Biogeosciences, 12, 2101–2117, 2015
www.biogeosciences.net/12/2101/2015/
doi:10.5194/bg-12-2101-2015

Greenhouse gas exchange of rewetted bog peat extraction sites and a *Sphagnum* cultivation site in northwest Germany

C. Beyer and H. Höper

State authority for Mining, Energy and Geology, Hanover, Germany

Correspondence to: C. Beyer (jcbeyer@uni-bremen.de)

Received: 8 January 2014 – Published in Biogeosciences Discuss.: 21 March 2014
Revised: 7 December 2014 – Accepted: 16 December 2014 – Published: 7 April 2015

Abstract. During the last decades an increasing area of drained peatlands has been rewetted. Especially in Germany, rewetting is the principal treatment on cutover sites when peat extraction is finished. The objectives are bog restoration and the reduction of greenhouse gas (GHG) emissions. The first sites were rewetted in the 1980s. Thus, there is a good opportunity to study long-term effects of rewetting on greenhouse gas exchange, which has not been done so far on temperate cutover peatlands. Moreover, *Sphagnum* cultivating may become a new way to use cutover peatlands and agriculturally used peatlands as it permits the economical use of bogs under wet conditions. The climate impact of such measures has not been studied yet.

We conducted a field study on the exchange of carbon dioxide, methane and nitrous oxide at three rewetted sites with a gradient from dry to wet conditions and at a *Sphagnum* cultivation site in NW Germany over the course of more than 2 years. Gas fluxes were measured using transparent and opaque closed chambers. The ecosystem respiration (CO_2) and the net ecosystem exchange (CO_2) were modelled at a high temporal resolution. Measured and modelled values fit very well together. Annually cumulated gas flux rates, net ecosystem carbon balances (NECB) and global warming potential (GWP) balances were determined.

The annual net ecosystem exchange (CO_2) varied strongly at the rewetted sites (from -201.7 ± 126.8 to 29.7 ± 112.7 g CO_2-C m^{-2} a^{-1}) due to differing weather conditions, water levels and vegetation. The *Sphagnum* cultivation site was a sink of CO_2 (-118.8 ± 48.1 and -78.6 ± 39.8 g CO_2-C m^{-2} a^{-1}). The annual CH_4 balances ranged between 16.2 ± 2.2 and 24.2 ± 5.0 g CH_4-C m^{-2} a^{-1} at two inundated sites, while one rewetted site with a comparatively low water level and the *Sphagnum* farming site show CH_4 fluxes close to 0. The net N_2O fluxes were low and not significantly different between the four sites. The annual NECB was between -185.5 ± 126.9 and 49.9 ± 112.8 g CO_2-C m^{-2} a^{-1} at the rewetted sites and -115.8 ± 48.1 and -77 ± 39.8 g CO_2-C m^{-2} a^{-1} at the *Sphagnum* cultivating site. The annual GWP100 balances ranged from -280.5 ± 465.2 to 644.5 ± 413.6 g CO_2-eq. m^{-2} a^{-1} at the rewetted sites. In contrast, the *Sphagnum* farming site had a cooling impact on the climate in both years (-356.8 ± 176.5 and -234.9 ± 145.9 g CO_2-C m^{-2} a^{-1}). If the carbon exported through the harvest of the *Sphagnum* biomass and the additional CO_2 emission from the decay of the organic material is considered, the NECB and GWP100 balances are near neutral.

Peat mining sites are likely to become net carbon sinks and a peat accumulating (“growing”) peatland within 30 years of rewetting, but the GWP100 balance may still be positive. A recommended measure for rewetting is to achieve a water level of a few centimetres below ground.

Sphagnum farming is a climate-friendly alternative to conventional commercial use of bogs. A year-round constant water level of a few centimetres below ground level should be maintained.

1 Introduction

Over many centuries, peatlands have been drained and used for peat extraction, agriculture and forestry worldwide and, in particular, in Germany (Couwenberg, 2011). In the last decades, peat has been extracted by industrial means on more than 30 000 ha in northwest Germany, and since the mid 1980s rewetting and restoration is obligatory on abandoned

Published by Copernicus Publications on behalf of the European Geosciences Union.

cutover peatlands as regulated by law (Höper, 2007; Höper et al., 2008).

In the long term, rewetting and restoration of the former cutover sites aims at establishing vegetation which is typical for growing, peat-accumulating bogs. Initially, the areas are flooded and natural succession starts. In the short term, flooding may lead to high methane emissions, depending on the water level and the time of year when flooding takes place (Waddington and Roulet, 1996; Le Mer and Roger, 2001; Houghton, 2004). Nevertheless, in the intermediate and long term, methane emissions are supposed to decrease and peat accumulation will lead to CO_2 uptake at the site (Augustin and Joosten, 2007). Little is known about the time dependency of these processes under temperate conditions and the total balance of the greenhouse gases.

About 3 decades ago, restoration programmes on cutover peatlands started in Germany (Höper and Blankenburg, 2000). Today, about 12 000 ha of former cutover sites are part of nature conservation areas and more than 23 500 ha will be rewetted in the future (Höper et al., 2008). Thus, there is a unique potential to study greenhouse gas emissions on sites which were rewetted about 30 years ago and to learn how to manage greenhouse gas emissions on future rewetted sites.

In comparison to other regions in Germany and many other European countries, bogs in Lower Saxony cover a comparatively high proportion of the land surface: almost 60 % of the peatland area or almost 6 % of the total terrestrial area (Höper, 2007).

Recently, *Sphagnum* cultivation has been proposed as a sustainable alternative to conventional peat extraction and as a climate-friendly use of abandoned cutover bogs (Gaudig et al., 2012). *Sphagnum* plants are grown under strongly controlled water conditions; the plant material is harvested in a 5-year cycle and used for horticultural purposes. Up to now, *Sphagnum* cultivation is still undergoing testing and no data on greenhouse gas exchange is available.

To date, studies on the gas exchange in peatlands have mainly been conducted in the boreal region (Alm et al., 1997; Nykänen et al., 1998; Joiner et al., 1999; Tuittila et al., 1999; Höper et al., 2008). In Scandinavian countries, measurements were mostly carried out during the summer months. For the remaining time period, the values are estimated or represent modelled fluxes (Byrne et al., 2004). This procedure can lead to false results (Roehm and Roulet, 2003), especially in temperate regions with mild winters. Most studies in restored peatlands are from recently rewetted sites. Investigations of the gas exchange and the global warming potential (GWP) balance of peatlands with a longer history of rewetting are needed because the gas exchange pattern may change with time (Joosten and Augustin, 2006). In the temperate zone, studies on the greenhouse gas (GHG) exchange in rewetted bogs were published by Nieveen et al. (1998), Drösler (2005), Bortoluzzi et al. (2006) and Beetz et al. (2013).

We present the greenhouse gas exchange of three sites on an abandoned cutover bog rewetted for restoration about 30 years ago and of one bog site rewetted for *Sphagnum* cultivation 5 years ago. We determined the exchange of CO_2, CH_4 and N_2O as well as the net ecosystem carbon balance (NECB) and the GWP balance.

We hypothesize that (a) the GWP balance of the rewetted former cutover area is about neutral when averaged across the three sites because, even 30 years after rewetting, methane emission is not as low and peat accumulation and the resulting uptake of CO_2 are not as high as at natural sites which are slight sinks of greenhouse gases; (b) the three sites of the rewetted former cutover area form a humidity gradient from a slightly lower to a slightly higher water table, which is underlined by its dominant vegetation and which corresponds to a gradient from slightly higher to lower greenhouse gas emissions; and (c) the GWP balance of the *Sphagnum* cultivation site is negative (cooling effect) because the water table is constantly kept some centimetres below the soil surface throughout the year, leading to low methane emission and optimal conditions for *Sphagnum* growth and carbon accumulation.

For the determination of gas flux rates, we used the closed-chamber method similar to that used in Drösler (2005). To obtain annual balances, modelling and interpolation were carried out. Additional field measurements of driving parameters were conducted.

2 Material and methods

2.1 Site description

The research area, Nordhümmlinger Moore, is located in the northwest part of Lower Saxony in Germany (53° N, 7.32° E longitude, about 5 m above mean sea level). The 30-year (1951–1980) mean annual temperature and annual precipitation amounts to 8.6 °C and 795 mm (Eggelsmann and Blankenburg, 1990). The warmest month is July (16.4 °C) and the coldest month is January (0.8 °C). Total precipitation is evenly distributed over the 12 months of the year.

One research area is the 450 ha large "Leegmoor", a former peat mining site, which was rewetted in 1983. Three measurement sites were installed (Table 1): "*Molinia*" is a Sapric Histosol or Norm-Erdhochmoor (KHn, AG Boden, 2005) and comparatively dry (vegetation: *Molinia*, *Erica tetralix* L., *Sphagnum cuspidatum* Ehrh. ex Hoffm., *Eriophorum angustifolium* Honck.; peat thickness: about 160 cm). There are two wetter sites 50 m to the west: "*Eriophorum*" (vegetation: *E. angustifolium* Honck., *Molinia*, *S. cuspidatum* Ehrh. ex Hoffm., *Betula pendula* Roth) and "*Sphagnum*" (about 10 cm deeper; vegetation: *S. cuspidatum* Ehrh. ex Hoffm., *E. angustifolium* Honck., *Molinia*). The two sites are Fibric Histosols or Norm-Hochmoor (HHn, AG Boden, 2005), with a peat thickness of about 95 cm.

The other research area is a peat mining area in the "Westermoor" (about 15 km northeast of Leegmoor). The measurement site ("*Sphagnum* cultivation") is a 60 m × 20 m test area, which was used agriculturally until 2000, from which peat was subsequently extracted, and which was rewetted in 2004 in order to cultivate peat mosses for harvesting (vegetation: *S. papillosum* Lindb., *S. Cuspidatum* Ehrh. ex Hoffm., *S. palustre* L., *S. fallax* H. Klinggr., *E. angustifolium* Honck., *E. tetralix* L., *Juncus effusus* L., *B. pendula* Roth, *Drosera*, *fungi*; peat thickness: 195 cm, consisting of 9 cm highly decomposed peat and 186 cm of weakly decomposed peat; Fibric Histosol or Norm-Hochmoor (HHn, AG Boden, 2005)). The water level is kept quite constant, just below ground level, all year round with the aid of a pump. To date, no harvesting has taken place.

2.2 Measurements of site factors and environmental controls

The soil identification (soil horizon, material, $CaCO_3$ content, pH) was conducted according to FAO (2006). The decomposition status was determined according to von Post. H1 and H2, H3 and H4, H5 and H6, H7 and H8 as well as H9 and H10 (von Post) correspond to z1, z2, z3, z4 as well as z5 (humification index, AG Boden, 2005), respectively.

Aboveground biomass at "*Sphagnum* cultivation" was sampled (cut by hand) from the measurement plots down to the original peat and separated into green (green biomass) and brown (dead biomass) plant parts as well as into moss and vascular plants. We determined the dry matter content by drying the samples in an oven at a temperature of 105 °C for two days (until constant weight). Fresh and dry biomass was quantified using a laboratory balance. The dry material was analysed for total carbon and nitrogen with an elemental analyser (Elementar vario plus CNS analyser).

"*Molinia*", "*Eriophorum*" and "*Sphagnum* cultivation" were equipped with tubes inserted into the peat body, close to the collars. Water levels were manually measured with an electric contact gauge during each gas measurement campaign. In addition, at "*Eriophorum*" and "*Sphagnum* cultivation" the water levels were continuously (half-hourly) recorded from June 2010 until December 2011 with a Schlumberger MiniDiver. The missing time periods were filled by interpolating between the manual measurements.

Meteorological parameters, such as temperatures (air temperature, soil temperature at 2, 5 and 10 cm depth), photosynthetic active radiation (PAR), air pressure and precipitation were measured and saved half-hourly at the meteorological station near "*Sphagnum* cultivation".

In addition, soil temperatures were measured and saved half-hourly with a data logger (DN Messtechnik, Norderstedt) at "*Molinia*" and "*Sphagnum* cultivation". The data of "*Molinia*" were used for "*Molinia*", "*Eriophorum*" and "*Sphagnum*".

2.3 Measurements and modelling of carbon dioxide exchange

Flux measurements were carried out every 4 weeks, starting September 2009 and ending in December 2011. A temperature-controlled portable closed-chamber technique was applied (see Drösler, 2005; Beetz et al., 2013). The chambers (0.78 m × 0.78 m; height: 0.5 m; equipped with a thermometer, a vent outlet with a rubber tube, a pair of turnable fans and a closed-cell rubber tube on the bottom to ensure airtightness) were connected via a tube with an electric pump and a portable CO_2 gas analyser (Licor LI-820; measurement of gas concentration every 5 s; one gas flux measurement procedure: 1–4 min). Thermal packs were used for cooling (temperature increase during measurement was kept below 1.5 °C). Ecosystem respiration (R_{eco}) was measured with opaque chambers (PVC) and net ecosystem exchange (NEE) with transparent chambers (3 mm strong Plexiglas). The research plots were arranged with boardwalks and three collars (3 mm strong PVC, about 20 cm apart).

Air pressure, air temperature, soil temperatures at 2, 5 and 10 cm depth (measured with inserting thermometers), and PAR were monitored during gas exchange measurements. Measurements started prior to sunrise and ended in the afternoon, in order to cover the entire range of PAR and temperatures. Per site and measurement day, about 12–18 measurements with opaque and 12–30 measurements with transparent chambers were carried out.

Flux rates were calculated according to Flessa et al. (1998), Drösler (2005) and Beetz et al. (2013), using the linear slope of gas concentration over time inside the chamber. To ensure the quality and representativeness of the slope, the following parameters were tested: (1) linearity of slope, (2) difference of the slope from 0 (slopes not different from 0 were set to 0), (3) variability of the slopes, and (4) constancy of the PAR (cv $<$ 5 %). Negative fluxes denote uptake by the ecosystem; positive fluxes loss to the atmosphere.

NEE was calculated as the difference between gross photosynthetic production (GPP), which has a negative sign and R_{eco}, with a positive sign.

For each measurement day, two models were fitted against the measured data using Microsoft Excel® Solver. Firstly, the ecosystem respiration (R_{eco}) was modelled according to Drösler (2005), Elsgaard et al. (2012) and Beetz et al. (2013), using an exponential regression equation (Lloyd and Taylor, 1994) of CO_2 flux against the temperature with the best fit (air; soil at 2 or 5 cm depth).

Secondly, GPP was derived from transparent (NEE) and opaque (R_{eco}) chamber measurements and modelled using a saturation function (Michaelis and Menten, 1913) and PAR as the input variable (Drösler, 2005; Elsgaard et al., 2012; Beetz et al., 2013). Because of the reduced transmissibility of the chamber Plexiglas, measured PAR was reduced by 5 %.

For the period between 2 measurement days, the flux rates of R_{eco} and NEE were calculated on a half-hourly basis, using the weather data and the model parameters of both campaigns.

In order to interpolate the flux rates in a half-hour time step, the model parameters were weighted according to the interval between the time step to be calculated and the measurement days using the following formula:

$$F_i = (t_i - t_n)/(t_{n+1} - t_n) \cdot F_n + (t_{n+1} - t_i)/(t_{n+1} - t_n) \cdot F_{n+1},$$

where F_i and t_i are the flux rate and time at time step i to be modelled and t_n and t_{n+1} are the time (day) of the campaigns n and $n+1$. F_n and F_{n+1} are the flux rates calculated with the model parameters of campaigns n and $n+1$.

Finally, monthly and annual balances were calculated by accumulating of the half-hourly flux rates.

2.4 Measurements of methane and nitrous oxide exchange

Measurement campaigns of N_2O and CH_4 exchange were held in intervals every 2 weeks, beginning in September 2009 and ending in December 2011.

The chambers were identical in construction to the opaque chambers used for R_{eco} (CO_2) but not ventilated. A measuring procedure lasted 1 h; every 20 min a gas sample was transferred from the headspace of the chamber to evacuated glass bottles (60 mL). Gas samples were analysed in the laboratory using the gas chromatograph Perkin Elmer Auto System, with ECD (electron capture detector) and FID (flame ionization detector) detectors (Beetz et al., 2013).

During gas exchange measurement, air temperature and soil temperatures at 2, 5 and 10 cm depth (measured by inserting thermometers) were monitored.

Flux rates were calculated according to Drösler (2005) and Beetz et al. (2013), using the linear slope of gas concentration over time inside the chamber. The slopes of gas concentration were tested for difference from 0. Slopes not different from 0 were set to 0.

Hourly flux rates over the whole research period were obtained by linear interpolation between the measurement campaigns and used to calculate annual balances.

2.5 Net ecosystem carbon balance and global warming potential

To obtain a complete carbon balance of an area of peatland, all fluxes of carbon must be considered (Chapin III et al., 2006). In addition to CO_2 flux rates, CH_4 flux rates, dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), carbon monoxide (CO) and volatile organic C (VOC) are factored in the NECB. Values of DOC, DIC, CO and VOC were assumed to be negligible and were not considered.

A widely used technique to establish the climatic impact of the GHG exchange at each site, expressed as CO_2 equivalents, is the global warming potential (GWP) methodology (IPCC, 1996). In general, the global warming potential over a time span of 100 years ($CO_2 : CH_4 : N_2O = 1 : 21 : 310$; IPCC, 1996) is taken (Drösler, 2005). Positive values represent efflux of CO_2 equivalents into the atmosphere.

2.6 Statistical analyses

Unless otherwise stated, Microsoft® Excel was used. Average values are arithmetic means.

The error analysis of the CO_2 fluxes was conducted by calculating the standard error for each calibrated regression model. Analogously to the interpolation of the half-hourly gas fluxes, we interpolated the standard errors. The monthly and annual standard errors were calculated using the law of error propagation.

For the CH_4 and N_2O fluxes, we calculated the standard error of the measurements of each measurement campaign and interpolated between the measurement campaigns in the same way as was done with the interpolation of the fluxes. The annual standard errors were calculated using the law of error propagation.

Significant linearity of the slopes was proved by a test of linearity according to Huber (1984). To test whether slopes are significantly different from 0, the t test was performed (Kreyszig, 1973; Neter et al., 1996). The variability of the slopes was determined by calculating the standard deviation of the residuals (s_{yx}). For the variability of the PAR we calculated the coefficient of variability (cv %).

Correlation and regression analyses were conducted with the coefficient of determination (quadrate of Pearson correlation coefficient $= R^2$) and tested for significance with the t test.

Significant differences between the annual gas exchange balances were tested with the permutation test "diffmean" (1000 permutations) using R script 0.97.237 (version 2.15.2) (simba package).

3 Results

3.1 Site factors

Peat at "*Molinia*" was highly decomposed (H10, von Post scale) and had a very low pH (Table 1). The uppermost horizons of "*Eriophorum*" and "*Sphagnum*" are built up of reduced bog peat and had a very low decomposition status. The peat of "*Eriophorum*" consisted mainly of herbs, while at "*Sphagnum*" we found *Sphagnum* peat. At "*Sphagnum* cultivation", the uppermost horizon (reduced bog peat, *Sphagnum* peat) also had a similar decomposition status but a higher pH. There was no $CaCO_3$ at the sites.

The vegetation at "*Sphagnum* cultivation" was grown on top of the original peat (consisting of highly decomposed peat) and built up a horizon of 15 cm of slightly decomposed *Sphagnum* material since the beginning of *Sphagnum* culti-

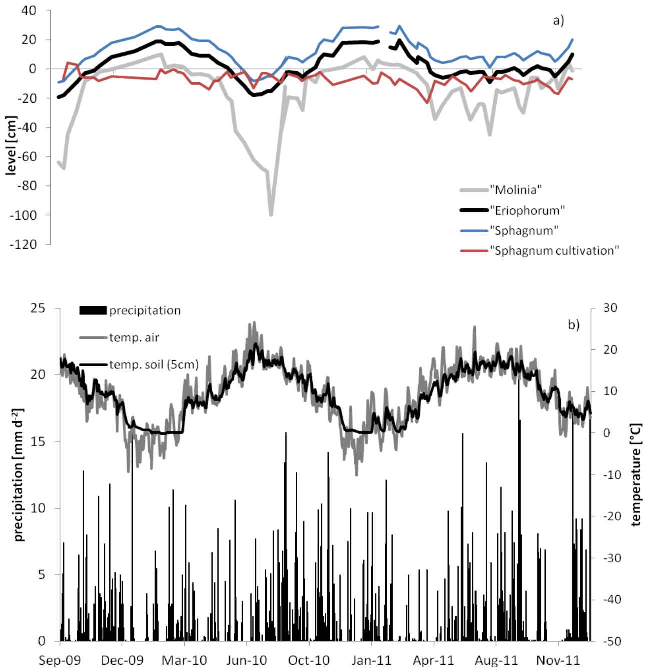

Figure 1. (a) Water level of the examination sites; **(b)** yearly development of temperatures and precipitation at the weather station near "*Sphagnum* cultivation", September 2009 until December 2011.

vation. Analysis of aboveground biomass was conducted in May of the last measurement year at "*Sphagnum* cultivation". The dry mass of the vegetation consisted primarily of *Sphagnum*. The total carbon stock of the aboveground biomass was $715.8 \pm 57.2\,\mathrm{g\,m^{-2}}$.

3.2 Environmental controls

The annual mean of the water table was 16.1 and 10.8 cm below ground in 2010 and 2011, respectively (Fig. 1, Table 1). The summer mean (May–October) was 34 and 21 cm below ground in 2010 and 2011, respectively. At "*Eriophorum*" the water table was higher and more stable over the course of the year (mean of 2010 and 2011: 4.4 and 3.8 cm above ground, respectively; summer mean: 4.9 and 2.5 cm below ground, respectively). "*Sphagnum*" was located about 10 cm lower than "*Eriophorum*"; thus, the mean was 14.4 and 13.8 cm above ground in 2010 and 2011, respectively. "*Sphagnum* cultivation" had a different water regime because the water table was regulated (annual mean in 2010 and 2011: 6.1 and 9.2 cm below ground, respectively; summer mean: 6.3 and 8.5 cm below ground, respectively).

According to the weather station near Westermoor, air temperatures were between −10 and 27 °C, soil temperature at a depth of 5 cm ranged from −0.2 to 22 °C and precipitation was highest on 7 September 2011, with 20 mm (Fig. 1).

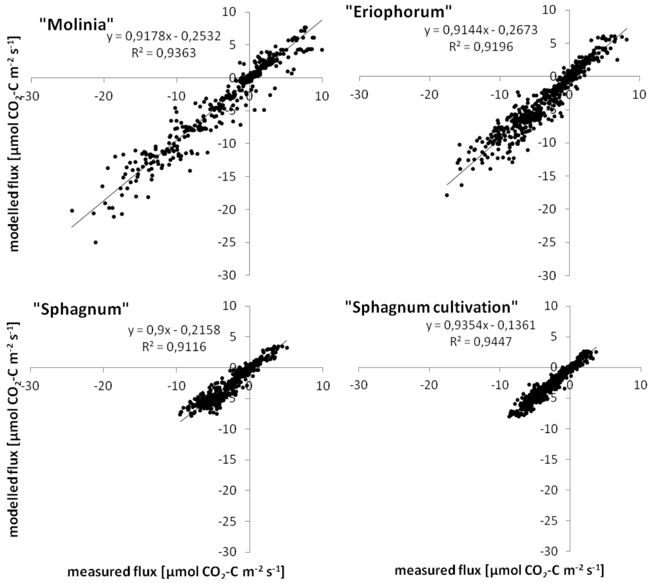

Figure 2. Modelled versus measured fluxes of NEE at the measurement sites. Regression equations and coefficients of determination (Pearson) (R^2).

3.3 Methane and nitrous oxide

At "*Molinia*" and "*Sphagnum* cultivation", the annual CH_4 balances were low and not significantly different between the two sites (Table 2). At "*Eriophorum*" flux rates were higher, and the highest methane emissions occurred at "*Sphagnum*". In 2011, the CH_4 emissions of "*Eriophorum*" and "*Sphagnum*" were not significantly different. The CH_4 emissions in 2010 and 2011 were not significantly different at any of the sites.

The annual N_2O balances did not differ significantly between all sites in both years (Table 2). While "*Sphagnum*" was a weak sink for nitrous oxide in both years, the other sites were a sink in one and a source in the other year. Highest emissions occurred at the dry sites and lowest emissions or uptake at the wetter sites. The annual values did not differ significantly between the years, except for those at "*Eriophorum*".

3.4 Carbon dioxide

The regressions between measured and modelled flux rates for R_{eco} and NEE of each measurement campaign at "*Molinia*" (Table 3) were significant in all cases ($P < 0.1$).

At the other three sites, in a few cases, mostly in winter, the difference between the lowest and the highest temperature was too small for modelling the R_{eco} (Tables 4–6). At "*Eriophorum*", this was the case on 25 November 2009, 15 December 2010 and 14 December 2011; at "*Sphagnum*" it was the case on 31 March, 21 April, 18 August and 15 December 2010. In these cases the model parameter E_0, which repre-

Table 1. Soil properties, mean water level and vegetation at the examination sites.

Depth (cm)	Soil horizon[a]	Material[a]	Decay degree[b]	pH_{CaCl2}	Mean water level (cm)[c]	Vegetation
(a) "*Molinia*" site						
0–10	Folic	organic	H10	3.4	13.5	*Molinia*
10–50	Folic	organic	H8	3.3		*Erica tetralix*
50–80	Histic	organic	H9	3.5		*S. cuspidatum*
80–105	Histic	organic	H9	3.6		*Eriophorum angustifolium*
105–130	Histic	organic	H9	4.0		
130–160	Histic	organic	H9	4.1		
160–170	Cambic	mineral (silty sand)		4.2		
(b) "*Eriophorum*" site						
0–20	Histic	organic	H1	3.7	−4.1	*Eriophorum angustifolium*
20–50	Histic	organic	H9	4.0		*Molinia*
50–95	Histic	organic	H9	3.7		*S. cuspidatum*
95–110	Cambic	mineral (silty sand)		3.6		*Betula pendula*
110–140	Cambic	mineral (silty sand)		4.4		
(d) "*Sphagnum*" site						
0–20	Histic	organic	H1	3.7	−14.1	*S. cuspidatum*
20–50	Histic	organic	H9	4.0		*Eriophorum angustifolium*
50–95	Histic	organic	H9	3.7		*Molinia*
95–110	Cambic	mineral (silty sand)		3.6		
110–140	Cambic	mineral (silty sand)		4.4		
(d) "*Sphagnum* cultivation" site						
0–9	Histic	organic	H1	3.9	7.7	*S. papillosum*
9–15	Histic	organic	H3	4.0		*S. cuspidatum*
15–45	Histic	organic	H9	4.1		*S. palustre*
45–100	Histic	organic	H9	4.4		*S. fallax*
						Eriophorum angustifolium
						Erica tetralix
						Juncus effusus
						Betula pendula
						Drosera
						fungi

[a] According to FAO (2006); [b] von Post scale; [c] below ground.

sents the ecosystem sensitivity parameter (K), was set to 0 and the model parameter R_{ref}, which is R_{eco} at the reference temperature (283.15 K), was replaced by the mean value of the measured values. This is a conservative way to obtain flux rates. The measurements on 9 February 2011 at "*Sphagnum*" had to be discarded because it was not possible to calibrate both models (R_{eco} and NEE) with the available data. At "*Sphagnum* cultivation" the regressions between measured and modelled flux rates for R_{eco} of the measurements on 29 September and 27 October 2009 were not significant; on 8 June 2011, gas fluxes at "*Sphagnum* cultivation" did not increase with increasing temperatures; and on 14 December 2010, there was almost no change in the soil temperature and the air temperature was below 0 °C for the whole day, which did not result in an appropriate relationship. In these cases it was possible to pool the results of two measurement campaigns together to achieve significant regressions because, in contrast to "*Molinia*", "*Eriophorum*" and "*Sphagnum*" the long-term controls at "*Sphagnum* cultivation" remained similar between the two pooled measurement campaigns. The measurement-campaign-specific regressions between measured and modelled flux rates for the NEE were significant in all cases ($P < 0.1$).

At each site the regression between all modelled and measured values for R_{eco} and NEE were always significant (R^2 between 0.88 and 0.98, $P < 0.0001$) and almost followed the 1 : 1 line (Fig. 2). The standard errors for the R_{eco} and the NEE at "*Molinia*" were 0.36 and 1.45 µmol CO_2-C m^{-2} s^{-1}, respectively. At "*Eriophorum*", standard errors of 0.70 and 1.32 µmol CO_2-C m^{-2} s^{-1}, respectively, were de-

Table 2. Annual and average balances for R_{eco}, NEE, CH_4-C, N_2O-N exchange, NECBs (net ecosystem carbon balances) and GWP (global warming potential for the time spans of 100 and 500 years) balances; m: mean; SE: standard error. Letters indicate that balances are not significantly different.

Site		Balances	2010		2011		Average	
			m	SE	m	SE	m	SE
"*Molinia*"	$R_{eco}CO_2$	[g CO_2-C m^{-2} a^{-1}]	759.5	29.9	997.3 f	37.4	878.4	118.9
	NEE CO_2	[g CO_2-C m^{-2} a^{-1}]	−75.8 a	91.4	9.2 g	138.9	−33.3	42.5
	CH_4	[g CH_4-C m^{-2} a^{-1}]	0.05 c	0.03	0.11 i	0.04	0.08	0.03
	N_2O	[mg N_2O-N m^{-2} a^{-1}]	88 d	57.1	−25 l	24.3	31.1	46.2
	NECB	[g CO_2-C m^{-2} a^{-1}]	−75.8	91.4	9.3	138.9	−33.2	42.5
	GWP100	[g CO_2-eq. m^{-2} a^{-1}]	−234.2	335.3	24.4	509.4	−104.9	156.0
	GWP500	[g CO_2-eq. m^{-2} a^{-1}]	−254.4	335.3	27.9	509.4	−113.3	156.0
"*Eriophorum*"	$R_{eco}CO_2$	[g CO_2-C m^{-2} a^{-1}]	856.3	66.2	1052.2 f	62.8	954.3	98.0
	NEE CO_2	[g CO_2-C m^{-2} a^{-1}]	−201.7	126.8	29.7 g	112.7	−86.0	115.7
	CH_4	[g CH_4-C m^{-2} a^{-1}]	16.2	2.2	20.2 k	2.8	18.2	1.7
	N_2O	[mg N_2O-N m^{-2} a^{-1}]	45 d	30.3	−21 l	12.1	12.0	27.3
	NECB	[g CO_2-C m^{-2} a^{-1}]	−185.5	126.9	49.9	112.8	−67.8	115.7
	GWP100	[g CO_2-eq. m^{-2} a^{-1}]	−280.5	465.2	644.5	413.6	182.0	424.3
	GWP500	[g CO_2-eq. m^{-2} a^{-1}]	−610.9	465.1	248.7	413.4	−181.1	424.2
"*Sphagnum*"	$R_{eco}CO_2$	[g CO_2-C m^{-2} a^{-1}]	420.3 e	29.4	584.5	43.5	502.4	82.1
	NEE CO_2	[g CO_2-C m^{-2} a^{-1}]	−113.6 ab	61.3	−76.2 h	79.6	−94.9	22.5
	CH_4	[g CH_4-C m^{-2} a^{-1}]	22.4	3.7	24.2 k	5.0	23.3	0.7
	N_2O	[mg N_2O-N m^{-2} a^{-1}]	−42 d	21.4	−9 l	16.1	−25.8	13.4
	NECB	[g CO_2-C m^{-2} a^{-1}]	−91.2	61.4	−52	79.9	−71.6	18.7
	GWP100	[g CO_2-eq. m^{-2} a^{-1}]	167.0	225.7	368.4	293.8	267.7	68.6
	GWP500	[g CO_2-eq. m^{-2} a^{-1}]	−266.7	225.0	−108.0	292.7	−187.3	68.6
"*Sphagnum* cultivation"	$R_{eco}CO_2$	[g CO_2-C m^{-2} a^{-1}]	414.5 e	50.6	490.1	24.0	452.3	37.8
	NEE CO_2	[g CO_2-C m^{-2} a^{-1}]	−118.8 b	48.1	−78.6 h	39.8	−98.7	20.1
	CH_4	[g CH_4-C m^{-2} a^{-1}]	3.1 c	0.2	1.6 i	0.2	2.4	0.6
	N_2O	[mg N_2O-N m^{-2} a^{-1}]	−8 d	15.5	19 l	9.9	5.5	11.3
	NECB	[g CO_2-C m^{-2} a^{-1}]	−115.8	48.1	−77	39.8	−96.4	20.1
	GWP100	[g CO_2-eq. m^{-2} a^{-1}]	−356.8	176.5	−234.9	145.9	−295.8	73.8
	GWP500	[g CO_2-eq. m^{-2} a^{-1}]	−415.8	176.5	−271.4	145.9	−343.6	73.7

termined. The standard errors at "*Sphagnum*" amounted to 0.39 and 0.83 µmol CO_2-C m^{-2} s^{-1}, respectively, and to 0.41 and 0.53 µmol CO_2-C m^{-2} s^{-1} at "*Sphagnum* cultivation", respectively. The gas fluxes at "*Molinia*" and "*Eriophorum*" were generally higher than at the other sites; consequently the standard errors were usually higher, at least for the NEE.

The annual development of R_{eco} showed a strong seasonal pattern at all sites, with high values in summer and low values in winter (Fig. 3). On average over the 2 years, the highest monthly cumulated R_{eco} occurred in July (192.2 ± 18.3, 173.5 ± 15.4, 94.2 ± 2.5 and 87.1 ± 9.5 g CO_2-C m^{-2}, at "*Molinia*", "*Eriophorum*", "*Sphagnum*" and "*Sphagnum* cultivation", respectively). The lowest monthly cumulated R_{eco} was determined in December.

R_{eco} and GPP showed characteristically seasonal patterns at all four sites (Fig. 3). "*Molinia*" and "*Eriophorum*" demonstrate a similar annual development for the most part of the year. However, at the beginning of the vegetation period, CO_2 fluxes started to increase much earlier at "*Eriophorum*" than at the other sites. The annual pattern of "*Sphagnum*" and "*Sphagnum* cultivation" differed strongly from the development of "*Molinia*" and "*Eriophorum*". "*Sphagnum*" and "*Sphagnum* cultivation" both revealed much lower R_{eco} and GPP. By comparing the annual development of the R_{eco} with the development of the temperature, it appeared that there is a lag in the development of the vegetation in spring at all sites with the exception of "*Eriophorum*". In late summer and autumn, when temperatures were still high, the R_{eco} had already dropped. In July 2010, the GPP at "*Sphagnum*" went against the general trend and dropped to lower values. Subsequently, it increased again. Comparing the annual development of the GPP with the development of the PAR, a delay is visible, similar to the delay in the R_{eco} (see above).

Table 3. Parameters for the R_{eco} and NEE models of "*Molinia*"; E_0: activation energy like parameter (K); R_{ref}: respiration at the reference temperature (µmol CO_2-C m^{-2} s^{-1}); temp: best fit temperature for R_{eco} model. GP_{max}: maximum rate of carbon fixation at PAR infinite (µmol CO_2-C m^{-2} s^{-1}); alpha: light use efficiency (µmol CO_2-C m^{-2} s^{-1}/µmol m^{-2} s^{-1}); R^2: coefficient of determination (Pearson) between modelled and measured values. SE: standard error of the model (µmol CO_2-C m^{-2} s^{-1}); *n*: number of samples. Max. and min. values are printed in bold. Eventually measurement campaigns were pooled together.

Date	E_0	R_{ref}	R^2	SE	*n*	Temp	GP_{max}	alpha	R^2	SE	*n*
30.09.09	850.5	2.34	0.59***	0.41	12	soil5	−13.09	−0.0203	0.59****	0.98	23
29.10.09	748.1	2.04	0.32**	0.41	13	soil5	−6.25	−0.0057	0.19**	0.34	21
25.11.09	**1106.8**	0.35	0.46**	0.04	10	soil2	−0.89	−0.0052	0.45***	0.09	21
03.03.10	68.2	0.36	0.45***	0.03	15	air	−0.59	−0.0053	0.67****	0.09	25
31.03.10	55.2	0.67	0.84****	0.02	15	air	−1.73	−0.0027	0.79****	0.19	26
21.04.10	723.9	0.68	0.60****	0.05	14	soil5	−0.78	−0.0014	0.55****	0.13	28
27.05.10	175.4	2.32	0.30**	0.28	14	soil2	−5.18	−0.0089	0.87****	0.41	30
23.06.10	49.1	4.52	0.68****	0.38	18	air	−15.39	−0.0441	0.94****	1.02	30
21.07.10	330.9	3.29	0.71****	0.69	16	soil2	−24.08	−0.0659	0.90****	2.15	30
18.08.10	332.3	1.69	0.28**	0.58	15	soil2	−29.19	−0.0261	0.87****	1.68	21
15.09.10	92.4	1.63	0.44***	0.14	15	air	−27.50	−0.0195	0.95****	1.11	27
13.10.10	632.2	2.23	0.24*	0.21	15	soil5	−8.92	−0.0393	0.94****	0.73	21
09.11.10	332.7	1.99	0.58***	0.10	12	air	−2.77	−0.0063	0.77****	0.20	21
15.12.10	565.6	2.14	0.52**	0.06	11	air	−0.51	−0.0014	0.29**	0.07	21
09.02.11	63.4	0.57	0.95****	0.03	12	air	−3.75	−0.0015	0.59****	0.15	21
09.03.11	220.6	**0.32**	0.46**	0.06	12	air	−1.20	**−0.0013**	0.64****	0.08	21
14.04.11	**19.1**	1.07	0.29**	0.09	15	air	−1.40	−0.0032	0.51****	0.23	27
03.05.11	131.3	1.43	0.88****	0.14	15	air	−2.69	−0.0038	0.56****	0.27	24
07.06.11	216.8	4.19	0.63***	0.03	12	soil5	−37.12	−0.0282	0.83****	3.11	27
29.06.11	273.1	2.33	0.48**	1.43	11	air	**−61.46**	−0.0312	0.952****	2.18	23
27.07.11	62.6	5.77	0.70****	0.52	15	air	−42.03	−0.0412	0.94****	2.04	30
24.08.11	43.9	**6.98**	0.30**	0.40	14	air	−30.56	−0.0459	0.81****	2.69	24
21.09.11	33.0	3.58	0.60**	0.05	9	air	−31.69	−0.0529	0.99****	0.64	21
20.10.11	789.1	2.06	0.93****	0.08	12	soil2	−15.33	−0.0069	0.88****	0.59	21
16.11.11	533.8	1.40	0.59***	0.02	10	soil2	−0.71	−0.0282	0.46****	0.16	21
14.12.11	574.9	1.29	0.41**	0.06	12	soil2	**−0.50**	**−0.8479**	0.80****	0.11	15

* $P < 0.1$; ** $P < 0.05$; *** $P < 0.01$; **** $P < 0.001$.

In summer, the gross uptake of CO_2 through GPP outbalanced the release through R_{eco}, while during the colder months the net fluxes were near 0 or net emissions occurred (Fig. 3). At "*Eriophorum*" and "*Sphagnum*" the highest cumulated monthly net uptake of CO_2 occurred on average in June (-49.5 ± 20.4 and -47.8 ± 16.2 g CO_2-C m^{-2}, respectively), whereas at "*Molinia*" the highest average uptake of CO_2 was detected in July (-74.8 ± 2.4 g CO_2-C m^{-2}) and, at "*Sphagnum* cultivation", in August (-25.0 ± 16.1 g CO_2-C m^{-2}). There was a gradient from highest net uptake at "*Molinia*" to lowest uptake at "*Sphagnum* cultivation" during the summer months of June until August. During the remaining part of the year, "*Molinia*" emitted CO_2; "*Eriophorum*" also emitted CO_2 but less than "*Molinia*". "*Sphagnum*" and "*Sphagnum* cultivation" sequestered CO_2, but "*Sphagnum* cultivation" sequestered more CO_2.

The highest annual R_{eco} was found at "*Eriophorum*", followed by "*Molinia*", "*Sphagnum*" and "*Sphagnum* cultivation" (Table 2). In 2011, the annual R_{eco} was higher than in 2010.

The net CO_2 sequestration (NEE) at "*Sphagnum*" and "*Sphagnum* cultivation" was about the same and not significantly different (Table 2). The uptake was higher in 2010 than in 2011. "*Molinia*" and "*Eriophorum*" were net sinks in 2010 and net sources in 2011. At all sites, the annual NEE balance was significantly different between the 2 years due to a higher R_{eco} in 2011 as compared to 2010. On average, a gradient from "*Molinia*" with a smaller uptake to "*Sphagnum* cultivation" with a higher uptake was apparent.

The standard errors of the annual CO_2 balances were high, compared to the annual balances, especially at "*Molinia*" in 2011. In addition, the difference between the 2 years was high, particularly at "*Molinia*" and "*Eriophorum*", where the standard errors of the annual balances were much higher than the mean values. "*Sphagnum* cultivation" showed the most stable values.

Table 4. Parameters for the R_{eco} and NEE models of "*Eriophorum*"; E_0: activation energy such as parameter [K]; R_{ref}: respiration at the reference temperature [µmol CO_2-C m^{-2} s^{-1}]; temp: best fit temperature for R_{eco} model. GP_{max}: maximum rate of carbon fixation at PAR infinite [µmol CO_2-C m^{-2} s^{-1}]; alpha: light use efficiency [µmol CO_2-C m^{-2} s^{-1}/µmol CO_2-C m^{-2} s^{-1}]; R^2: coefficient of determination (Pearson) between modelled and measured values. SE: standard error of the model [µmol CO_2-C m^{-2} s^{-1}]; n: number of samples. Max. and min. values are printed in bold. Eventually measurement campaigns were pooled together.

Date	E_0	R_{ref}	R^2	SE	n	Temp	GP_{max}	alpha	R^2	SE	n
30.09.09	**799.8**	1.93	0.40**	0.40	11	soil5	−42.75	−0.0144	0.63****	0.85	20
29.10.09	222.0	2.88	0.28**	0.09	15	soil5	−22.28	−0.0107	0.64****	0.56	24
25.11.09	0.0	1.06	0.10	0.23	12		−55.97	−0.0127	0.90****	0.16	21
03.03.10	442.0	2.72	0.60****	0.10	15	soil5	−1.99	−0.0039	0.64****	0.22	25
31.03.10	36.6	2.29	0.27*	0.22	13	air	−7.02	−0.0089	0.77****	0.65	29
21.04.10	472.2	2.37	0.30*	0.42	15	soil2	−9.78	−0.0301	0.87****	0.94	30
27.05.10	132.5	2.60	0.48***	0.51	15	air	−20.40	−0.0302	0.90****	1.22	30
23.06.10	170.9	3.12	0.78****	0.88	18	air	−15.56	−0.0394	0.91****	0.93	30
21.07.10	110.3	**4.62**	0.24**	2.04	18	air	−18.26	−0.0427	0.85****	1.65	30
18.08.10	169.9	2.85	0.21*	0.55	15	soil2	−21.52	**−0.0513**	0.86****	1.77	24
15.09.10	152.7	1.82	0.41**	0.13	10	soil2	−29.23	−0.0227	0.81****	2.17	26
13.10.10	389.5	1.69	0.32**	0.42	14	soil2	−37.51	−0.0223	0.74****	2.38	18
09.11.10	440.8	1.53	0.34**	0.09	12	soil2	−6.82	−0.0180	0.97****	0.16	18
15.12.10	0.0	0.28	0.04	0.13	12		**−1.25**	−0.0126	0.84****	0.14	21
09.02.11	**23.4**	**1.39**	0.47**	0.07	12	air	−54.19	**−0.0022**	0.82****	0.20	18
09.03.11	250.8	2.12	0.25*	0.47	12	air	−4.80	−0.0045	0.23**	0.33	19
14.04.11	115.1	2.33	0.47***	0.77	15	air	−19.20	−0.0089	0.88****	0.86	24
03.05.11	500.6	2.18	0.73****	0.45	12	soil2	−19.65	−0.0151	0.92****	1.03	24
07.06.11	145.9	4.53	0.28*	0.71	13	air	−17.95	−0.0334	0.82****	1.98	27
29.06.11	147.8	4.32	0.21*	0.83	14	air	**−72.79**	−0.0283	0.94****	1.44	23
27.07.11	259.6	3.08	0.75****	0.97	15	soil2	−33.18	−0.0286	0.90****	1.50	30
24.08.11	483.1	1.74	0.55***	1.08	15	soil2	−29.23	−0.0356	0.93****	1.24	24
21.09.11	625.0	**1.39**	0.25*	0.53	12	soil2	−32.84	−0.0436	0.95****	1.30	24
20.10.11	391.1	1.96	0.59***	0.29	12	soil2	−21.47	−0.0265	0.84****	1.59	24
16.11.11	308.4	2.23	0.31*	0.20	12	air	−39.93	−0.0142	0.93****	0.25	21
14.12.11	0.0	1.40	0.02	0.56	24		−7.09	−0.0064	0.73****	0.38	12

* $P < 0.1$; ** $P < 0.05$; *** $P < 0.01$; **** $P < 0.001$.

3.5 Carbon and climate budget

The NECB of "*Molinia*" and "*Sphagnum* cultivation" were similar to the annual NEE, because the NECB was mainly determined by the NEE (Table 2). In spite of the higher CH_4 emissions at "*Eriophorum*" and "*Sphagnum*", there is still a gradient from "*Molinia*", with the lowest, to "*Sphagnum* cultivation", with the highest NECB.

At "*Eriophorum*" and "*Sphagnum*", the GWP100 balance revealed a different picture than the NECB because methane exerted a greater climatic impact (Table 2). "*Sphagnum*" was a greenhouse gas source (GWP100 balance) in both years and on average the highest source of all sites. "*Eriophorum*" and "*Molinia*" were sinks (GWP100 balance) in one year and sources in another year; "*Sphagnum* cultivation" was a sink in both years.

Changing the time perspective of the GWP assessment from 100 to 500 years leads to the conversion of "*Eriophorum*" and "*Sphagnum*" from a GHG source to a sink (Table 2). "*Sphagnum* cultivation" and "*Molinia*" become stronger sinks. Due to the short life time span of CH_4, the climatic impact of this gas decreases from the 100 (GWP100) to the 500 year perspective (GWP500).

3.6 Statistical analysis of the relations between control factors and gas exchange

At the sites in the Leegmoor, the annual development of the methane fluxes showed no seasonal trends but, rather, a diffuse pattern (Fig. 4). At "*Sphagnum* cultivation" a relationship between CH_4 fluxes and temperature as well as between CH_4 fluxes and water table was evident (Fig. 4). Analogous to the rising temperatures in spring and falling temperatures in autumn, the methane emissions increased in spring and dropped in autumn. In 2010, the water table and emissions were higher than in 2011. The relationships between CH_4 fluxes and water levels ($R^2 = 0.32$) as well as between CH_4 fluxes and soil temperatures ($R^2 = 0.59$) were significant.

Table 5. Parameters for the R_{eco} and NEE models of "*Sphagnum*"; E_0: activation energy such as parameter [K]; R_{ref}: respiration at the reference temperature [µmol CO_2-C m^{-2} s^{-1}]; temp: best fit temperature for R_{eco} model. GP_{max}: maximum rate of carbon fixation at PAR infinite [µmol CO_2-C m^{-2} s^{-1}]; alpha: light use efficiency [µmol CO_2-C m^{-2} s^{-1}/µmol CO_2-C m^{-2} s^{-1}]; R^2: coefficient of determination (Pearson) between modelled and measured values. SE: standard error of the model [µmol CO_2-C m^{-2} s^{-1}]; *n*: number of samples. Max. and min. values are printed in bold. Eventually measurement campaigns were pooled together.

Date	E_0	R_{ref}	R^2	SE	*n*	Temp	GP_{max}	alpha	R^2	SE	*n*
30.09.09	136.4	**2.33**	0.43*	0.27	9	air	**−17.89**	−0.0157	0.74****	0.68	23
29.10.09	425.3	1.17	0.20*	0.15	15	soil5	−13.91	−0.0178	0.95****	0.29	24
25.11.09	**29.4**	0.51	0.43*	0.01	9	air	−4.64	−0.0161	0.90****	0.17	24
03.03.10	247.7	0.53	0.26*	0.04	12	soil2	−4.89	**−0.0001**	0.21**	0.03	25
31.03.10	0.0	0.42	0.00	0.27	15		−17.35	−0.0003	0.55****	0.10	27
21.04.10	0.0	0.42	0.00	0.27	15		−2.83	−0.0045	0.94****	0.18	28
27.05.10	183.7	0.98	0.44***	0.15	15	soil2	−9.46	−0.0253	0.95****	0.50	30
23.06.10	231.8	1.74	0.86****	0.53	18	air	−13.46	−0.0224	0.91****	0.72	30
21.07.10	247.5	1.64	0.17*	0.47	18	soil5	−4.39	−0.0130	0.65****	0.67	30
18.08.10	0.0	2.49	0.02	0.57	15		−11.82	−0.0195	0.86****	0.94	24
15.09.10	175.8	1.04	0.47**	0.21	12	air	−13.80	−0.0170	0.74****	1.32	27
13.10.10	297.1	1.09	0.25*	0.26	15	soil2	−9.80	**−0.0360**	0.92****	0.74	21
09.11.10	404.8	1.23	0.66**	0.07	8	soil2	−3.19	−0.0190	0.66****	0.39	18
15.12.10	0.0	0.08	0.16	0.02	12		**−0.58**	−0.0026	0.71****	0.08	18
09.03.11	100.7	0.45	0.56**	0.03	8	air	−0.66	−0.0010	0.29**	0.07	21
14.04.11	110.0	1.23	0.40**	0.45	15	air	−9.80	−0.0047	0.74****	0.70	24
03.05.11	217.7	1.52	0.68****	0.56	15	air	−10.33	−0.0131	0.65****	1.21	24
07.06.11	267.6	2.25	0.39**	0.62	15	air	−12.20	−0.0237	0.88****	1.01	27
29.06.11	213.8	2.00	0.35**	0.64	14	air	−15.02	−0.0344	0.89****	1.18	24
27.07.11	197.9	1.99	0.68****	0.80	15	air	−13.62	−0.0269	0.80****	1.01	30
24.08.11	335.1	1.43	0.74****	0.52	13	soil5	−17.71	−0.0282	0.74****	1.23	24
21.09.11	**1069.0**	**0.39**	0.41**	0.36	12	soil5	−15.98	−0.0294	0.90****	0.81	24
20.10.11	253.1	0.84	0.62***	0.20	12	air	−9.14	−0.0180	0.86****	0.72	24
16.11.11	396.5	1.33	0.42**	0.08	12	air	−5.46	−0.0168	0.96****	0.14	21
14.12.11	308.6	2.29	0.56**	0.16	12	air	−3.45	−0.0032	0.82****	0.13	12

* $P < 0.1$; ** $P < 0.05$; *** $P < 0.01$; **** $P < 0.001$.

Taking the measurements from all sites, it was obvious that at a water level of less than 20 cm below ground level the CH_4 fluxes were around 0 and, at a water level of above 20 cm below ground level, the CH_4 fluxes increased. The highest fluxes could be determined at a water level of around 0.

The correlation analyses revealed a highly significant correlation between CH_4 balance and mean water level ($R^2 = 0.93$).

4 Discussion

4.1 Reliability of the research methods

Especially in the cold months it was not possible to establish a good correlation between temperature and R_{eco} because the temperature span was too small or even inexistent during the day. In this case, results from two or three campaigns were pooled or R_{eco} was set constant to the mean values of the measurements. The error in the annual balance due to this procedure is low because the CO_2 exchange is low at low temperatures. Nevertheless, winter conditions are taken into consideration as well as is possible by keeping up a schedule of one campaign every 4 weeks.

Temperatures and PAR were used for the modelling during each measurement campaign, while other controls, such as soil moisture or vegetation, were not considered in the short term (i.e. daily) but only in the long term (i.e. monthly), regardless of the fact that these may also change over the course of the day. Petrone et al. (2003) suppose that soil moisture may be the primary controlling factor of GPP. However, we found coefficients of determination (Pearson) between modelled and measured values of the NEE model well above $R^2 = 0.5$ (Tables 3–6). Factors having an effect in the long term are accounted for by the repeated measurement campaigns, which result in different model parameters as a consequence of the different field situations. The linear interpolation between measurement campaigns assumed that long-term controls also change linearly, which is certainly not the case. For this reason, we kept the time between

Table 6. Parameters for the R_{eco} and NEE models of "*Sphagnum* cultivation"; E_0: activation energy such as parameter [K]; R_{ref}: respiration at the reference temperature [$\mu mol\,CO_2$-$C\,m^{-2}\,s^{-1}$]; temp: best fit temperature for R_{eco} model. GP_{max}: maximum rate of carbon fixation at PAR infinite [$\mu mol\,CO_2$-$C\,m^{-2}\,s^{-1}$]; alpha: light use efficiency [$\mu mol\,CO_2$-$C\,m^{-2}\,s^{-1}$/$\mu mol\,CO_2$-$C\,m^{-2}\,s^{-1}$]; R^2: coefficient of determination (Pearson) between modelled and measured values. SE: standard error of the model [$\mu mol\,CO_2$-$C\,m^{-2}\,s^{-1}$]; *n*: number of samples. Max. and min. values are printed in bold. Eventually measurement campaigns were pooled together.

Date	E_0	R_{ref}	R^2	SE	*n*	Temp	GP_{max}	alpha	R^2	SE	*n*
29.09.09	277.8	0.91	0.43****	0.41	26	soil5	−6.12	−0.0194	0.86****	0.46	36
27.10.09							−4.73	−0.0114	0.79****	0.29	39
24.11.09	969.8	0.39	0.40*	0.07	9	soil5	−2.16	−0.0231	0.83****	0.20	27
02.03.10	772.4	0.66	0.34**	0.05	12	soil2	−4.59	**−0.0014**	0.62****	0.24	41
30.03.10	264.9	0.48	0.61****	0.15	18	air	−3.46	−0.0102	0.96****	0.12	45
20.04.10	97.3	1.04	0.34**	0.22	18	air	−4.10	−0.0125	0.95****	0.21	47
26.05.10	144.6	1.70	0.19*	0.52	17	soil5	−12.56	−0.0051	0.87****	0.43	50
22.06.10	300.7	1.45	0.73****	0.70	18	soil2	−11.89	−0.0116	0.84****	0.66	57
20.07.10	301.3	1.29	0.26**	1.08	18	soil5	−9.72	−0.0190	0.67****	0.86	57
17.08.10	930.2	**0.26**	0.54****	0.82	18	soil5	−10.81	−0.0273	0.83****	0.81	48
14.09.10	430.2	0.84	0.18*	0.62	18	soil5	**−15.20**	−0.0262	0.88****	0.43	33
12.10.10	694.6	0.70	0.48***	0.25	15	soil5	−7.70	−0.0219	0.94****	0.46	42
10.11.10	240.1	0.35	0.64****	0.05	27	soil2	−3.03	−0.0317	0.90****	0.21	42
14.12.10							**−0.37**	−0.0028	0.74****	0.04	27
08.02.11	406.5	0.65	0.50***	0.09	15	soil2	−3.05	−0.0146	0.92****	0.18	35
08.03.11	648.1	2.20	0.21*	0.09	15	soil5	−1.65	−0.0193	0.86****	0.18	24
12.04.11	94.0	0.76	0.24**	0.08	18	soil2	−3.41	−0.0142	0.89****	0.30	46
08.06.11	**67.2**	**2.30**	0.33***	0.44	30	air	−6.78	−0.0286	0.93****	0.31	33
28.06.11							−11.15	−0.0212	0.91****	0.69	57
26.07.11	322.6	1.22	0.67****	0.29	18	soil2	−13.84	−0.0304	0.98****	0.49	57
23.08.11	225.0	1.57	0.44***	0.20	14	soil2	−13.78	−0.0275	0.97****	0.58	44
20.09.11	229.5	1.43	0.89****	0.23	18	soil2	−14.17	−0.0294	0.95****	0.58	45
19.10.11	88.2	1.11	0.50***	0.16	12	air	−6.44	−0.0237	0.94****	0.31	30
15.11.11	114.4	0.62	0.23*	0.04	15	air	−2.57	−0.0244	0.95****	0.10	33
13.12.11	**1015.1**	1.81	0.51**	0.07	11	soil5	−1.43	**−0.0624**	0.93****	0.09	27

* $P < 0.1$; ** $P < 0.05$; *** $P < 0.01$; **** $P < 0.001$.

two measurement campaigns as short as possible (Beetz et al., 2013).

4.2 Importance of site and control factors

At all sites the seasonal pattern of R_{eco} and GPP basically followed the development of the temperature and the PAR, respectively (Figs. 1 and 3). It can be assumed that the deviations from these patterns were caused by the vegetation (Lafleur et al., 1997; Buchmann and Schulze, 1999; Tuittila et al., 1999; Wilson et al., 2007; Kivimäki et al., 2008). In spring, when temperatures and PAR are already raised, the vegetation is not yet fully developed, while in late summer and autumn, senescence occurs, and R_{eco} as well as GPP are low although temperatures and PAR are still quite high. In both cases, autotrophic respiration is low and is not outbalanced by heterotrophic respiration, which is more closely related to temperature. In July, temperatures are highest and the vegetation is fully developed; thus, highest R_{eco} occurs during July, which is consistent with Beetz et al. (2013). The daily GPP of "*Molinia*" and "*Eriophorum*", on the one hand, and "*Sphagnum*" and "*Sphagnum* cultivation", on the other hand, were similar, due to similar types of vegetation. In comparison to the other sites, the GPP at "*Eriophorum*" increased early in spring and decreased late in fall because *Eriophorum* has a high potential for photosynthesis early in the season and throughout most of the season (Tuittila et al., 1999).

Another important driver of the gas exchange is the water level (Tuittila et al., 1999; Waddington and Warner, 2001; Lafleur et al., 2003; Glatzel et al., 2006; Wilson et al., 2007). The strong decrease of GPP in July 2010 at "*Sphagnum*" was caused by the decline of the water table in connection with warm and dry weather (Fig. 1), leading to a drying-out of the *Sphagnum* (Titus et al., 1983; Schipperges and Rydin, 1998). In contrast, the other sites were not affected by the dry period in July 2010 because "*Molinia*" and "*Eriophorum*" were not dominated by *Sphagnum* but by species such as *Eriophorum*, which are less vulnerable to fluctuations of the water table (Tuittila et al., 1999). The clearly visible effect of the dry pe-

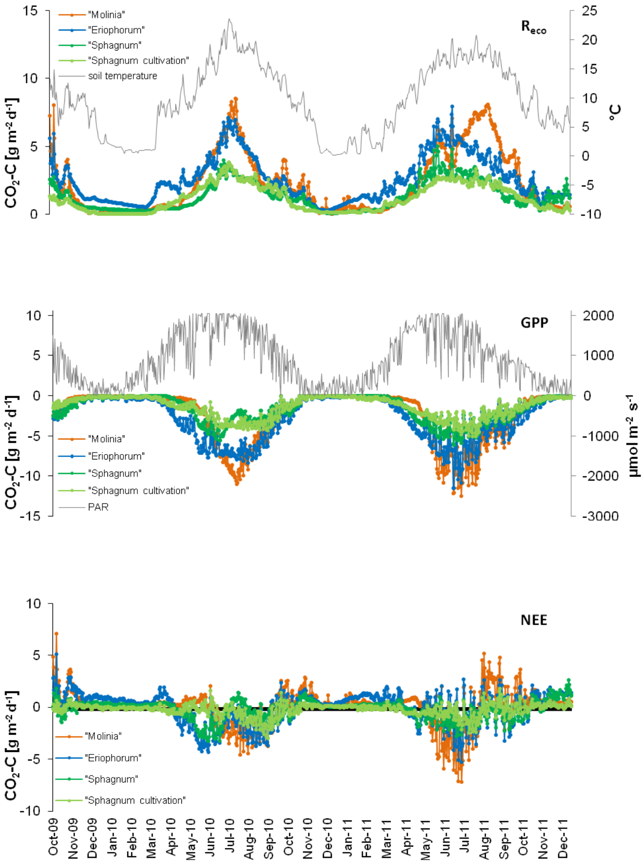

Figure 3. Yearly development of daily R_{eco}, GPP and NEE of the measurement sites (left axis). Soil temperature and PAR of the measurement sites (right axis of the upper and middle diagram, respectively).

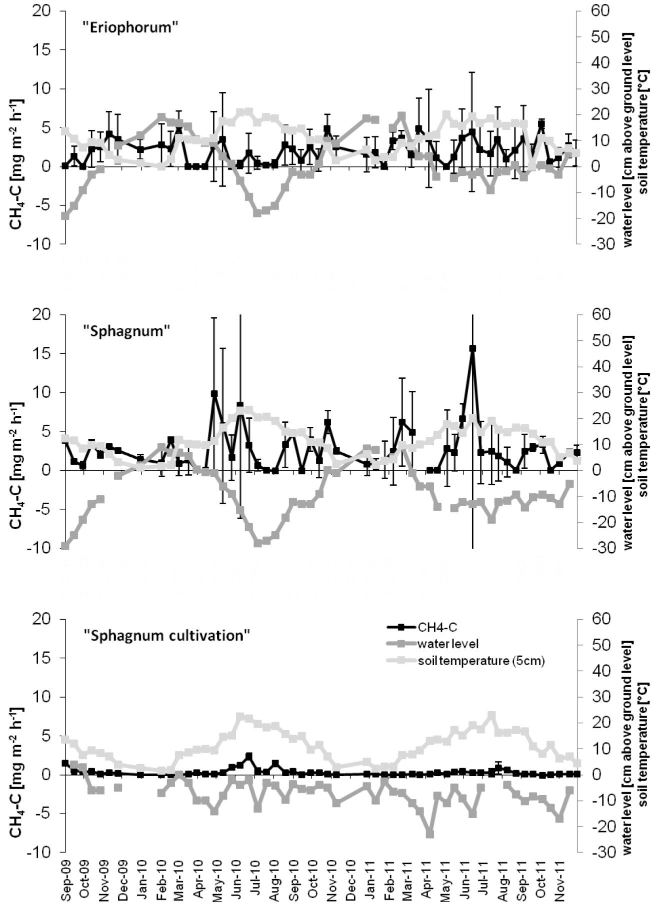

Figure 4. Yearly development of CH_4 flux at "*Eriophorum*", "*Sphagnum*" and "*Sphagnum* cultivation" (left axis). Mean of the three collars; error bars are standard errors. Yearly development of water level and soil temperature at a depth of 5 cm (right axis).

riod on GPP at "*Sphagnum*" proves the ability of our model to account for such influencing parameters.

For a meta-analysis we used the data of this paper, our own unpublished data from a bog near Bremerhaven (NW Germany) and published data of rewetted (mostly former peat cut sites) in the temperate zone (Nieveen et al., 1998; Drösler, 2005; Bortoluzzi et al., 2006; Beetz et al., 2013). CO_2 balances of our sites are in line with those of other bogs, but if only published values from German bogs are taken into consideration, it seems that our results fit the results of natural bogs better than those of rewetted bogs: Drösler (2005) and Beetz et al. (2013) found annual balances in the range of -157 to $-8\,g\,CO_2\text{-}C\,m^{-2}\,a^{-1}$. Our values ranged from -201.7 ± 126.8 to $29.7\pm112.7\,g\,CO_2\text{-}C\,m^{-2}\,a^{-1}$ (Table 2). In contrast, rewetted bogs in Germany reveal annual balances in the range of -148 to $192\,g\,CO_2\text{-}C\,m^{-2}\,a^{-1}$ (Drösler, 2005; Beetz et al., 2013). Water level and vegetation partly explains the variation in the meta-analysis (Fig. 5). However, small differences in mean water level between the sites lead to vanishingly small differences in gas fluxes. Thus, "*Sphagnum*" and "*Sphagnum* cultivation" were not significantly different, while "*Eriophorum*" revealed a slightly lower net CO_2 uptake due to a different type of vegetation, and "*Molinia*" showed a much lower net accumulation because of different vegetation and a much lower water level in summer.

A rewetted *Sphagnum*-dominated bog in Finland with a similar water level to "*Sphagnum*" shows CO_2 balances in the same range (Kivimäki et al., 2008). However, other rewetted bogs in the boreal zone with comparable water levels and vegetation composition reveal much lower annual exchange rates (with -800 to $1644\,kg\,CO_2\text{-}C\,ha^{-1}\,a^{-1}$) compared to rewetted bogs in the temperate zone, which range between -2960 and $1920\,kg\,CO_2\text{-}C\,ha^{-1}\,a^{-1}$ (Tuittila et al., 1999; Yli-Petays et al., 2007; Kivimäki et al., 2008). Also, natural bogs in the boreal zone show lower uptake rates (Lafleur et al., 2003). A comparison of the annual balances of our sites and other sites in the temperate zone with rewetted bogs in the boreal zone indicate that, on average, a net accumulation in both zones takes place, but the average annual uptake rate is much higher in the temperate zone.

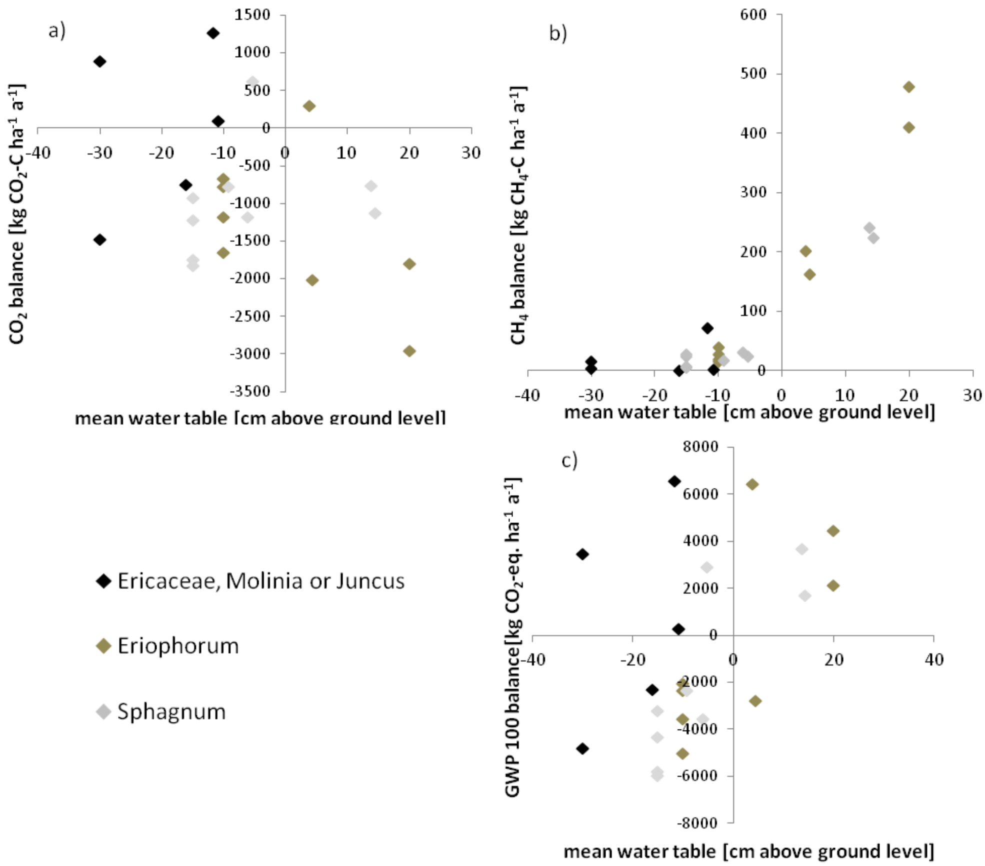

Figure 5. Yearly gas exchange balances versus mean water level of rewetted bogs in temperate zone: categories according to dominant vegetation (*Ericaceae*-, *Molinia*-, or *Juncus*-dominated; *Eriophorum*-dominated; *Sphagnum*-dominated). **(a)** Yearly NEE balance versus mean water level; **(b)** yearly CH_4 balance versus mean water level; **(c)** yearly GWP100 balance versus mean water level. Only data from rewetted bogs in the temperate zone are included; the data used come from this paper, own unpublished data, Nieveen et al. (1998), Drösler (2005), Bortoluzzi et al. (2006) and Beetz et al. (2013). Please note: in general, values of flux rates and water level are given in the text or in tables of the corresponding publications. If values of water level are not given, but only presented in the form of a figure, then mean water level was estimated from the figures in the corresponding publications.

The high variation of the annual CH_4 emissions between the sites (Table 2) is in line with the results of other studies in rewetted (mostly former peat cut sites) bogs in the temperate zone (Drösler, 2005; Bortoluzzi et al., 2006; Beetz et al., 2013; our own unpublished data) and can be mainly explained by the variation in the mean water level (Fig. 5). The relationship between CH_4 balances and water level was also described by Drösler (2005) and Couwenberg et al. (2011). Therefore, "*Eriophorum*" and "*Sphagnum*" revealed significantly higher annual methane emissions than "*Molinia*" and "*Sphagnum* cultivation". Our meta-analysis showed a threshold value for the mean annual water level of about 10 cm below ground level. At the rewetted sites, the methane emissions are strongly determined by the water level ($R^2 = 0.78$, $P < 0.001$). The *Eriophorum* (*E. vaginatum* and *E. angustifolium*)-dominated rewetted sites show slightly higher CH_4 balances compared to the *Ericaceae*-, *Molinia*- or *Juncus*-dominated sites and *Sphagnum*-dominated sites with a similar average water level. *E. vaginatum* and *E. angustifolium* are plants with aerenchymatous leaves and contribute to the methane emissions because methane is transported through the aerenchyma (Joabbson et al., 1999; Joabbson and Christensen, 2001; Drösler, 2005; Couwenberg et al., 2011). One *Ericaceae*-dominated site showed unusually high CH_4 emissions (see Fig. 5). This site was a drained *Calluna vulgaris* heathland, which was rewetted about 10 years ago (Drösler, 2005). The vegetation still consists mainly of *C. vulgaris* although the water level is too high to support such a type of vegetation in the long term. *C. vulgaris* is found at places with a lower water level (Poschlod, 1988; Drachenfels, 2011). A comparison between rewetted and natural bogs with the data from our study and literature data (Drösler, 2005, Bortoluzzi et al., 2006; Beetz et al., 2013) reveals that, in contrast to the findings of Augustin and Joosten (2007), CH_4 emissions from rewetted bogs are not higher than from natural bogs.

Also, rewetted bogs in the boreal zone show increasing annual CH_4 emissions with rising water levels (Yli-Petays et al., 2007). Compared to the temperate zone the emissions are much higher: Yli-Petays et al. (2007) found CH_4 emissions between 113 and 378 $kg\,CH_4-C\,ha^{-1}\,a^{-1}$ at mean water levels of between 0 and 7.5 cm below ground. Methane emissions of bogs are low compared to fens, rice fields and freshwater ecosystems (Moore and Knowles, 1989; Le Mer and Roger 2001; Höper et al., 2008).

It can be summarized that the GHG exchange patterns depend mainly on temperature, PAR, vegetation and water level, while the state of the bog (rewetted or natural) seems to be of minor importance.

The rewetted, former peat mining site Leegmoor consists of a small-scale mosaic of areas with different water levels; hence the spatial pattern of CH_4 emissions is very heterogeneous. In order to obtain the methane emissions of the whole rewetted area, a mapping of mean water tables and/or vegetation type is needed. The relationship between water table and methane emission can than be used to estimate the overall emission.

By contrast, the *Sphagnum* farming site is very homogenous on the spatial scale, and, due to the active water management, the water table is well regulated during the whole year. Methane emissions from this site will generally be low if the water level is kept below the land surface.

Annual GPP and R_{eco} are both high and of the same magnitude; consequently, the annual NEE, which represents the small difference between both gross values, is generally close to 0. A change in weather conditions and water table can easily convert a sink into a source and vice versa. This high interannual fluctuation of the CO_2 balances in organic soils, with years releasing CO_2 and others sequestering CO_2, has been observed by many authors (Tuittila et al., 1999; Lloyd, 2001; Arneth et al., 2002; Roulet et al., 2007; Yli-Petays et al., 2007; Beetz et al., 2013). Natural bogs can be sources in the short term, but, on average over many years, they are sinks. Therefore, measurements should be conducted over several years.

Rewetted and natural bogs generally have low fluxes of nitrous oxide due to anoxic conditions (Byrne et al., 2004; Drösler, 2005; Beetz et al., 2013); this is confirmed in our study (Table 2).

4.3 Evaluation of the effectiveness of the methods for bog revitalization

All sites in Leegmoor revealed negative NECB on average over the 2 measurement years (Table 2). Thus, the aim of carbon accumulation is achieved. On the other hand, "*Eriophorum*" and "*Sphagnum*" have, on average over the 2 years, a small positive GWP100 balance, which means that they have a warming effect on the climate. This can be attributed to the methane emissions.

A meta-analysis of the data of our research sites and other data of rewetted (mostly former peat cut sites) bogs in the temperate zone (Drösler, 2005; Bortoluzzi et al., 2006; Beetz et al., 2013; our own unpublished data) shows that inundated bogs are generally GHG sources in terms of the GWP100 balance, due to the high methane emissions (Fig. 5). At a mean water level between 0 and 20 cm below ground level, most rewetted bogs seem to be GHG sinks in terms of the GWP100 balance. In contrast, rewetted bogs in Finland with water levels between 7.5 and 0 cm below ground have high GWP100 balances of up to 10 600 $kg\,CO_2-eq.\,ha^{-1}\,a^{-1}$ due to high CH_4 emissions (Yli-Petays et al., 2007). At a lower mean water level, an increase in GHG emissions is expected due to higher CO_2 emissions. A comparison between natural and rewetted bogs with the data of our study sites and published data (Drösler, 2005; Bortoluzzi et al., 2006; Beetz et al., 2013) shows that natural bogs do not have lower emissions or higher accumulation rates of GHG than rewetted bogs.

In contrast, agriculturally used drained bogs are huge net GHG sources. Sites used for cropland and grassland in the temperate zone in Europe show NECBs between 434 and 1150 $g\,CO_2\text{-}C\,m^{-2}\,a^{-1}$ (Höper, 2007; Elsgaard et al., 2012; Beetz et al., 2013). In addition, high nitrous oxide releases at cropland sites might occur. Petersen et al. (2012) observed emissions of 6100 $mg\,N_2O\text{-}N\,m^{-2}\,a^{-1}$ at a Danish bog used for cropland.

In conclusion, rewetted former peat mining areas may become net carbon sinks and a growing are of peatland within 30 years of rewetting. In single years, a net loss of carbon may occur, but, in the long term, a small accumulation of carbon takes place or, at least, the carbon balance is 0. Near-natural conditions are therefore required. A high water table (above ground level) leads to the release of high amounts of methane, resulting in a net warming effect (positive GWP100 balance) instead of a cooling effect. Rewetted bog areas such as Leegmoor always have a heterogeneous spatial distribution of areas differing in water level and vegetation. A high spatial variability in GHG fluxes was also observed by Fest et al. (2009) and Merbold et al. (2013). Moreover, the water level shows interannual variation. On one hand, there are always zones with a high water level where a positive GWP100 balance due to high CH_4 emissions has to be expected. On the other hand, there are always places with low water levels and positive GWP100 balances due to carbon dioxide emissions. Therefore, the water level should be kept a few centimetres below ground in most of the area and inundation should be avoided if possible.

4.4 Evaluation of the effectiveness of the methods for *Sphagnum* farming

"*Sphagnum* cultivation" shows the highest accumulation of carbon, compared to the other sites (Table 2). "*Sphagnum* cultivation" and "*Sphagnum*" have a similar NEE, but the net carbon accumulation (NECB) at “*Sphagnum* cultivation” is higher due to lower methane emissions. The main difference in the environmental controls between “*Sphagnum* cultivation” and “*Sphagnum*” are the water level dynamics (Fig. 1). The water level at “*Sphagnum* cultivation” is kept quite constant at a level which is unfavourable for high CH_4 emissions.

At “*Sphagnum* cultivation” the carbon stock of the biomass grown on the old peat layers revealed that, on average, $-102.3\pm8.2\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$ had been accumulated. This is similar to the annual NECB. The good fit of the values confirmed the results of the gas flux measurements and modelling. The roots of vascular plants in the peat layer are not included in the analysed biomass. However, the proportion of vascular plants is low (about 15 % of all of the biomass).

“*Sphagnum* cultivation” was a GHG sink in terms of the GWP100 balance in both examination years, and, with $-295.8\pm73.8\,\mathrm{g\,CO_2\text{-eq.}\,m^{-2}\,a^{-1}}$, it was the strongest sink of GHG on average over the 2 years compared to Leegmoor (Table 2, Fig. 5). The annual average water level is about 6–9 cm below ground, which is quite unfavourable for peat mineralization but obviously deep enough for the oxidation of most of the methane produced.

At “*Sphagnum* cultivation” no biomass had been harvested up to now. If the carbon which will be exported by the harvest and its mineralization to carbon dioxide due to the use of the biomass for horticultural purposes are taken into account, the NECB and GWP100 balance will be near neutral because almost all of the biomass built up during the years of *Sphagnum* farming is removed. Nevertheless, commercial *Sphagnum* farming would be by far the most convenient use of bogs. Conventional commercial uses of bogs, such as use as cropland, grassland or for peat mining, cause high emissions of GHG.

The results indicate that keeping the water table constant year-round just a few centimetres below ground level leads to a neutral GWP balance. Providing this, a conversion from conventional farming with deep drainage to *Sphagnum* farming would lead to a great reduction in climate impact.

4.5 Can the results be generalized?

“*Molinia*” was a net carbon sink in one year and a source in another year (Table 2: -74.1 ± 91.4 and $11.0\pm138.9\,\mathrm{g\,CO_2\text{-}C\,m^{-2}\,a^{-1}}$, respectively). Beetz et al. (2013) and Yli-Petays et al. (2007) observed the same in similar rewetted bogs. A literature survey of the data of our research sites and other data (Drösler, 2005; Bortoluzzi, et al., 2006; Beetz et al., 2013; our own unpublished data) shows that the NECB and the GWP100 balances of our sites (Table 2) are similar to the balances of other rewetted bogs in the temperate zone (Fig. 5). Most rewetted bogs in the boreal zone show lower NECB and GWP100 balances (Tuittila et al., 1999; Yli-Petays et al., 2007; Kivimäki et al., 2008). A time-dependent effect of gas flux dynamics is not visible in the temperate and in the boreal zone. The gas exchanges of natural and rewetted sites are similar.

5 Conclusions

Our study showed that former cutover bogs which had been rewetted 30 years ago were net carbon sinks and, therefore, peat accumulating sites, at present. The high water level led to a slowdown of the oxidation processes and to the accumulation of plant material as the base for peat formation. Nevertheless, the GWP100 balance is slightly positive due to methane emissions under inundated conditions, and the bog therefore has a small warming impact on the climate. Thus, in order to promote carbon accumulation, the water level should be high, whereas, in order to achieve a climate cooling effect, inundation should be avoided. However, in practice an exactly regulated water level is impossible or too expensive to achieve. In addition, the ground is never flat. Rewetted bogs always show a mosaic of comparatively dry and wet places. Thus, it can be concluded that, firstly, the rewetted area should be levelled in order to achieve an appropriate water level as far as possible, and, secondly, sites for the measurement of GHG fluxes should be placed in such a way as to represent the spatial heterogeneity. Due to the interannual variation of weather conditions, rewetted and natural bogs may be net carbon sources in single years; however, in the long term, they function as sinks. Measurements of GHG fluxes should be conducted over more than 1 year to account for temporal variability.

Temperature, PAR, water level and type of vegetation were identified as the main driving forces of GHG exchange in rewetted bogs. Thus, modelling approaches should consider these drivers. A measurement-campaign-based modelling procedure which considers driving forces in the short term (e.g. temperature, PAR) as well as in the long term (e.g. water level, phenology) seems to be an appropriate method, leading to flux rates with a high temporal resolution.

This study shows that *Sphagnum* farming is a climate-friendly way to use former peat extraction sites. Nevertheless, bogs used as grassland are also suitable for *Sphagnum* farming if the nutrient-rich topsoil is removed and the surface is levelled, as long as nutrient-poor water is available for rewetting. These sites represent a high potential in area and in the reduction of greenhouse gas emissions in northwest Germany. *Sphagnum* farming results in a win–win situation, because the production has a near-neutral climate impact, provides an alternative renewable material for peat, which is a nonrenewable resource, and results in an economic use of land.

Acknowledgements. This research was funded by the von Thünen Institut (vTI, Germany). The study was part of a nationwide project under the direction of M. Drösler (Weihenstephan-Triesdorf University of Applied Sciences, Germany). The authors thank

S. Köhler, N. Rosskopf, H. Fell and E. Pluquet for assistance with laboratory analyses and F. Wieczorek for assistance with field work.

Edited by: T. Laurila

References

AG Boden: Bodenkundliche Kartieranleitung, 5th Edn., E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, 2005.

Alm, J., Talanov, A., Saarnio, S., Silvola, J., Ikkonen, E., Aaltonen, H., Nykanen, H., and Martikainen, P. J.: Reconstruction of the carbon balance for microsites in a boreal oligotrophic pine fen, Finland, Oecologia, 110, 423–431, 1997.

Arneth, A., Kurbatova, J., Kolle, O., Shibistova, O. B., Lloyd, J., Vygodskaya, N. N., and Schulze, E.-D.: Comparative ecosystem–atmosphere exchange of energy and mass in a European Russian and a central Siberian bog II. Interseasonal and interannual variability of CO_2 fluxes, Tellus B, 54, 514–530 2002.

Augustin, J. and Joosten, H.: Peatland rewetting and the greenhouse effect, IMCG Newsletter, 29–30, 2007.

Beetz, S., Liebersbach, H., Glatzel, S., Jurasinski, G., Buczko, U., and Höper, H.: Effects of land use intensity on the full greenhouse gas balance in an Atlantic peat bog, Biogeosciences, 10, 1067–1082, doi:10.5194/bg-10-1067-2013, 2013.

Bortoluzzi, E., Epron, D., Siegenthaler, A., Gilbert, D., and Buttler, A.: Carbon balance of a European mountain bog at contrasting stages of regeneration, New Phytol., 172, 708–718, 2006.

Buchmann, N. and Schulze, E.-D.: Net CO_2 and H_2O fluxes of terrestrial ecosystems, Global Biogeochem. Cy., 13, 751–760, 1999.

Byrne, K. A., Chojnicki, B., Christensen, T. R., Drösler, M., Freibauer, A., Friborg, T., Frolking, S., Lindroth, A., Mailhammer, J., Malmer, N., Selin, P., Turunen, J., Valentini, R., and Zetterberg, L.: EU Peatlands: Current Carbon Stocks and Trace Gas Fluxes, CarboEurope-GHG Concerted Action – Synthesis of the European Greenhouse Gas Budget, Report 4/2004, Specific Study, Tipo-Lito Recchioni, Viterbo, October 2004, ISSN 1723-2236, 2004.

Chapin III, F. S., Woodwell, G. M., Randerson, J. T., Rastetter, E. B., Lovett, G. M., Baldocchi, D. D., Clark, D. A., Harmon, M. E., Schimel, D. S., Valentini, R., Wirth, C., Aber, J. D., Cole, J. J., Goulden, M. L., Harden, J. W., Heimann, M., Howarth, R. W., Matson, P. A., McGuire, A. D., Melillo, J. M., Mooney, H. A., Neff, J. C., Houghton, R. A., Pace, M. L., Ryan, M. G., Running, S. W., Sala, O. E., Schlesinger, W. H., and Schulze, E.-D.: Reconciling Carbon-cycle Concepts, Terminology, and Methods, Ecosystems, 9, 1041–1050, 2006.

Couwenberg, J.: Greenhouse gas emissions from managed peat soils: is the IPCC reporting guidance realistic?, Mires and Peat, 8, Article 02, 1–10, 2011.

Couwenberg, J., Thiele, A., Tanneberger, F., Augustin, J., Bärisch, S., Dubovik, D., Liashchynskaya, N., Michaelis, D., Minke, M., Skuratovich, A., and Joosten, H.: Assessing greenhouse gas emissions from peatlands using vegetation as a proxy, Hydrobiologia, 674, 67–89, 2011.

Drachenfels, O. V.: Kartierschlüssel für Biotoptypen in Niedersachsen, NLWKN, Niedersachsen, 2011 (in German).

Drösler, M.: Trace gas exchange and climatic relevance of bog ecosystems, southern Germany, PhD thesis, Technische Universität München, 2005.

Eggelsmann, R. and Blankenburg, J.: Zur Entwicklung der Heidemoore am Nordhümmling in Niedersachsen, TELMA, 20, 55–78, 1990 (in German).

Elsgaard L., Goerres, C.-M., Hoffmann, C. C., Blicher-Mathiesen, G., Schelde, K., and Petersen, S. O.: Net ecosystem exchange of CO_2 and carbon balance for eight temperate organic soils under agricultural management, Agr. Ecosyst. Environ., 162, 52–67, 2012.

FAO: World reference base for soil resources 2006, A framework for international classification, correlation and communication, World soil resources reports 103, Food and agriculture organization of the United Nations, ISSN 0532-0488, 2006.

Fest, B. J., Livesley, S. J., Drösler, M., van Gorsel, E., and Arndt, S. K.: Soil–atmosphere greenhouse gas exchange in a cool, temperate Eucalyptus delegatensis forest in south-eastern Australia, Agr. Forest Meteorol., 149, 393–406, 2009.

Flessa, H., Wild, U., Klemisch, M., and Pfadenhauer, J.: Nitrous oxide and methane fluxes from organic soils under agriculture, Eur. J. Soil Sci., 49, 327–335, 1998.

Gaudig, G., Gahlert, F., Krebs, M., Prager, A., Schulz, J., Wichmann, S., and Joosten, H.: *Sphagnum* farming in Germany – 10 years on the road to sustainable growing media, in: Proceedings 14th Int. Peat Congress, Stockholm, Schweden, 374, 1–7, 2012.

Glatzel, S., Lemke, S., and Gerold, G.: Short-term effects of an exceptionally hot and dry summer on decomposition in a restoring temperate bog, Eur. J. Soil Biol., 42, 219–229, 2006.

Höper, H.: Freisetzung von Treibhausgasen aus deutschen Mooren, Telma, Band 37, 85–116, 2007 (in German).

Höper, H. and Blankenburg, J.: Emissionen klimarelevanter Gase aus niedersächsischen Mooren und Möglichkeiten der Reduzierung, Schneverdingen Norddeutsche Naturschutzakademie, NNA – Berichte Klimaveränderungen und Naturschutz, 13. Jahrgang, Heft 2, 110–117, 2000 (in German).

Höper, H., Augustin, J., Cagampan, J. P., Drösler, M., Lundin, L., Moors, E., Vasander, H., Waddington, J. M., and Wilson, D.: Restoration of peatlands and greenhouse gas balances, in: Peatlands and climate change, edited by: Strack, M., IPS, Saarijärvi, Finland, 2008.

Houghton, J.: Global Warming, The complete briefing, 3rd Edn., Cambridge University Press, 2004.

Huber, W.: Nachweis von Ausreißern und Nichtlinearitäten bei der Auswertung von Eichreihen über eine Regressionsrechnung, Fresenius Zeitschrift für Analytische Chemie, 319, 379–383, 1984 (in German).

IPCC: Climate Change, The Science of Climate Change, in: Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA, 1996.

Joabbson, A. and Christensen, T. R.: Methane emissions from wetlands and their relationship with vascular plants: an Arctic example, Glob. Change Biol., 7, 919–932, 2001.

Joabbson, A., Christensen, T. R., and Wallen, B.: Vascular plant controls on methane emissions from northern peatforming wetlands, TREE, 14, 385–388, 1999.

Joiner, D. W., Lafleur, P. M., McCaughey, H., and Bartlett, P. A.: Interannual variability in carbon dioxide exchanges at a boreal wetland in the BOREAS northern study area, J. Geophys. Res., 104, 27663–27672, 1999.

Joosten, H. and Augustin, J.: Peatland restoration and climate: on possible fluxes of gases and money, in: Proceedings of the International conference "peat in solution of energy, agriculture and ecology problems", Minsk, Belarus, 412–417, 2006.

Kivimäki, S. K., Yli-Petäis, M., and Tuittila, E.-S.: Carbon sink function of sedge and *Sphagnum* patches in a restored cut-away peatland: increased functional diversity leads to higher production, J. Appl. Ecol., 45, 921–929, 2008.

Kreyszig, E.: Statistische Methoden und ihre Anwendung, 7th Edn., Vandenhoeck & Ruprecht, Göttingen, 1979 (in German).

Lafleur, P. M., McCaughey, J. H., Joiner, D. W., Bartlett, P. A., and Jelinski, D. E.: Seasonal trends in energy, water, and carbon dioxide fluxes at a northern boreal wetland, J. Geophys. Res., 102, 29009–29020, 1997.

Lafleur, P. M., Roulet, N. T., Bubier, J. L., Frolking, S., and Moore, T. R.: Interannual variability in the peatland-atmosphere carbon dioxide exchange at an ombrotrophic bog, Global Biogeochem. Cy., 17, 1036, doi:10.1029/2002GB001983, 2003.

Le Mer, J. and Roger, P.: Production, oxidation, emission and consumption of methane by soils: A review, Eur. J. Soil Biol., 37, 25–50, 2001.

Lloyd, C. R.: The measurement and modelling of the carbon dioxide exchange at a high Arctic site in Svalbard, Glob. Change Biol., 7, 405–426, 2001.

Lloyd, J. and Taylor, J. A.: On the temperature dependence of soil respiration, Funct. Ecol., 8, 315–323, 1994.

Merbold, L., Steinlin, C., and Hagedorn, F.: Winter greenhouse gas fluxes (CO_2, CH_4 and N_2O) from a subalpine grassland, Biogeosciences, 10, 3185–3203, doi:10.5194/bg-10-3185-2013, 2013.

Michaelis, L. and Menten, M. L.: Die Kinetik der Invertinwirkung, Biochem. Z., 49, 1–34, 2013 (in German).

Moore, T. R. and Knowles, R.: The influence of water table levels on methane and carbon dioxide emissions from peatlands soils, Can. J. Soil Sci., 69, 33–38, 1989.

Neter, J., Kutner, M., Nachtsheim, C., and Wasserman, W.: Applied Linear Statistical Models, 4th Edn., McGraw-Hill, Boston, Massachusetts, 1996.

Nieveen, J. P., Jacobs, C. R. M., and Jacobs, A. F. G.: Diurnal and seasonal variation of carbon dioxide exchange from a former true raised bog, Glob. Change Biol., 4, 823–833, 1998.

Nykänen, H., Alm, J., Silvola, J., Tolonen, K., and Martikainen, P. J.: Methane fluxes on boreal peatlands of different fertility and the effect of long-term experimental lowering of the water table on flux rates, Global Biogeochem. Cy., 12, 53–69, 1998.

Petersen, S. O., Hoffmann, C. C., Schäfer, C.-M., Blicher-Mathiesen, G., Elsgaard, L., Kristensen, K., Larsen, S. E., Torp, S. B., and Greve, M. H.: Annual emissions of CH_4 and N_2O, and ecosystem respiration, from eight organic soils in Western Denmark managed by agriculture, Biogeosciences, 9, 403–422, doi:10.5194/bg-9-403-2012, 2012.

Petrone, R. M., Waddington, J. M., and Price, J. S.: Ecosystem-scale flux of CO_2 from a restored vacuum harvested peatland, Wetl. Ecol. Manag., 11, 419–432, 2003.

Poschlod, P.: Vegetationsentwicklung ehemaliger Torfabbaugebiete in Hochmooren des bayrischen Alpenvorlandes, Tuexenia, 8, 31–53, 1988 (in German).

Roehm, C. L. and Roulet, N. T.: Seasonal contribution of CO_2 fluxes in the annual C budget of a northern bog, Global Biogeochem. Cy., 17, 1029, doi:10.1029/2002GB001889, 2003.

Roulet, N., Lafleur, P. M., Richard, P. J. H., Moore, T. R., Humphreys, E. R., and Bubier, J.: Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland, Glob. Change Biol., 13, 397–411, 2007.

Schipperges, B. and Rydin, H.: Response of photosynthesis of *Sphagnum* species from contrasting microhabitats to tissue water content and repeated desiccation, New Phytol., 140, 677–684, 1998.

Titus, J. E., Wagner, D. J., and Stephens, M. D.: Contrasting water relations of photosynthesis for two *Sphagnum* mosses, Ecology, 64, 1109–1115, 1983.

Tuittila, E.-S., Komulainen, V.-M., Vasander, H., and Laine, J.: Restored cut-away peatland as a sink for atmospheric CO_2, Oecologia, 120, 563–574, 1999.

Waddington, J. M. and Roulet, N. T.: Atmosphere-wetland carbon exchanges: Scale dependency of CO_2 and CH_4 exchange on the developmental topography of a peatland, Global Biogeochem. Cy., 10, 233–245, 1996.

Waddington, J. M. and Warner, K. D.: Atmospheric CO_2 sequestration in restored mined peatlands, Ecoscience, 8, 359–368, 2001.

Wilson, D., Tuittila, E.-S., Alm, J., Laine, J., Farrell, E. P., and Byrne, K. A.: Carbon dioxide dynamics of a restored maritime peatland, Ecoscience, 14, 71–80, 2007.

Yli-Petays, M., Laine, J., Vasander, H., and Tuittila, E.-S.: Carbon gas exchange of a re-vegetated cut-away peatland five decades after abandonment, Boreal Environ. Res., 12, 177–190, 2007.