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

[3]Parmentier, F. J. W., Hendriks, D. M. D., de Jeu, R. A. M., and van der Molen, M. K.: Evaporation and CO2 exchange of a peat bog independent of water table, in preparation, 2007.

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 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 g C m^{-2} yr^{-1} and 18 g C m^{-2} yr^{-1}, respectively. According to Van der Molen et al. (2007)[4] the error introduced by the calculation routines is 13% of the total annual NEE.

4.3 Carbon dioxide

The net CO_2 flux follows a daily pattern with periods of net CO_2 uptake during daytime and respiration during night time (Fig. 3). In Fig. 6 the CO_2 fluxes are shown as daily fluxes of C-CO_2 per m^2 as well as C-CO_2 per 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 g C m^{-2}. The NEE for 2004 was cumulated, resulting in a net annual CO_2 uptake of 276±61 g C m^{-2}. The growing season in 2005 lasts from 7 April to 8 September and has a net uptake of 331 g C m^{-2}, while the annual NEE for 2005 amounts 311±58 g C m^{-2}.

[4]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.

Net eco-system exchange (NEE) is determined directly from the eddy covariance CO_2 flux measurements and is considered to be the sum of the gross ecosystem production (GEP) and ecosystem respiration (R_{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 W m^{-2}) assuming photosynthesis is absent and the NEE consist only of R_{eco}. Next, the soil respiration is described as a function of the soil temperature by using the Arrhenius relation (Lloyd and Taylor, 1994):

$$\mathbf{R}_{eco} = 0.0077 * e^{(0.1415 * \mathbf{Tsoil})} \text{ (error variance = 0.77 and } R^2 = 0.5137) \quad (2)$$

This equation results in a partitioning of a annual NEE for 2004 of 276 g C m^{-2} in a GEP of 1145±881 g C m^{-2} yr and a Reco of 869±668 g C m^{-2} yr. The annual NEE for 2005 of 311 g C m^{-2} is partitioned in a GEP of 1177±905 g C m^{-2} yr and a Reco of 866±666 g C m^{-2} 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^{-2} yr NEE in a GEP of 1135 g C m^{-2} yr and Reco of 823 g C m^{-2} 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_{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^{-3}, 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^{-1} 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; Worral, 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. 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_4 flux and between soil water level and CH_4 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 temporal variation of the CH_4 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_4 flux and soil water level is caused by the soil characteristics at our research site. Peaty and clayey soils often contain anaerobe areas above the water level. In those zones in the soil methanogenesis occurs and CH_4 fluxes at the surface can be higher than expected. As a consequence of the low correlation with CH_4 fluxes, soil water levels are not taken into account in the regression analyses of the CH_4 fluxes. The following exponential regression equations describe the CH_4 flux (in mg $CH_4/m^2/h$) for the three land elements:

Dry land:

$$\mathbf{CH_4\ flux} = e^{(-0.261+0.060*\mathbf{Tsoil})} \text{ (error variance = 1.84 and } R^2 = 0.086) \quad (3)$$

Saturated land:

$$\mathbf{CH_4\ flux} = e^{(2.205+0.045*\mathbf{Tsoil})} \text{ (error variance = 0.29 and } R^2 = 0.243) \quad (4)$$

Ditches:

$$\mathbf{CH_4\ flux} = e^{(0.767+0.079*\mathbf{Tsoil})} \text{ (error variance = 0.29 and } R^2 = 0.457) \quad (5)$$

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Using these regression equations and continuous soil temperature data, the annual CH_4 flux for the three land elements could be determined. This resulted in annual CH_4 fluxes for 2005 of 10.4±19.2 g C m^{-2} yr for the dry land, 101±30 g C m^{-2} yr for the saturated land and 37.3±10.9 g C m^{-2} yr for the ditches and a weighed total annual CH_4 emission of 31.3±20.4 g C m^{-2} yr. The CH_4 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_4 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_4 show that the soil water has a very high concentration of dissolved CH_4 (almost 88±11.4 g CH_4 m^{-3}) while the ditchwater and groundwater contain relatively little dissolved CH_4 (Table 8) (Hope, 2004; Worral, 2004; Ding, 2004). Theoretically, the maximum concentration of dissolved CH_4 in water under the conditions of the soil in the Horstermeerpolder is 35 g CH_4 m^{-3} (10°C; 2 m deep). Higher concentrations of CH_4 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_4 m^{-3} soil water is used. The fluxes of dissolved CH_4 by water transport are calculated by multiplying the dissolved CH_4 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_4) 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.

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_4 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±905 g C m^{-2} yr^{-1} (99.4% of all CO_2-equiv.) enters the system due to accumulation of plant material (GEP), while 3.3±0.8 g C m^{-2} yr^{-1} (0.55% of all CO_2-equivalents) enters the system with groundwater seepage. From the total emitted carbon 866±666 g C m^{-2} yr^{-1} (74.4% of all CO_2-equiv.) leaves the system through ecosystem respiration, 31.3±20.4 g C m^{-2} yr^{-1} (22.5% of all CO_2-equiv.) through emission of CH_4 gas, 11.4±2.9 g C m^{-2} yr^{-1} (2.0% of all CO_2-equivalents) through infiltration of soil- and ditchwater to deeper aquifers and 9.6±1.4 g C m^{-2} yr^{-1} (1.2% of all CO_2-equiv.) through discharging ditch water.

When concerning only fluxes with the atmosphere the area is a considerable carbon sink of 279±78 g C m^{-2} yr^{-1}, while it is a smaller GHG sink of 182 g CO_2-equiv. m^{-2} 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±84 g C m^{-2} yr^{-1}, and only a small GHG sink of 71 g CO_2-equiv. m^{-2} yr^{-1} (see Table 9 and

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_2, CH_4 and N_2O simultaneously, while also paying attention to fluxes of organic carbon and dissolved methane trough 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_2 uptake was 276±61 g C m^{-2} for 2004 and 311±58 g C m^{-2} for 2005. Ecosystem respiration was estimated using the soil flux chamber measurements and soil temperature as 887±668 g C m^{-2} for 2004 and 866±666 g C m^{-2} for 2005. NEE of CO_2 at the Horstermeer site is high compared to the average NEE of European peat areas which ranges from 33 g C m^{-2} (uptake) for undisturbed peat lands to −188 g C m^{-2} (emission) for drained peat lands (Janssens et al., 2003). The high CO_2-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_4 emissions of the area are the net result of methanogenesis in the anaerobic parts of the soil and CH_4 oxidation in the aerated parts of the soil. A significant difference between CH_4 emissions from water, from saturated soils and from relatively

dry soils was observed. Over 2005 the annual CH_4 fluxes are 10.4±19.2 g C m^{-2} yr^{-1}, 101±30 g C m^{-2} yr^{-1} and 37.3±10.9 g C m^{-2} yr^{-1}, respectively. Especially the CH_4 fluxes from the ditch water and from the saturated soil bordering the ditches are high. Here, anaerobic processes, including methanogenesis, prevail over aerobe processes as result of the water saturated conditions. These observations suggest even higher CH_4 emissions in the case of a further rise of the water table. Total observations result in a relatively high net CH_4 emission (31.3±20.4 g C m^{-2} yr^{-1}), even compared to the high average fluxes of 11.4 g C m^{-2} yr^{-1} from peat lands in Germany and the Netherlands mentioned by Christensen et al. (2007[1]). The emission of CH_4 in the Horstermeer polder accounts for 22.5% of the emitted CO_2-equivalents from the peat meadow site. The uncertainty of the up scaling of CH_4 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_4 emission. Nutrient addition may enhance CH_4 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_4) m^{-2} yr^{-1} (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_4 emissions during wetland restoration.

N_2O fluxes appeared to make negligible contribution to the GHG balance at the site.

The formation of N_2O 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_2O emission is reduced to insignificant proportions.

Water, as transport medium of organic carbon and dissolved CH_4, plays only a minor role in the balance of greenhouse gases in the area. Only 3.2% of the total CO_2-equivalents are exchanged by transport of water. Although concentrations of dissolved CH_4 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_4 and organic carbon. Ditchwater and soil water are therefore barely fed with total organic carbon and CH_4 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; Worral, 2004; Ding, 2004).

Although the Horstermeer site apparently is a large sink for CO_2 (311 g C-CO_2 $m^{-2}\,yr^{-1}$) and is a considerable carbon sink of 262 g C $m^{-2}\,yr^{-1}$ when CH_4 fluxes and transport by water are considered, the area is only a small net GHG sink in CO_2-equivalents (71 g CO_2-equiv $ha^{-1}\,yr^{-1}$). Similar results were found by Friborg 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_4 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_2-uptake, and extra CO_2 emission from peat decom-

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_2-emission of 157 m^{-2} and a net annual CO_2-uptake of 62.4 g C m^{-2} over 2005 were measured (Van Veenendaal et al., 2007[5]). We have also modelled the CO_2 and CH_4 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_2 emission from peat degradation of 330 g C m^{-2} yr^{-1}, which is 2.36 times the peat decomposition for the present situation. The CH_4 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_2O 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/m2) 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

Data observed over 2005

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

Depth (m)	Color	Material	Decomposition	Roots (kg/m^3)	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
30-48	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		none	5.8	5.3	50.3	
128-178	2YR1.7/1	reworked peat, clay			6.1	5.6	73.1	
178-210	10YR2/3	compact peat						
210-250		sand						

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

variable	minimum value	maximum value
uw [m^2 s^{-2}]	-0.10	0.10
T [^oC]	-10	50
CO_2 concentration [ppm]	330	600
H_2O concentration [kg m^{-3}]	0.002	0.018
CO_2 flux [umol m^{-2} s^{-1}]	-40	30
LE [W m^{-2}]	-400	1000
H [W m^{-2}]	-100	300
LW_{in} and LW_{out} [W m^{-2}]	50	700
SW_{in} and SW_{out} [W m^{-2}]	-50	1200
P_{air} [kPa]	70	130
T_{bole} [^oC]	-40	70

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^3/ha/year)	error	+/-' (m^3)
Precipitation	1.85	*10%*	*0.19*	*6756*	*10%*	*676*
Vertical Flow on Land	*-1.86*			*-6790*		
Vertical Flow at Ditches	*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_2/ha/yr)	-3.35	0.59	-2.76	-3.27	0.16	-3.11
GEP (tonC-CO_2/ha/yr)	-10.06	-1.39	-11.45	-8.77	-3.00	-11.77
Reco (tonC-CO_2/ha/yr)	6.71	2.16	8.87	5.50	3.16	8.66

Table 6. Statistical analyses of the relation between CH_4 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_4flux and soil temperature (R^2), F-test with significance (p-value) and variance error variance as well as the regression equation for CH_4 with soil temperature are shown.

	correlation coefficients			statistical parameters				Regression equation
	$ln(CH_4)$-T_{soil}	$ln(CH_4)$-soil wll	T_{soil}-soil wll	R^2	F-test	p-value	Error (variance)	
dry land	0.294	-0.132	-0.663	0.086	14.273	0.000	1.845	$CH_4 = exp(-0.261 + 0.060*T_{soil})$
saturated land	0.493	-0.362	-0.671	0.243	3.210	0.103	0.292	$CH_4 = exp(2.205 + 0.045*T_{soil})$
ditches	0.676	0.000	0.000	0.457	9.261	0.011	0.292	$CH_4 = exp(0.767 + 0.079*T_{soil})$

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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_2 transported by water.

	TOC (gC/m^3 water)		error	water flux (m^3/ha/year)	error	total TOC (gC/ha/yr)	*+/- (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*

Table 8. Results of the water analyses for dissolved CH_4 in the water, water fluxes over the year and total fluxes of dissolved CH_4 transported by water.

	CH_4 conc. (gCH_4/m^3 water)		error	water flux (m^3/ha/yr)	error	total CH_4 (gC/ha/yr)	*+/- (gC/ha/yr)*
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_4						-16,786.18	*4,750.50*

Table 9. Summary of all carbon fluxes in the research area over 2005. Fluxes are presented in tonC, tonCO_2-equivalents as well as in percentages of CO_2-equivalents.

	ton C/ha	+/-' ton C/ha	CO_2 equivalents ton/ha	percentage
1 GEP (CO_2)	11.770	*9.051*	43.157	99.4%
2 dissolved CH_4 in seepage	0.004	*0.001*	0.138	0.3%
3 TOC in seepage	0.029	*0.007*	0.105	0.2%
TOTAL INCOMING CARBON	11.803	*9.059*	43.399	100.0%
4 $R_{ecosystem}$ (CO_2)	-8.660	*6.660*	-31.753	74.4%
5 CH_4 emission from land	-0.073	*0.134*	-2.233	5.2%
6 CH_4 emission from saturated land	-0.203	*0.059*	-6.212	14.6%
7 CH_4 emission from water	-0.037	*0.011*	-1.144	2.7%
8 dissolved CH_4 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_4 in discharge	-0.005	*0.000*	-0.153	0.4%
11 TOC in discharge	-0.091	*0.014*	-0.334	0.8%
TOTAL OUTGOING CARBON	-9.183	*6.907*	-42.688	100.0%
NET CARBON FLUX with ATMOSPHERE	2.797	*0.784*	1.815	
NET CARBON FLUX with ATMOSPHERE and WATEF	2.620	*0.835*	0.712	
NEE (CO_2) = GPP(1) - $R_{ecosystem}$(2)	3.110	*0.580*	11.403	

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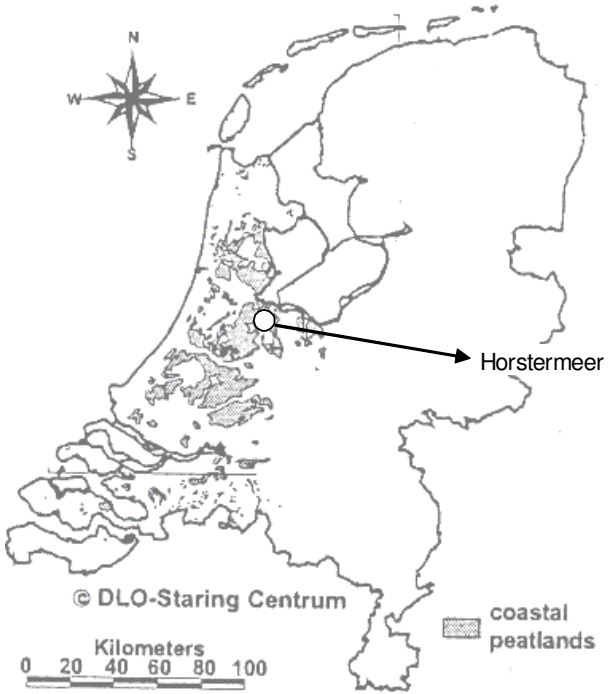

Fig. 1. Current distribution of peat soils in the western part of the Netherlands (SC-DLO 1992) and location of Horstermeer research site.

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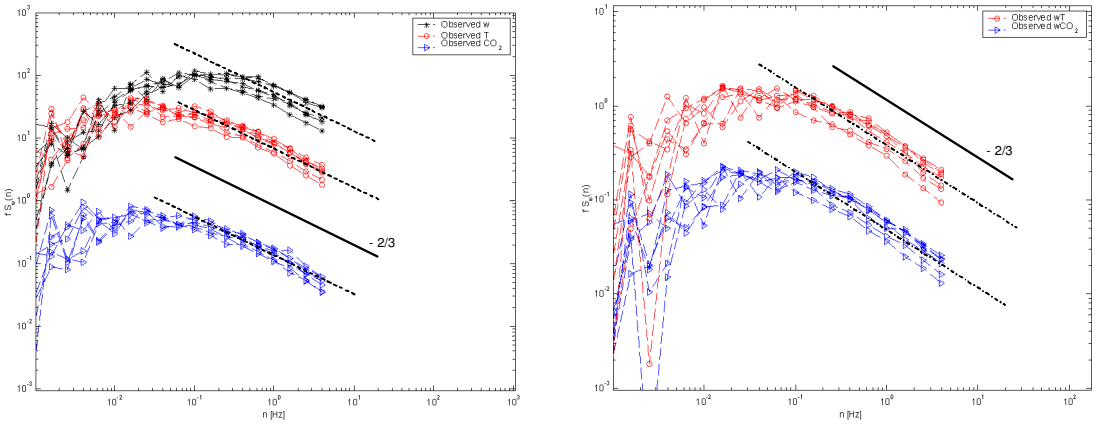

Fig. 2. Spectra of w, T and CO_2-concentration (left) and co-spectra of $w'T'$ and $w'CO_2'$ (right) for 10 Hz eddy-correlation data seven half hours in springtime (2005). Data are averaged per half hour.

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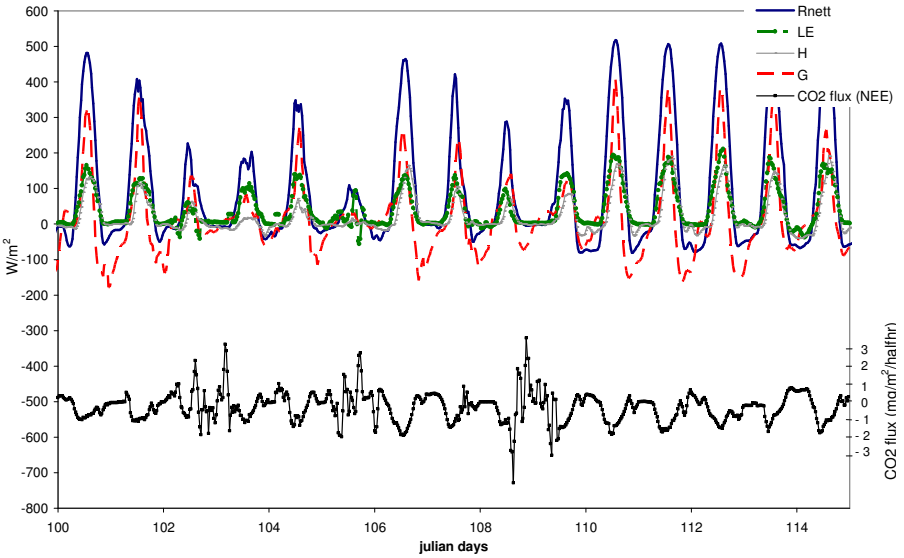

Fig. 3. Diurnal pattern of energy balance components net radiation, latent heat, sensible heat and ground heat flux and CO_2 flux for seven days in the springtime of 2005.

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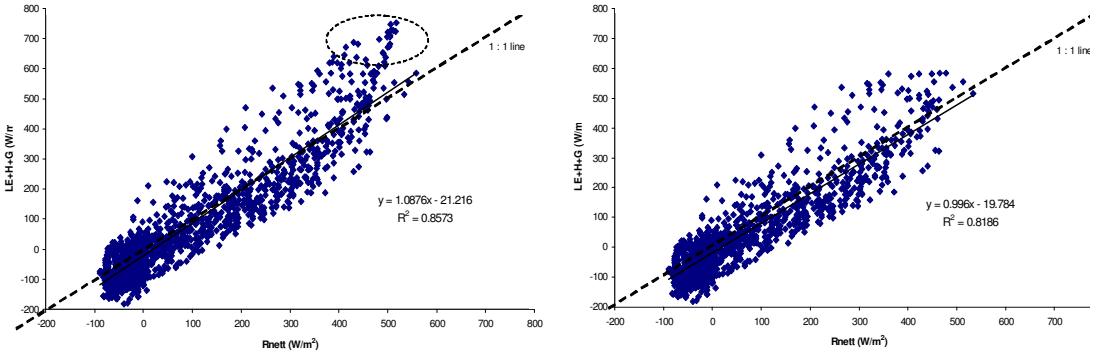

Fig. 4. Energy balance closure for daytime periods over a three week period during the spring of 2005 with 1:1 lines and linear relations. In the plot on the left, a circle is drawn around the outlying mid-day data points. In the plot on the right, mid-day measurements are removed.

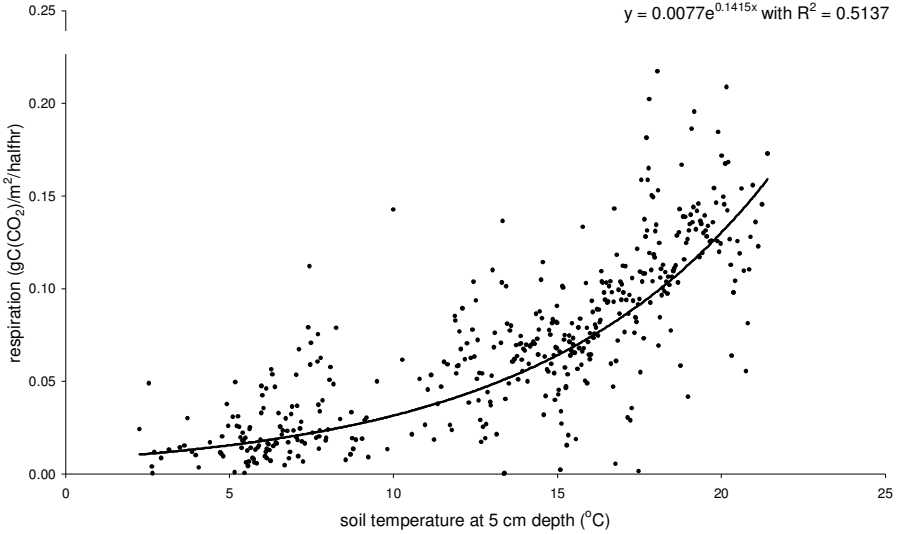

Fig. 5. Relation between soil temperature and respiration using nightly eddy correlation CO_2 fluxes: best fit line with its equation and R^2 value.

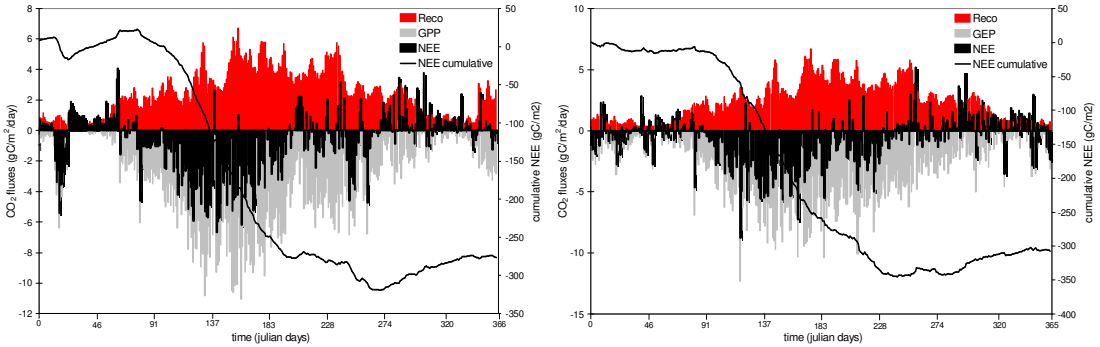

Fig. 6. NEE, GEP and Ecosystem Respiration for 2004 (left) and 2005 in g C/m^2/day and NEE (g C/m^2) accumulated over the year.

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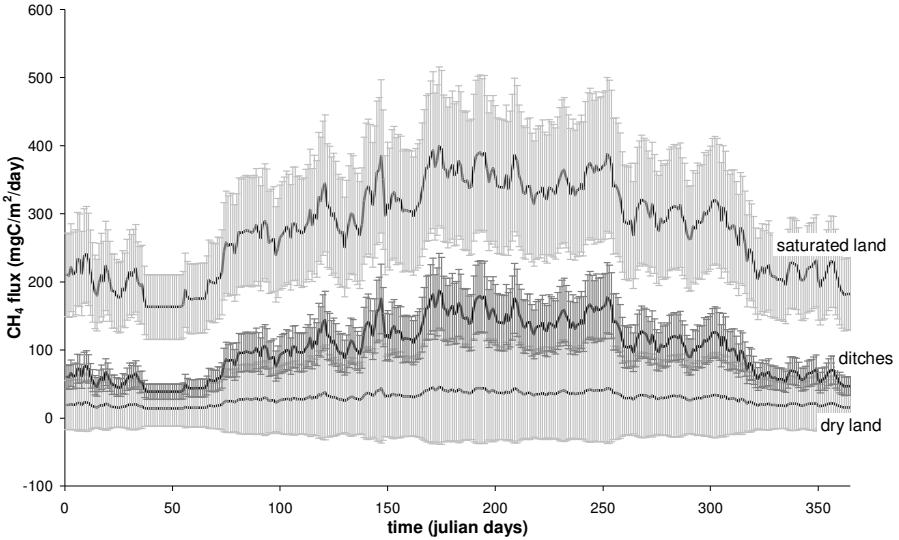

Fig. 7. Modeled daily fluxes of CH_4 in g C/m^2/day for dry land, saturated land and ditches over 2005. Error-bars indicate the variance from the regression analysis.

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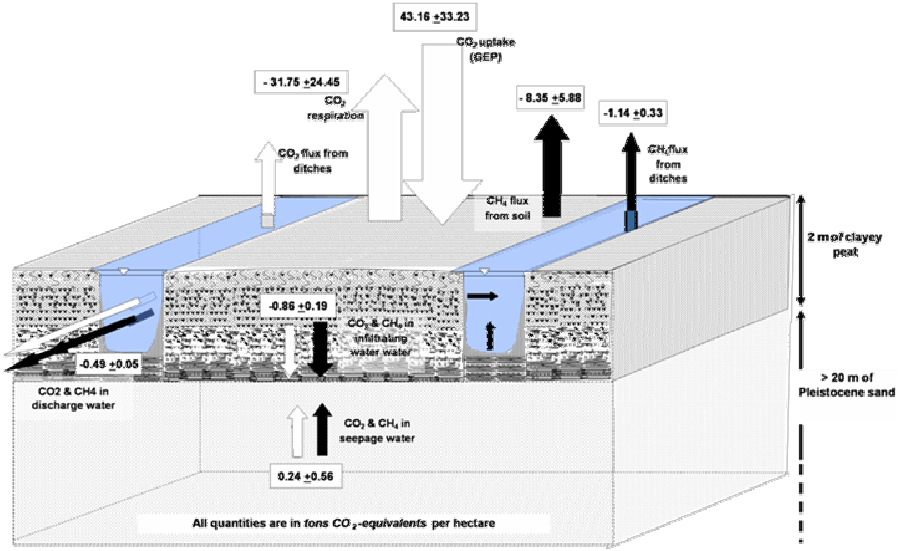

Fig. 8. Schematic cross section of the underground of the Horstermeer polder and yearly fluxes. Arrows indicate the respective fluxes of CO_2 (white) and CH_4 (black).

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