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Agricultural peat lands; towards a greenhouse gas sink – a synthesis of a Dutch landscape study

A. P. Schrier-Uijl[1], P. S. Kroon[2], D. M. D. Hendriks[3], A. Hensen[2], J. C. Van Huissteden[4], P. A. Leffelaar[5], F. Berendse[1], and E. M. Veenendaal[1]

[1]Nature Conservation and Plant Ecology, Wageningen University, Droevendaalse steeg 3a, 6708 PD Wageningen, the Netherlands
[2]Energy research Centre of the Netherlands (ECN), Department of Air Quality and Climate Change, 1755 LE Petten, the Netherlands
[3]Deltares, dept. Soil and Groundwater Systems, Princetonlaan 6, 3584 CB Utrecht, the Netherlands
[4]Hydrology and Geo-Environmental Sciences, Faculty of Earth and Life Sciences, Vrije Universiteit Amsterdam, De Boelelaan 1085, 1081 HV Amsterdam, the Netherlands
[5]Plant Production Systems, Wageningen University, P.O. Box 430, 6700 AK, Wageningen, the Netherlands

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Correspondence to: A. P. Schrier-Uijl (arina.schrier@wetlands.org)

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Abstract

It is generally known that managed, drained peatlands act as carbon sources. In this study we examined how mitigation through the reduction of management and through rewetting may affect the greenhouse gas (GHG) emission and the carbon balance of intensively managed, drained, agricultural peatlands. Carbon and GHG balances were determined for three peatlands in the western part of the Netherlands from 2005 to 2008 by considering spatial and temporal variability of emissions (CO_2, CH_4 and N_2O). One area (Oukoop) is an intensively managed grass-on-peatland, including a dairy farm, with the ground water level at an average annual depth of 0.55 m below the soil surface. The second area (Stein) is an extensively managed grass-on-peatland, formerly intensively managed, with a dynamic ground water level at an average annual depth of 0.45 m below the soil surface. The third area is an (since 1998) rewetted former agricultural peatland (Horstermeer), close to Oukoop and Stein, with the average annual ground water level at a depth of 0.2 m below the soil surface. During the measurement campaigns we found that both agriculturally managed sites acted as carbon and GHG sources but the rewetted agricultural peatland acted as a carbon and GHG sink. The terrestrial GHG source strength was 1.4 kg CO_2-eq $m^{-2}\,yr^{-1}$ for the intensively managed area and 1.0 kg CO_2-eq $m^{-2}\,yr^{-1}$ for the extensively managed area; the unmanaged area acted as a GHG sink of 0.7 kg CO_2-eq $m^{-2}\,yr^{-1}$. Water bodies contributed significantly to the terrestrial GHG balance because of a high release of CH_4 and the loss of DOC only played a minor role. Adding the farm-based CO_2 and CH_4 emissions increased the source strength for the managed sites to 2.7 kg CO_2-eq $m^{-2}\,yr^{-1}$ for Oukoop and 2.1 kg CO_2-eq $m^{-2}\,yr^{-1}$ for Stein. Shifting from intensively managed to extensively managed grass-on-peat reduced GHG emissions mainly because N_2O emission and farm-based CH_4 emissions decreased. Overall, this study suggests that managed peatlands are large sources of GHG and carbon, but, if appropriate measures are taken they can be turned back into GHG and carbon sinks within 15 yr of abandonment and rewetting.

1 Introduction

Although peatlands cover only 6 % of the earth surface, they play a central role in the global carbon cycle (Gorham et al., 2012). In their natural state, peatlands capture carbon as carbon dioxide (CO_2) with a long term average uptake rate of $25\,g\,C\,m^{-2}\,yr^{-1}$ (Borren et al., 2006). Natural peatlands emit methane (CH_4) as a result of anaerobic conditions that lead to methanogenisis. The total balance between CO_2 uptake and CH_4 release is in most cases negative (sequestration of carbon) and is dependent on moisture conditions, temperature, vegetation composition, availability of degradable substrates and microbial activity (e.g. Hendriks et al., 2009). Generally, nitrous oxide (N_2O) does not play a significant role in the greenhouse gas (GHG) budgets of natural peatlands. While natural peatlands act as sinks for carbon, agricultural peatlands commonly act as sources for carbon and GHGs.

In Europe, 50 % of all peatlands are subject to various sorts of agricultural practices (Joosten and Clarke, 2002), often associated with drainage resulting in oxidation of peat and release of CO_2 to the atmosphere. In the Netherlands about 270 000 ha (7 % of the land surface) is peatland. Since the industrial period these peat soils were heavily drained and fertilized and they turned into carbon sources (e.g. Langeveld et al., 1997; Veenendaal et al., 2007). As a result, peat subsidence rates in the Netherlands are up to $10\,mm\,yr^{-1}$ and already 20 % of the peat soils have disappeared and classified as mineral soil in the last 30 yr (Kempen et al., 2009). In wet peatlands however, CH_4 is commonly released (e.g. Carter et al., 2012; Teh et al., 2011; Schrier-Uijl et al., 2010; Hendriks et al., 2007). Also water bodies in peat ecosystems are important contributors to the GHG balance and have therefore to be considered when calculating GHG budgets (Schrier-Uijl et al., 2011; Billet and Harvey, 2012). Emissions from wetlands, water bodies and grasslands are currently not (or only partly) included in national emission inventories (Maas et al., 2008; Nol et al., 2008). While it does not play a significant role in the GHG budgets of natural peatlands, in intensively managed peatlands high inputs of chemical fertiliser and manure lead to increased N_2O emissions.

Since there are still few comprehensive studies that report on the effects of restoration activities on the total GHG emission balance, the main goal of this paper is to analyze the long term effects of restoration through reducing the management and decreasing the ground water table depth on the GHG balance of intensively managed peatlands.

Here we present the synthesis of a landscape scale experiment that has been performed in three temperate peatlands in the Netherlands under different management regimes (intensively managed, extensively managed and a rewetted peatland under restoration). To obtain spatially and temporally explicit GHG sources and sinks, three to four years of simultaneous measurements were conducted with chamber and micrometeorological techniques to cover different spatial and temporal scales and the entire suite of biogenic key GHGs (CO_2, CH_4 and N_2O). The studies that published on the first results of the separate sites are Schrier-Uijl et al. (2009, 2010, 2011), Kroon et al. (2010a,b,c), Hendriks et al. (2007) and Veenendaal et al. (2007). In this paper results of later years have been analysed and the three sites have been compared. For full accounting of the carbon and GHG balance also carbon import and export by management has been analysed and water bodies are included in the calculations.

2 Materials and methods

At three low land peat sites in the Mid West of the Netherlands, the exchange of CO_2, CH_4 and N_2O between the soil–plant continuum and the atmosphere was measured in detail at various scales, using various measurement techniques. Measurements have been cross-checked to robustly investigate the effect of restoration on the GHG balance. The three research sites (Oukoop, Stein and Horstermeer) are located below sea level in a moderate climate. All sites are (fibric) eutric histosols, the mean annual air temperature is 9.8 °C and the mean annual rainfall is 797 mm. In this publication a general description of materials and methods is given; the reader is referred to previous publications (Schrier-Uijl et al., 2009, 2010, 2011; Kroon et al., 2010a,b,c; Nol

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et al., 2008; Hendriks et al., 2007; Veenendaal et al., 2007) for more detailed information for the specific sites and methods used. Table 1 gives an overview of the main site characteristics and the management per site.

2.1 Measurement sites

The Oukoop site (Ou) is an intensively managed grassland polder on peat in the west of the Netherlands (lat. 52°02′ N, long. 4°47′ E, altitude – 1.8 m a.s.l.). The site is part of a dairy farm and grass is regularly mowed to feed cows that are kept on the farm. Manure and fertilizers are applied four or five times anually in the period February to September. The area has a clayey peat or peaty clay top layer of about 0.25 m thickness on a 12 m thick peat layer on a mineral subsoil. Sixteen percent of the total polder is open water (drainage ditches, small ponds, shallow lakes), 5 % are bordering (water saturated) edges and the remaining part consists of relatively dry fields with dynamic mean annual ground water tables at 0.55 m below field level. The dominant grass species are *Lolium perenne* and *Poa trivialis*.

The Stein site (St) is an extensively managed grassland polder on peat 4 km South-West of the Oukoop site (lat. 52°01′ N, long. 4°46′ E, altitude – 1.7 m a.s.l.). The area has been managed as a meadow bird reserve since 2001 which implies that no manure or artificial fertilizers are applied ever since and that management only comprises the removal of above ground biomass three times a year. The polder was intensively used for grass production in the same way as the Oukoop polder before it gradually became a meadow bird reserve. The area has the same soil characteristics as the Oukoop site and land use history was similar before Stein was taken out of production. The ground water table is dynamic since 2006 with high water tables in winter and low water tables in summer; the ground water table is on average 0.45 m below field level. The proportions of land and water are similar to the Oukoop site (16 % open water; 5 % water saturated borders; 79 % relatively dry land). The dominating plant species were *Lolium perenne* and *Poa triviales*, but over time *Anthoxantum odoratum* and *Rumex acetosa* have become more abundant.

The Horstermeer site (Ho) is a grassland/wetland polder on peat in a former intensively used dairy farm area in the centre of the Netherlands (lat 52°02′ N, 5°04′ E, altitude −2.2 m a.s.l.) located about 40 km NE from Oukoop and Stein. The site has been abandoned in 1998 and has not been exploited agriculturally ever since. The management was about similar to that of Stein and Oukoop until abandonement. After abandonment, the ditch water table has been raised to approximately 0.10 m below the land surface. The vegetation has developed towards a semi-natural grassland. Five percent of the area is open water (ditches), 10 % is year-round saturated soil (mostly along the ditches), 25 % is relatively wet soils and 60 % is relatively dry land with a fluctuating ground water table (between 0–0.40 m below the soils surface, 0.20 m annual average) with an aerated top-layer during the largest part of the year. No management takes places, except for ditch water table regulation. Dominant species are *Holcus lanatus, Phalaris arundinacea, Glyceria fluitans*, reeds and high forbs.

2.2 Instrumentation and methodology

To capture temporal variability of fluxes, all three sites were equipped with eddy covariance (EC) systems for CO_2since the end of 2004 for four years (for details of the systems see Veenendaal et al., 2007 for Oukoop and Stein and Hendriks et al., 2007 for Horstermeer). In addition, Oukoop was equipped with an EC system for CH_4 and N_2O since the beginning of 2006 for three years (details in Kroon et al., 2007, 2010b). In April 2006 the Horstermeer site was equipped with an EC system for CH_4 (Hendriks et al., 2008, 2009). At the Oukoop and Stein sites chamber measurements were performed from January 2006 to December 2008 (Schrier-Uijl et al., 2010) and at the Horstermeer site from January 2005 to December 2008 (Hendriks et al., 2007). For the three sites, similar measurement procedures, flux calculation methods, gap filling techniques and up-scaling methods were used to calculate annual GHG fluxes. Procedures to calculate annual fluxes are explained in more detail in Schrier-Uijl et al. (2009, 2010); Kroon et al. (2007, 2010b); Hendriks et al. (2009, 2007) and Veenendaal et al., (2007). For spatial up-scaling of chamber measurements, the landscape elements (ditches, saturated soil, dry soil) that contributed significantly different to the GHG balance were taken into account proportionally.

2.3 Small-scale flux measurements

Small-scale flux measurements were performed on fields and open water for CO_2 and CH_4 using a Photo Acoustic Field Gas Monitor (type 1412, Innova AirTech Instruments, Ballerup, Denmark) connected with Teflon tubes to closed opaque chambers (height 0.2 m, diameter 0.3 m). A fan was installed in the chamber to homogenize the inside air and two external filters were added: a soda lime filter for CO_2 (when measuring CH_4) and a silica gel filter for water vapour. To avoid disturbances, vegetation was not removed prior to the flux measurements. Concentration build-up in the chamber headspace was measured for 6 min at one minute intervals. Because the relations with explanatory variables were non-linear, multiple non-linear regression was used to calculate annual emissions, and the landscape elements that contributed significantly differently to the GHG balance were taking into account by using a weight factor. Additional to the three years measurements on ditches, in the summer of 2009 an intensive measurement campaign was performed on 6 large shallow lakes and 14 drainage ditches in peatlands (Schrier-Uijl et al., 2011) to compared fluxes from water bodies that were different in depth, size and nutrient status. Cross-checks of emission values were performed by comparing eddy covariance measurements to upscaled chamber measurements within the footprint of the eddy covariance systems (Schrier-Uijl et al., 2009; Hendriks et al., 2009).

2.4 Landscape scale flux measurements

Landscape scale flux measurements of CO_2, CH_4 and N_2O were performed using the EC flux technique. Footprints of all EC flux towers were over the entire landscape, including fields, ditches and ditches edges but excluding farms and other GHG hotspots. EC flux systems for CO_2 at the three sites consisted of a sonic anemometer and a fast

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response CO_2-H_2O analyzer. Open path infrared gas analyzers (LI-COR Lincoln, NE, USA) were used 4.3 m above the soil surface in Horstermeer and 3.05 m above the soil surface in Oukoop and Stein. Oukoop was also equipped with an EC flux system for CH_4 and N_2O in the period 2006–2008 consisting of a sonic anemometer and a Quantum cascade laser spectrometer (model QCL-TILDAS-76, Aerodyne Research Inc., Billerica MA, USA). In all three sites additional micrometeorological measurements were performed.

2.5 Additional measurements

In addition to EC devices and chamber measurements, towers with meteorological instruments were installed at each site which provided 30 min averages of global radiation (R_{in}), net radiation (R_{net}), air temperature (T_{air}), vapour pressure (P_{vap}), wind speed (U), wind direction (D) and precipitation (P). Soil measurement sensors included soil heat flux plates (HPF01, Campbell Scientific, USA), soil temperature sensors at depths of 0.02, 0.04, 0.08, 0.16 and 0.32 m (Campbell Scientific, USA) and soil moisture probes to measure volumetric moisture contents at depths of 0.10, 0.20 and 0.30 m (Theta probes ML 2x; Delta T devices Burwell, UK). These systems provided 30 min values for soil heat fluxes, soil temperature, soil moisture and water table. At the beginning and the end of the experiments (2005 and 2008), soils were sampled and analyzed for C and N content, organic matter, NO^{3-}, NH^{4+}, PO_4^{3-} and pH. Water from drainage ditches was sampled for pH, C content (not for Horstermeer), N content (not for Horstermeer), organic matter, NO_3^-, NH_4^+, PO_4^{3-}, SO_4^{2-}, Fe^{2+}, dissolved CH_4, oxygen saturation and electrical conductivity. Well-stirred samples of slurry manure were sampled just before manure application in the Oukoop site and were analyzed for dry matter and C content. To estimate the above ground biomass and biomass removal, vegetation height was measured every three to four weeks to estimate above ground biomass and biomass removal using the relationship between vegetation height and biomass weight as discussed in Veenendaal et al. (2007).

2.6 Estimates of GHG balances and carbon balances

The total GHG balance and carbon balance of the sites consist of (1) ecosystem sinks and sources (including fluxes from fields, saturated parts of the land and drainage ditches and release of dissolved organic carbon (DOC) through water bodies) and in the managed sites (2) sinks and sources related to farm activities such as carbon that is lost or gained through mowing of plant biomass, animal body mass and milk production and slurry and fertilizer application. An overview of the GHG fluxes and C fluxes that have been considered in the calculation of balances in this study is given in Fig. 1.

The ecosystem GHG balance of each experimental site was calculated for three years by summation of the net ecosystem exchange of CO_2, CH_4 and N_2O using the global warming potential (GWP) of each gas at the 100 yr time horizon (IPCC, 2007). Thus

$$\mathrm{NEE_{GHG}} = \mathrm{NEE_{CO_2}} + 25\mathrm{NEE_{CH_4}} + 298\mathrm{NEE_{N_2O}} \tag{1}$$

where 25 and 298 are the global warming potentials of CH_4 and N_2O relative to the GWP of CO_2 Eq. (1), for a 100 yr time horizon.

A more detailed overview of carbon flows in the intensively managed peat area Oukoop is given in Fig. 2. The dashed box represents the boundary of the total polder system.

External carbon inputs from imported feeds and outputs through milk and meat and dissolved organic carbon losses (arrows 12, 13 and 14, Fig. 2) in Oukoop have been considered negligible. The farm-based N_2O source strength was estimated by using the farm measurements of Hensen et al. (2005). The ecosystem N_2O fluxes which are shown in Fig. 1. were measured in the Oukoop site with Eddy covariance, whereas for the Stein and Horstermeer sites these components have been estimated from Velthof et al. (1997) who estimated peat N_2O emissions from 2 yr of measurements on similar peat soils.

Farm-based CO_2 emissions (arrows 1 and 3, Fig. 2) were estimated from the amount of biomass-C imported into the farm subtracted by the amount of manure-C added on

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the fields and the amount of C emitted as CH_4. A production efficiency of 7 % for large mammals is used (Van Raamsdonk et al., 2007; Nieveen et al., 2005; Guinand-Flament et al., 2007).

Farm-based CH_4 emissions (arrows 2 and 4, Fig. 2) from the cattle and the stable were estimated following the emission factor approach described by Hensen et al. (2006)

$$E_{CH_4 farm} = N_{dairy} + N_{heiferEy} + N_{CalvesEc} + A_{manureEm} + A_{FYMEf} \quad (2)$$

with N the number of animals, A the amount of manure or farmyard manure (m^3) and with emission factors for dairy cows (Ed), heifers (Ey), calves (Ec), manure in storages (Em) and farmyard manure (Ef). The emission parameters were 274 g CH_4 day^{-1} $animal^{-1}$ for cows 170 g CH_4 day^{-1} $animal^{-1}$ for heifers, 48 g CH_4 day^{-1} $animal^{-1}$ for calves, 53 g CH_4 day^{-1} m^{-3} for fertiliser and 40 g CH_4 day^{-1} m^{-3} for farmyard manure – all ±50 % (Sneath et al., 2006; Van Amstel et al., 2003).

For the fluxes that are considered in the Horstermeer site, the reader is referred to Hendriks et al. (2007). Indirect emissions due to leaching and run-off were measured in the Horstermeer site, but were not directly measured in the Oukoop and Stein site. In Kroon et al. (2010b) an estimate of leaching and runoff based on the annual amount of synthetic fertilizer and the annual amount of applied cow manure (IPCC, 2006) is given for the Oukoop site.

Emissions from large water bodies such as shallow lakes were measured in the summer season, and thus no annual values have been presented for these ecosystems in this paper. Summer emissions from water bodies within peat areas and emissions from peatland were therefore compared using June and July data only. These summer fluxes have been shown to represent around 70 % of the annual CH_4 emission from drainage ditches (Schrier-Uijl et al., 2010).

2.7 Up-scaling of fluxes to regional scale

To be able to scale the site fluxes up to the entire western peatland area (115 000 ha) of the Netherlands, a detailed database was compiled using the topographic vector-based Top10Vector database (TDN, 2006), a field inventory (Nol et al., 2008), and databases of Dutch natural peatlands (Natuurmonumenten, Staatsbosbeheer, Provinciale landschappen). The resulting database distinguishes between intensively and extensively managed peatland and ditches and ditch edges within these peatlands. Under the assumption that fluxes measured in the intensively managed area and the extensively managed area in this study were representative for the Dutch western peatland area, the emissions have been extrapolated to a larger area. Table 2 shows the areas of the land use and landscape elements.

3 Results

3.1 Carbon dioxide balance

Figure 3 shows the daily measured CO_2 NEE for all three sites for the period 2005–2008 and the cumulative NEE for each year. The unmanaged site was a CO_2 sink in all years (range −1034 to −1939 g CO_2 m^{-2} yr^{-1}), with periods of a net (small) release in late winter/early spring periods and with net uptake in the rest of the year. The managed sites appeared to be sources of CO_2 in all years, except for Oukoop being a marginal sink for CO_2 in 2007 which was a relatively wet and cold year and Stein being a marginal sink of CO_2 in 2005 (range −173 to +747 and −88 to +790 g CO_2 m^{-2} yr^{-1} for Oukoop and Stein, respectively).

Temporal variability of the annual net ecosystem exchange (NEE) (excluding management related fluxes) was high, but NEE of CO_2 in the three areas showed a clear difference between the managed (Oukoop and Stein, net release) and the unmanaged (Horstermeer, net uptake) peatlands (Table 3). The unmanaged peatland (Horstermeer) had an average CO_2 NEE uptake of 1.4 kg CO_2 m^{-2} yr^{-1}, while the two managed peatlands (Stein and Oukoop) had an average release of 0.4 kg CO_2 m^{-2} yr^{-1} over a four years period. Inter-annual variability was high, but seasonal trends were the same for each year (Fig. 3). In the years 2006 and 2008 the managed systems had the highest release of CO_2 in, while the unmanaged system had the highest uptake in the year 2007.

Monthly CO_2 NEE values show (Fig. 4) that the difference between the managed areas with low water tables and the unmanaged area with high water table is largest in the growing season. The former agricultural peatland, Horstermeer, with its unmanaged vegetation is a large sink in this period while Oukoop and Stein are only minor sinks.

Farm-based CO_2 emissions were calculated from the biomass-C fed to the cows on the farm and the transformation to manure-C. With an assimilation efficiency of 7 % for large mammals, and 142 g C m^{-2} yr^{-1} exported as manure to the fields and a farm based CO_2 emission of 57 g C m^{-2} yr^{-1}, the total farm based CO_2 release is estimated at 0.7 kg CO_2 m^{-2} yr^{-1}. The total (ecosystem + farm based) CO_2 emission is than 2.7, 2.1 and −1.4 kg CO_2 m^{-2} yr^{-1} for Oukoop, Stein and Horstermeer, respectively.

3.2 Methane balance

For all three sites, soil and water temperature were the most significant predictors of CH_4 emissions and temperature is therefore used as explanatory variable to determine annual balances (Schrier-Uijl et al., 2010; Hendriks et al., 2007). Annual emissions of Oukoop and Stein for 2006–2008 and for Horstermeer from 2005–2008 are given in Table 4.

Figure 5 shows the temporal variability (daily values) and the cumulative terrestrial NEE_{CH_4} (including fields, saturated land and open water) over three years for all three sites, calculated from chamber measurements based regressions. For the Oukoop site also three years of eddy covariance measurements are shown. Modelled emissions

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based on chamber measurements are less detailed compared to the eddy covariance measurements because only temperature is used as predictive variable. Annual cumulative CH_4 values are similar for Oukoop and Stein and are higher for the Horstermeer site. The CH_4 emissions varied widely with the season, reaching highest levels during summer. Spatial variability was found to be high between landscape elements within an ecosystem (Schrier-Uijl et al., 2010; Hendriks et al., 2007, 2009) and between ecosystems (this study).

Schrier-Uijl et al. (2010) reported additional farm-based emissions of 17 and 26 g CH_4 m^{-2} yr^{-1} for Stein and Oukoop, respectively, for the years 2006, 2007 and 2008. The sum of terrestrial CH_4 emissions and farm-based CH_4 emissions amounted to 43.0 g CH_4 m^{-2} yr^{-1} for Oukoop, 33.7 g CH_4 m^{-2} yr^{-1} for Stein, and 19.2 g CH_4 m^{-2} yr^{-1} for Horstermeer.

3.3 Carbon balance

The terrestrial CO_2 source estimates of 0.4 kg CO_2 m^{-2} on average over four years for Oukoop and Stein and −1.4 kg CO_2 m^{-2} for Horstermeer result in an average carbon source strength of 1091 kg C ha^{-1} yr^{-1} for Oukoop and Stein and 4515 kg C ha^{-1} yr^{-1} for Horstermeer.

The average CH_4 emission estimates of 17.0 and 16.7 g CH_4 m^{-2} for Oukoop and Stein and 19.2 for Horstermeer (Table 4) result in an average carbon source strength of 127.5, 125.3 and 144.0 kg C ha^{-1} yr^{-1}, respectively.

The average annual remittal of C through manure into the field was estimated at 157 g C m^{-2} on average over the period 2005–2008; 64.5 m^3 ha^{-1} manure was applied during this period of which 310 kg N ha^{-1}. Fertiliser application amounted to 88 kg N ha^{-1} on average for the four years.

Removal of biomass in Oukoop was estimated at 8.1 t dry matter on average for 2005, 2006 and 2008, respectively or on average a loss of 400 g C m^{-2} yr^{-1}. In Stein carbon loss by biomass removal was similar in al years estimated at 420 g C m^{-2} yr^{-1}.

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The removed biomass was fed to the dairy cattle in Oukoop and is transformed to manure-C. With a assimilation efficiency of 7 % for large mammals, 142 g C m^{-2} yr^{-1} exported to the fields as manure and a farm based CH_4 emission of 57 g C m^{-2} yr^{-1}, the farm based C release will be around 0.19 kg m^{-2} yr^{-1}.

Figure 6 shows the total carbon balance for the three sites, taking into account the emissions of CO_2 and CH_4, manure application and biomass export as described above. The total C-release in Oukoop and Stein is 5.9 and 7.4 Mg C ha^{-1} yr^{-1}, respectively and the total C-uptake in Horstermeer is 4.4 Mg C ha^{-1} yr^{-1}.

3.4 Nitrous oxide balance

Measured cumulative NEE N_2O over a three years period was in the intensively managed site (Oukoop) previously determined (Kroon et al., 2010b). Emissions have been separated in (1) background emissions, (2) fertilizer related indirect (peak) emission and (3) emissions due to atmospheric deposition. In Oukoop also farm-based N_2O emissions from manure storages (estimated at 1.5×10^{-2} g N_2O m^{-2} yr^{-1}) were added to the total N_2O balance, although not significant. Nitrous oxide emissions in the extensively managed site (Stein) and unmanaged site (Horstermeer) were estimated based on (Velthof et al., 1997), since the used chamber set-up was not sufficient to detect the low N_2O emissions in these sites. Table 5 shows all N_2O flux estimates.

3.5 Total GHG balance

Figure 7 shows the total GHG balance of the three sites in terms of warming potential.

Methane emissions from drainage ditches and saturated soil edges along ditches were significantly higher compared to fluxes from the relatively dry land (Schrier et al., 2010; Hendriks et al., 2007). The CH_4 component in the GHG balance in the studied sites consists of outgoing fluxes only and N_2O emission in the intensively managed site consists of emissions originating from fertilizer events and from background emission.

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Overall, the managed peatlands acted as terrestrial GHG sources of 1.4 and 1.0 kg CO_2-eq $m^{-2} yr^{-1}$ (including CO_2, CH_4 and N_2O), respectively for Oukoop and Stein and the unmanaged site acted as a GHG sink of 0.8 kg CO_2-eq $m^{-2} yr^{-1}$. Ecosystem N_2O emissions were dominant in the intensively managed peatland, while CO_2 and CH_4 dominated the ecosystem GHG balance of the extensively managed peatland. In the unmanaged peatland CO_2 was the dominating ecosystem GHG. Adding the farm based CH_4 and CO_2 emissions decreased the relative importance of N_2O in the total GHG balance of the intensively managed peatland. The difference in total source strength between the intensively managed peatland and the extensively managed peatland was mainly attributed to the higher N_2O emission and the higher farm-based CH_4 emissions in the intensively managed site.

4 Discussion

4.1 Balances

Long term emission values of the GHGs and carbon fluxes were compared for peatlands under different management: a drained intensively managed grass-on-peatland with application of fertilizer and biomass export, a drained extensively managed grass-on-peatland with biomass export only and a shallow drained former agricultural peatland under restoration since 1998. Significant differences in GHG emissions have previously been reported between landscape elements within these three sites: CH_4 emissions from drainage ditches and saturated soil were significantly higher compared to CH_4 emissions from the relatively dry land, (Schrier-Uijl et al., 2009; Hendriks et al., 2007) and CH_4 fluxes from shallow lakes in the peat area contribute significantly to the GHG balance (Schrier-Uijl et al., 2010). Emissions originating from the operating farm in the intensively managed peat were found to be important contributors to the GHG balance and as well as to the carbon balance (Schrier-Uijl et al., 2009; Veenendaal et al., 2007).

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Both managed experimental grass-on-peat-areas, Oukoop and Stein, acted as CO_2 emissions sources. Variation in NEE CO_2 in Oukoop and Stein was mainly a result of management: Oukoop has the most variable NEE which is a result of the very high frequency of mowing, grazing and manure application. Sharp decreases in NEE are a direct result of mowing events in Oukoop. In Stein management, and therefore variability in NEE, showed less variability with the first biomass removal on the 15th of June and the second biomass removal in September of each year. Both areas had the same history in terms of management, and only during the past 20 yr the Stein site has gradually become a meadow bird reserve. This change has not resulted in a significant difference of annual NEE compared to the intensively managed site. The unmanaged site, Horstermeer, the site under restoration, acted as a CO_2 sink. The cumulative NEE shows a stable pattern with high uptake rates in spring and summer. The Horstermeer site is still under restoration and despite its abandonment since 1998 soil conditions have remained eutrophic because of influx of eutrophic ground water from the surrounding area. The continuing nutrient-rich conditions generate high plant productivity and microbial activity, resulting in high carbon fluxes (both uptake and emissions) and more organic matter is accumulated than oxidized (Hendriks et al., 2009). However, as succession may move this system to a more natural peat vegetation, NEE (and thus uptake) may reduce in the future.

All three sites, Oukoop, Stein and Horstermeer, acted as sources for CH_4. Temporal variability (daily, seasonally and annually) was high at all three sites, but in the two managed sites no diurnal cycles were observed after correction for temperature (Schrier-Uijl et al., 2011). In the Horstermeer site clear diurnal cycles were found during all seasons synchronous to incoming radiation (Hendriks et al., 2009). They attribute this to the stomatal opening and/or pressurized convective gas transport through the vascular plants with highest emissions in the late afternoon and lowest emissions during the night, as is also reported for other swamp areas (e.g. Whiting and Chanton, 1993; Hirota et al., 2004). Differences in ecosystem CH_4 emissions between sites were not

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significant. Farm practices in Oukoop and Stein caused an estimated additional CH_4 emission of 26 and 17 g CH_4 m^{-2}.

The total source strength (ecosystem + farm-based emissions) decreases when management intensity decreases. The Horstermeer is a polder under restoration, but the end stage of restoration will depend on management intensity of the surrounding area affecting groundwater supply and nutrient input. Even if influx of nutrient rich water from surrounding areas and atmospheric nutrient deposition stops, it may be necessary to remove the strongly eutrophic top layer for succession to reach a near-natural system as e.g. studied by Van den Pol-van Dasselaar et al. (1999). Van den Pol-van Dasselaar et al. (1999) studied the emission of CH_4 over two years in three near-natural peatlands in a Dutch nature preserve with narrow grasslands (mown once a year), reed fields and ditches and ground water level at 18 cm below field level. Soils were similar to the soils of the sites in this research. The average field-CH_4 fluxes were 13.3, 20.4 and 7.9 g CH_4 m^{-2} yr^{-1} and ditch fluxes were 11.3 g m^{-2} yr^{-1}on average. After weighing the contributions of water and land CH_4 emissions were on average significantly lower than the emissions measured in this study. Reported CH_4 emissions from undisturbed peatlands are highly variable. For example a natural peatland in Quebec, Canada showed CH_4 emissions of 9.8 g m^{-2} yr^{-1} (Moore and Knowles, 1990), and Nykänen et al. (1995) reported CH_4 emissions of 34.7 g CH_4 m^{-2} yr^{-1} for Scandinavian undisturbed peat lands.

Summer CH_4 emissions from the lakes were significantly higher compared to the emissions from the managed ecosystems. In a study of Schrier-Uijl et al. (2011) the emissions from lakes appeared to be smaller than the emission from drainage ditches within the managed and unmanaged ecosystems. Comparison of "polder-ecosystem emissions" to emissions from large shallow fresh water lakes shows that water bodies are important contributors to the CH_4 balance. Summer CH_4 emissions from the three peatlands were compared to emissions from 5 large shallow fresh water lakes located in peatlands (Fig. 8).

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Calculation of the total CH_4 polder balances for the three sites is based on the current classification of the landscape with 16 % open water in Oukoop and Stein and 5 % in Horstermeer. Changing the contribution of water and/or saturated land in the landscape by reclassification will cause large changes in the CH_4 balance because these landscape elements together are responsible for over 50 % of the total flux. In conclusion, large scale spatial differences in CH_4 emission depend on the combination of management and water table and the presence or absence of water bodies. Drainage ditches, large shallow lakes and saturated land are CH_4 hotspots and therefore spatial differences greatly depend on the proportion of these landscape elements in the landscape. Temporal variability within sites was largely driven by temperature.

The carbon balance considered in this study consisted of CO_2-C, CH_4-C, biomass removal and manure and fertilizer application. The two managed sites acted as C-sources and the unmanaged site acted as a C-sink. In the two managed sites, the CO_2 emission (farm based + terrestrial) and the biomass removal accounted for the largest part of the C-release. Because in Oukoop carbon was added through manure and fertilizer inputs, the total C-release turned out to be smaller compared to Stein. In the unmanaged site Horstermeer, the C-balance was dominated by the uptake of CO_2-C. Except for the small release of C through CH_4, no other C-sources or sinks were involved in this undisturbed system. Release of C through ditch water was marginal (Hendriks et al., 2007). Measurements at the three contrasting sites show that an intensively managed fen meadow area can shift from a carbon source towards a carbon sink when the water table is raised and when management is reduced to zero. It has to be noted that possible CO_2 and/or CH_4spikes after rewetting are not included in the calculations. These possible spikes may cause an initial increase in emissions in the first years after rewetting. Estimates of these "spike emissions" are currently uncertain, more research is needed to get robust emissions factors for this emission after rewetting.

The higher background emission in Oukoop compared to Stein is likely the result of the build-up of easily decomposable organic materials in the soil due to manure

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application 5 times a year. In Stein this application has stopped almost 20 yr ago. N_2O in these types of ecosystems is produced during nitrification and/or denitrification of NO^{3-}. Nitrate is released during mineralization of soil organic N. Leaching is considered to be negligible, but this is not measured. Eddy covariance measurements in Oukoop showed a typical pattern of long periods with low emissions (background emissions) followed by short periods of high emissions (peak-emissions) around manure application (Kroon et al., 2010b). Emissions due to manure application accounted for 25 % of the total annual N_2O emissions in Oukoop. Hensen et al. (2006) show that manure based emissions from storages around the farm can cause an additional emission of 14.8 mg N_2O m^3 manure d^{-1}. With the 700 m^{-3} slurry stored around the Oukoop farm this would result in an extra (marginal) emission of 3.8 kg N_2O yr^{-1} over 50 ha or 0.08 kg N_2O ha^{-1} yr^{-1}. Emission factors around manure application were calculated by subtracting the background emission from the total emissions measured by the EC system. The emission factor range was from 1.2 to 2.8 % which is higher than the IPCC default emission factor of 1 % (Kroon et al., 2010b).

Combining all incoming and outgoing GHG fluxes shows that Oukoop is the largest GHG source in terms of warming potential. N_2O dominated the emissions in Oukoop and CO_2 and CH_4 contributed equally. In Stein N_2O was the least contributing GHG and the total emission was lower compared to Oukoop. The Horstermeer appeared to be a GHG sink with a release of CH_4 and N_2O from the system, but a large uptake of CO_2. It suggests that changing the management from intensively to extensively and further to unmanaged may change the total GHG balance from release to uptake. Water bodies were large contributors to the GHG balance when considering summer emissions of CO_2 and CH_4 (Schrier-Uijl et al., 2009, 2010).

4.2 Upscaling GHG emissions from Netherlands peatlands areas

In the western Dutch peat area 68 % is intensively managed grassland, 8 % is extensively managed grassland or unmanaged grassland, 6 % is water (Table 6) and the

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remaining part is road, farm or has other land use. With the emission values found in this study for intensively and extensively managed peatland and the total area for both of these land uses, emission estimates are performed for the total intensively managed grassland and extensively managed/unmanaged grasslands in the western peatland. The total emission, estimated using a time-horizon of 100 yr from the western peatlands is approximately 1210 Gg CO_2-eq (= kton CO_2-eq). In lakes the annual CO_2 emissions are estimated from summer measurements only, however, these fluxes have to be verified by performing year round measurements and by including all three GHG's in the balance.

4.3 Potential ways for mitigation

Mitigation of CO_2, CH_4 and N_2O in peat areas is important for two reasons: (1) to maintain this ecosystem, stop the degradation of peat soils and to stop soil subsidence and (2) to reduce GHG emissions from drained peatlands. Strategies to reduce GHG emissions from these areas and to increase carbon uptake may be oriented toward rewetting of intensively cultivated peatlands combined with reducing farm-based fluxes and decreasing management intensity.

This study shows that rewetting of agricultural peatland may turn areas of carbon release into areas of carbon uptake; the GHG balance switched from GHG source to sink. The effect might be even stronger in peat soils that lack a clay layer on top of the peat. These peat soils are extremely vulnerable to oxidation (Schothorst, 1977) and to subsidence. The dynamic water tables in the extensively managed polder (high water tables in winter and low water tables in summer) resulted in only a small reduction in GHG emission mainly due to a decrease in farm-based CH_4 emissions and a reduction in N_2O emissions because no fertilizer is applied. High water tables both in winter and in summer will likely reduce emissions. Inverse drainage systems may for this purpose be applied. The long-term duration for the sink strength in the unmanaged polder may slow down at centennial timescales due to a decrease in nutrient availability.

Farm-based emissions have not been studied separately. Sommer et al. (2009) studied farm-based emissions in Sweden, Denmark, France and Italy. The results showed that shortening the in-house manure storage and decreasing storage temperatures reduced GHG emissions from manure by 0–40 % depending on current management and climatic conditions. Large GHG reductions were obtained with slurry separation in a liquid phase and a solid, organic phase in combination with the early application of the liquid fraction compared to the solid fraction.

Summer emissions on large shallow lakes are higher than the emissions from the intensively and extensively managed polder ecosystems, but lower than the emissions from drainage ditches within the polders. It has been shown that summer emissions from water bodies can contribute significantly to the summer release in the fen meadow area. In the establishment of emission factors for the peatlands these landscape elements should be included in further inventories (Schrier-Uijl et al., 2009, 2010; Kankaala et al., 2007; Billet et al., 2012). Reduction of inputs of organic material and nutrients from the surroundings will likely reduce emissions from these water bodies (Schrier-Uijl et al., 2009, 2010).

5 Conclusions

This study strongly suggests that intensively managed, drained, agricultural peat soils, which are large GHG and carbon sources, can be turned into sinks in the long term if appropriate mitigation measures are taken. Appropriate mitigation measures are decreasing the water table depth in combination with reducing the management intensity. The switch from an intensively managed peatland to an extensively managed peatland may not significantly alter the ecosystem GHG balance, however, if farm-based emissions are zero, the total (ecosystem + farm-based) emissions decrease significantly. In addition, when implementing mitigation strategies to reduce emissions from one source, GHG emissions from other sources might also be reduced. For example, when the input of nutrient-rich (ground) water in lakes and drainage ditches will be reduced by reducing management in the surrounding catchments, also emissions from water bodies will likely be decreased. Conclusions related to the effect of management on GHG emissions from peatlands are summarized in Table 7.

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Table 1. Site descriptions, land use and management per peat site.

Loc.	Peat depth	Land elements				Land use	Grazing[b]	Biomass	Cow manure	Fertiliser
		Dry land	Wet land	Saturated land	Water			removal[b]	applied[b]	applied[b]
	(m)	%	%	%	%			($t\,ha^{-1}\,yr^{-1}$)	($kg\,N\,ha^{-1}\,yr^{-1}$)	($kg\,N\,ha^{-1}\,yr^{-1}$)
Ou[a]	12	79		5	16	intensively managed grassland	2005 and 2006 by some cows	12	300	88
St[a]	12	79		5	16	extensively managed hayfield	young cattle few days per year	10	0	0
Ho[a]	2.1	60	25	10	5	former managed area under restoration	none	0	0	0

[a] Ou = Oukoop, St = Stein, Ho = Horstermeer.
[b] Values related to management are averaged over the years 2006, 2007 and 2008.

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Table 2. Landscape elements in the Dutch peatlands.

Landscape element/land use	Surface area (ha)	Surface area (%)
Grassland/intensively managed	78 375	68 %
Grassland/extensively managed	8786	8 %
Water	6717	6 %
Urban area (incl. greenhouses)	983	1 %
Roads	4490	4 %
Forest	2716	2 %
Cropland	1818	2 %
Other land use	11 258	10 %
Total	115 142	100 %

[a] n.e. = not estimated
Kadaster, 2010. Product information TOP10vector (in Dutch). Topografische Dienst Kadaster, Emmen, the Netherlands. Available at http://www.tdn.nl/ (verified 3 May 2010).

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Table 3. Terrestrial carbon dioxide flux estimates (kg CO_2 m^{-2}) measured by eddy covariance in the period 2005–2008 for the intensively managed production grassland on peat (Ou), the extensively managed hayfield on peat (St) and the unmanaged former agricultural peatland (Ho). Fluxes from shallow lakes are measured in the summer of 2009. Fluxes from removed biomass are not included in this table.

Site	Carbon dioxide NEE[a] per year (kg CO_2 m^{-2} yr^{-1}) 2005	2006	2007	2008	Average
Ou	0.4	0.7	−0.2	0.7	0.4
St	−0.09	0.8	0.3	0.8	0.4
Ho	−1.0	−1.0	−1.9	−1.5	−1.4

[a] NEE = Net Ecosystem Exchange.

[b] Fluxes are measured in the summer (June/July) of 2009 in 5 large shallow lakes located in peatlands.

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Table 4. Yearly methane fluxes ($g\,CH_4\,m^{-2}\,yr^{-1}$) (1) measured by the chamber method and calculated by using landscape element weighted predictive relationships for Oukoop, Stein and Horstermeer and (2) measured by eddy covariance in the intensively managed site and modelled by using predictive relationships. Uncertainties are given within brackets and are averaged over the three or four years. Farm based emissions are not included in this table.

Ecosystem	Annual methane fluxes ($g\,CH_4\,m^{-2}\,yr^{-1}$)				Average emission ($g\,CH_4\,m^{-2}\,yr^{-1}$)
Spatially weighted for contribution of fields, ditches and edges	2005	2006	2007	2008	Average
Ou (chamber-method)	NA[1]	20.3	16.2	14.6	17.0 (±56 %)
Ou (eddy covariance-method)	NA[1]	17.2	16.6	15.5	16.4 (±37 %)
St (chamber-method)	NA[1]	15.7	18.0	16.3	16.7 (±59 %)
Ho (chamber-method)	19.1	20.5	19.8	17.6	19.2 (±65 %)

[a] NA = not available.

Table 5. Nitrous oxide flux estimates (kg N_2O ha^{-1} yr^{-1}) and their uncertainties (u) for the intensively managed site (Oukoop), extensively managed site (Stein) and the unmanaged peatland (Horstermeer).

Site	Source	Reference	Total emission (kg N_2O ha^{-1} yr^{-1})
Oukoop	Background emission[a]	Kroon et al. (2010)	24 (±28 %)
	due to fertilizers[b]	Kroon et al. (2010)	
	due to leaching and run-off	Kroon et al. (2010); IPCC (2006)	
	due to deposition	Kroon et al. (2010); IPCC (2006)	
Stein	Total emission	Velthof et al. (1997); IPCC (2006)	8 (±100 %)
Horstermeer	Total emission	Velthof et al. (1997); IPCC (2006)	8 (±100 %)

[a] Background emissions are determined by a multivariate regression model based on EC flux data excluding EC fluxes measured around a management event.
[b] Emissions due to fertilizer application have been determined by subtraction the background emission from the total measured N_2O emission around fertilizer application. The IPCC default value of 1 % is used for the missing fertilizing events.

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Table 6. Estimated area and annual GHG release for the area of intensively managed and extensively managed (mown only) or unmanaged grasslands on peat within the total western peatland region of the Netherlands. Farm-based emissions are not included.

Ecosystem type	Area in western peatland		Total N_2O emission	Total CH_4 emission	Total CO_2 emission
	(ha)	(% of total)	10^3 kg N_2O yr^{-1}	10^3 kg CH_4 yr^{-1}	10^3 kg CO_2 yr^{-1}
Intensively managed grassland	78 375	68 %	1,653	12 853	313 498
Extensively managed/ unmanaged grassland	8786	8 %	43	1577	35 145
Shallow water bodies	87	6 %	unknown	unknown	33 583[a]

[a] An annual emission of 0.5 kg CO_2 m^{-2} yr^{-2} was assumed (Table 3).

Table 7. Overview of the expected effects of different mitigation strategies on the total GHG balance (ecosystem + farm based emissions). The effect on the GHG balance has been determined for the three research sites Oukoop (intensively managed), Stein (extensively managed) and Horstermeer (unmanaged) and are not including the expected future temperature rise. (–) = decrease in emission, (+) = increase in emission, (0) = neutral effect, (?) = effect unknown, (x) = not relevant.

	Rewetting + management reduction			Management reduction towards extensively managed			Increase in % open water with no reduction of management in the catchment		
	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O
Intensive management	–	–	–	0	–	–	–	+	–
Extensive management	–	–	–	x	x	x	–	+	?
Unmanaged/rewetted	x	x	x	x	x	x	–	+	?
Open water	–	–	–	–	–	–	x	x	x

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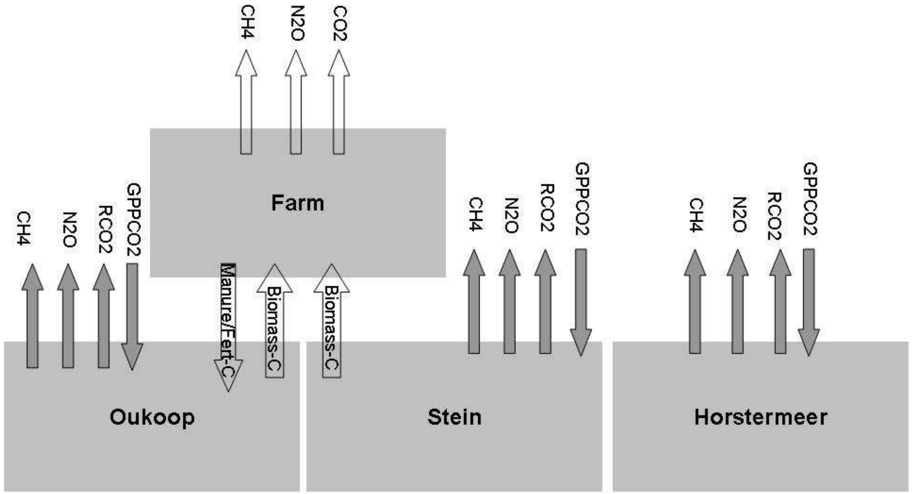

Fig. 1. Ecosystem and farm-based GHG fluxes (CO_2 respiration (R_{CO_2}), CO_2 gross primary production or photosynthesis (GPP_{CO_2}), CH_4 and N_2O) and carbon fluxes (CO_2-C, CH_4-C, manure and fertilizer-C, biomass-C) that are being considered in the current study for Oukoop, Stein and Horstermeer. White arrows are farm-related fluxes and dark grey arrows are ecosystem fluxes.

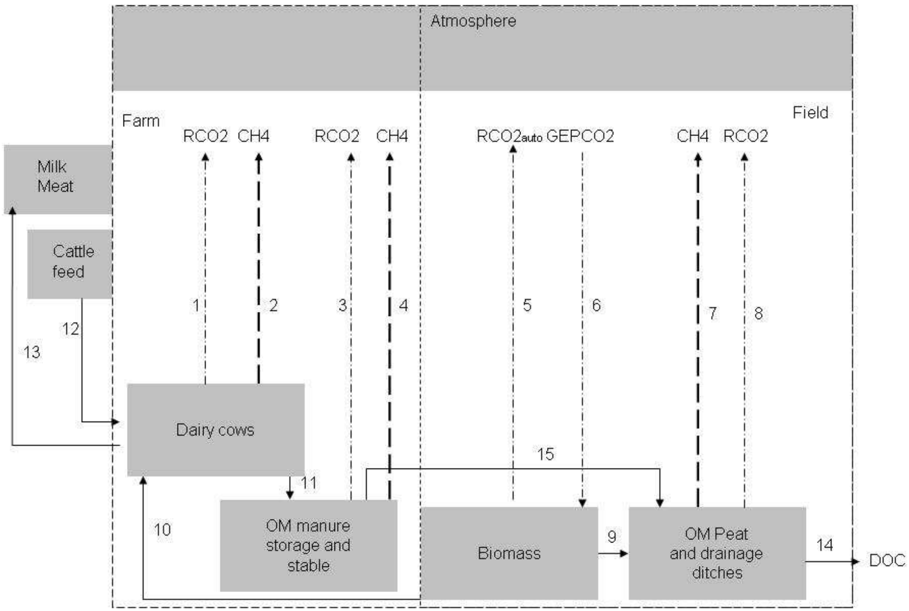

Fig. 2. System boundaries and fluxes of the intensively managed area Oukoop. Black arrows are C flows, thick dashed arrows are CH_4 fluxes and dashed arrows are CO_2 fluxes (autotrophic and heterotrophic respiration; $R_{CO2auto}$ and R_{CO_2}, respectively and photosynthesis (GEP_{CO_2})).

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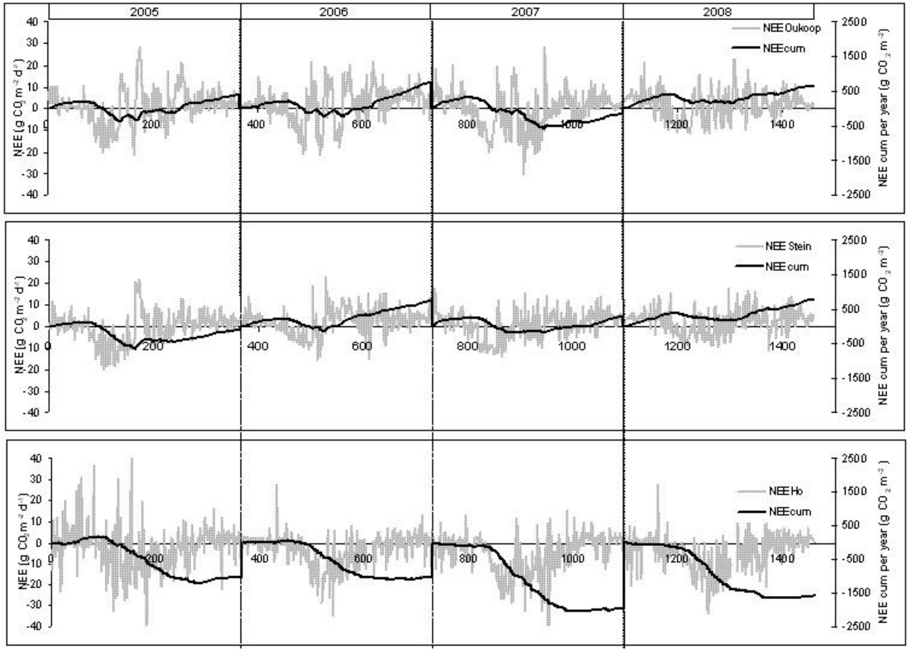

Fig. 3. Daily NEE CO_2 for the Oukoop (intensively managed), Stein (extensively managed) and Horstermeer (unmanaged) peatlands measured by the eddy covariance flux technique. The black line represents the cumulative NEE for each year separately (y-axis on the right) and the grey line represents the temporal variability of NEE on the time scale of a day (y-axis on the left).

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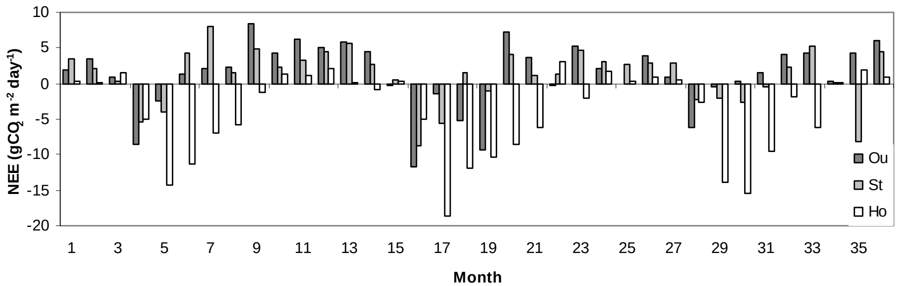

Fig. 4. Monthly NEE CO_2 values for the three experimental sites. The CO_2 NEE is given on the y-axes in g CO_2 m^{-2} d^{-1} and the month numbers are given from 2006–2008 on the x-axes.

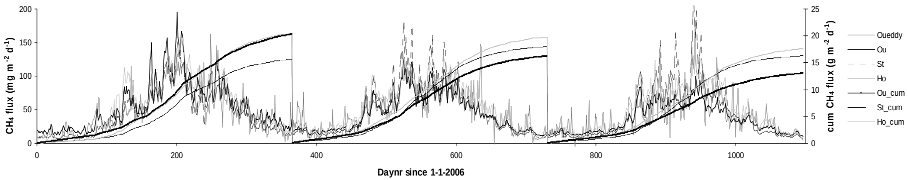

Fig. 5. Temporal variability of terrestrial CH_4 fluxes for the three experimental sites modelled by predictive relationships based on chamber measurements and additionally for Oukoop measured by eddy covariance. The right-hand y-axes represents the cumulative CH_4 flux over the three years. Fluxes are weighted by the contribution of each landscape element.

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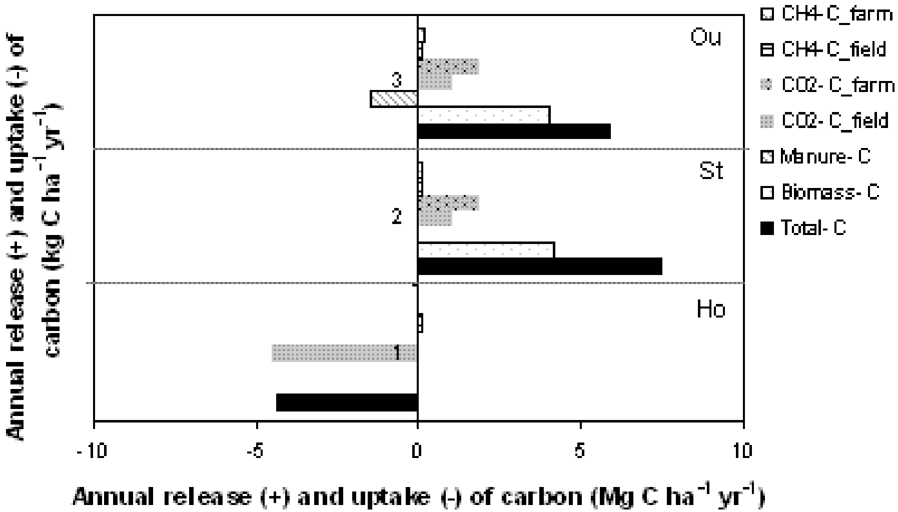

Fig. 6. Summary of all considered carbon fluxes in the research areas Horstermeer (Ho), Stein (St) and Oukoop (Ou) averaged over 2005, 2006, 2007 and 2008. The annual carbon balance is presented in Mg C ha^{-1} yr^{-1}, (+) is release and (–) is uptake, and consists of fluxes due to GHG emissions (NEE CO_2 and NEE CH_4) and fluxes due to management (farm based fluxes, manure application and biomass removal).

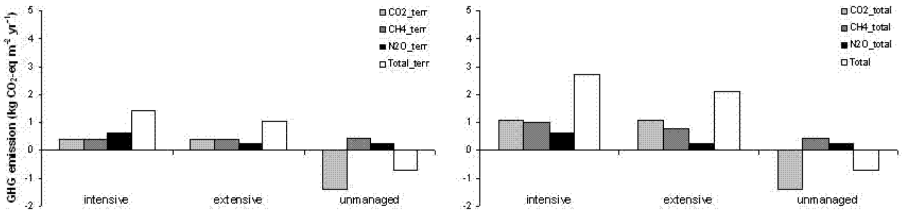

Fig. 7. The GHG balances including CO_2, CH_4 and N_2O for the three sites: intensive (Oukoop), extensive (Stein) and unmanaged (Horstermeer). On the left excluding farm-based CH_4 and CO_2 emissions and on the right including farm-based CH_4 and CO_2 emissions, averaged over 2006, 2007 and 2008 (fluxes are given in warming potentials, kg CO_2-equivalents $m^{-2}\,yr^{-1}$).

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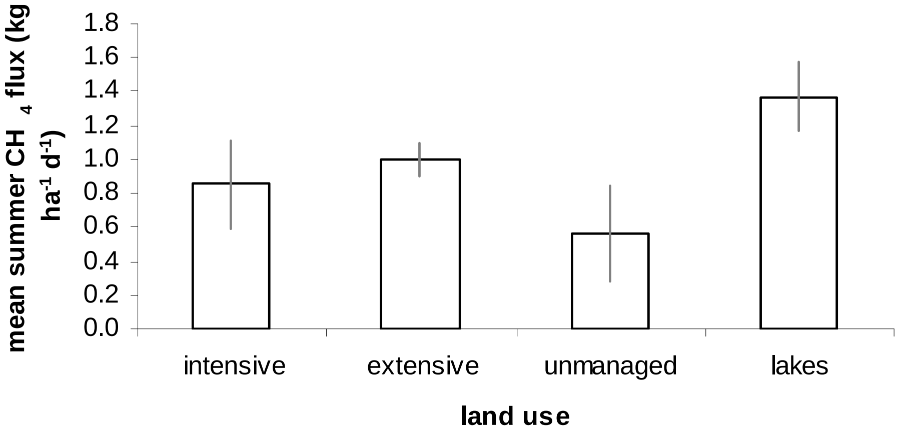

Fig. 8. Comparison of summer (June/July) CH_4 fluxes between different ecosystems in peatlands. Fluxes are averaged over three years for the polder Oukoop (intensive), the polder Stein (extensive) and the polder Horstermeer (unmanaged). The lake fluxes are measured in one summer (June/July, $n = 97$) and are averaged over 5 large shallow lakes; error bars represent the standard deviation of the mean.

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