Biogeosciences Discuss., 11, 4493–4530, 2014
www.biogeosciences-discuss.net/11/4493/2014/
doi:10.5194/bgd-11-4493-2014

Biogeosciences
Discussions
Open Access

# Greenhouse gas emissions from 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, Hannover, Germany

Received: 8 January 2014 – Accepted: 10 February 2014 – Published: 21 March 2014

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

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

## Abstract

During the last three decades, an increasing area of drained peatlands was rewetted. This was done with the objective to convert these sites from sources back to sinks or, at least, to much smaller sources of greenhouse gases (GHG). However, available data is still scarce, especially on the long-term climatic effects of rewetting of temperate bogs. Moreover, first field trials are established for *Sphagnum* cultivating (paludiculture) on wet bog sites and an assessment of 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 more than two 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 in high time resolution using automatically monitored climate data. Measured and modelled values fit very well together ($R^2$ between 0.88 and 0.98). 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 $-201.7 \pm 126.8$ to $29.7 \pm 112.7\,\mathrm{g\,CO_2\text{-}C\,m^{-2}\,a^{-1}}$) due to different weather conditions, water level and vegetation. The *Sphagnum* cultivation site was a sink of $CO_2$ ($-118.8 \pm 48.1$ and $-78.6 \pm 39.8\,\mathrm{g\,CO_2\text{-}C\,m^{-2}\,a^{-1}}$). The yearly $CH_4$ balances ranged between $16.2 \pm 2.2$ and $24.2 \pm 5.0\,\mathrm{g\,CH_4\text{-}C\,m^{-2}\,a^{-1}}$ 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 zero. The net $N_2O$ fluxes were low and not significantly different between the four sites. The annual NECB at the rewetted sites was between $-183.8 \pm 126.9$ and $51.6 \pm 112.8\,\mathrm{g\,CO_2\text{-}C\,m^{-2}\,a^{-1}}$ and at the *Sphagnum* cultivating site $-114.1 \pm 48.1$ and $-75.3 \pm 39.8\,\mathrm{g\,CO_2\text{-}C\,m^{-2}\,a^{-1}}$. The yearly GWP100 balances ranged from $-280.5 \pm 465.2$ to $644.5 \pm 413.6\,\mathrm{g\,CO_2\text{-eq.}\,m^{-2}\,a^{-1}}$ at the rewetted sites. In contrast, the *Sphagnum* farming site had a cooling impact on the climate in both years ($-356.8 \pm 176.5$ and $-234.9 \pm 145.9\,\mathrm{g\,CO_2\text{-}C\,m^{-2}\,a^{-1}}$). If the exported carbon 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 after 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 surface.

*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 (organic soils) have been drained and used for peat extraction, agriculture and forestry worldwide and in particular in Germany (Couwenberg, 2011). The consequences are accelerated mineralisation of the high amounts of carbon that have been accumulated over thousands of years, and the promotion of the formation of nitrous oxide as a byproduct of nitrification and a product of incomplete denitrification (Firestone and Davidson, 1989; Scheffer, 1994; Schlesinger, 1997; Meyer, 1999; Höper, 2007; Kasimir-Klemedtsson et al., 2009). Tremendous amounts of the climate relevant gases $CO_2$ and $N_2O$ are released into the atmosphere. About three decades ago, restoration programmes started in Germany (Höper and Blankenburg, 2000). Today, a small area is rewetted with an increasing tendency. The restoration of a drained peatland converts the area from a source of $CO_2$ back into a sink of $CO_2$, or at least to a much smaller source. $N_2O$ emissions are turned back to a minimum. Otherwise, peatlands that are not drained emit methane, which is produced under anoxic conditions in the waterlogged soil (Waddington and Roulet, 1996; Le Mer and Roger, 2001; Houghton, 2004).

To determine the climatic impact of a peatland, all three trace gases ($CO_2$, $CH_4$ and $N_2O$) have to be considered. Each gas has an individual radiative forcing capability, thus in addition it is necessary to multiply the emission of each gas by the corresponding global warming potential (GWP) to establish the climatic impact (IPCC, 1996; Drösler, 2005; Drösler et al., 2008).

In Lower Saxony about ten % of the whole area is covered with peatland. More than half of the peatland area is bog, and most of the nationwide bogs are located in Lower Saxony. Almost the entire area is drained (Höper, 2007). The yearly emissions from bogs in Lower Saxony have a proportion of about 3.2 % of the total emissions of climate relevant gases in Lower Saxony (Höper and Blankenburg, 2000).

However, the available data is still scarce. To date, research studies about the gas exchange in peatlands were conducted mainly 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 modeled fluxes (Byrne et al., 2004). Most studies in restored peatlands are from recently rewetted sites. Investigations about the gas exchange and the GWP balance of peatlands having a longer history of rewetting are needed because the gas exchange pattern changes with time (Joosten and Augustin, 2006). Up to now, no research has been performed in *Sphagnum* cultivating sites (paludiculture) for harvesting. *Sphagnum* farming constitutes a sustainable alternative to conventional peat extraction and a climate friendly use of abandoned cut-over bogs (Gaudig et al., 2012).

In our study, we present the results of bogs rewetted for a longer time, and of a bog used for cultivation of peat mosses. To date, no research about trace gas emissions have been done in the examination area.

The aim of this study is to determine the exchange of $CO_2$, $CH_4$ and $N_2O$ as well as net ecosystem carbon balances (NECB) and GWP balances of different sites in a former peat cut bog which was rewetted about 30 years ago and one site in a test area to cultivate *Sphagnum* in Northern Germany. We hypothesize that the rewetted bog has a nearly neutral GWP balance, while the test site is a sink in terms of the GWP balance (cooling effect).

The main questions of our research are: (a) how high are the GHG emissions about 30 years after rewetting began?, (b) how high is the gas exchange of rewetted and partly restored former peat cut bogs compared to natural bogs?, (c) how is the GWP balance of rewetted bogs used for cultivation of *Sphagnum* compared to ordinary rewetted bogs?, and (d) which measures should be conducted for mitigation of GHG emissions and for promotion of carbon accumulation?

For determination of gas flux rates, we used the closed chamber method. This technique is frequently-used and recently improved by Drösler (2005). The advantages are its ability to measure flux rates in a small scale environment, its suitability for field conditions, and its low cost. The vegetation plays an important role in peat degradation processes and in soil-atmosphere gas exchange, but the function of the vegetation is not fully determined (Meyer, 1999; van den Bos, 2003; Drösler et al., 2008). We included the vegetation in our measurements and used transparent and opaque chambers to yield the most appropriate estimates (Drösler, 2005). To obtain yearly balances modeling and interpolation were carried out. Additional field measurements of driving parameters were conducted.

## 2 Material and methods

### 2.1 Site discription

The research area, Nordhümmlinger Moore, is located in the northwest part of Lower Saxony in Germany (53° N latitude, 7.32° longitude, about 5 m a.m.s.l.). 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 quite evenly distributed among 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: LM is a Sapric Histosol or Norm-Erdhochmoor (KHn, AG Boden, 2005) and comparatively dry (vegetation: *Molinia*, *Erica tetralix*, *Sphagnum cuspidatum*, *Eriophorum angustifolium*; peat thickness: about 160 cm). 50 m west are two wetter sites: LE (vegetation: *Eriophorum angustifolium*, *Molinia*, *Sphagnum cuspidatum*, *Betula pendula*) and LS (about ten cm deeper; vegetation: *Sphagnum cuspidatum*, *Eriophorum angustifolium*, *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 (WS) is a 60 m × 20 m test area, which was agriculturally used until 2000, subsequently under peat extraction, and rewetted in 2004 in order to cultivate peat mosses for harvesting (vegetation: *Sphagnum papillosum*, *S. Cuspidatum*, *S. palustre*, *S. fallax*, *Eriophorum angustifolium*, *Erica tetralix*, *Juncus effusus*, *Betula pendula*, *Drosera*, mushrooms; peat thickness: 195 cm: 9 cm highly decomposed peat, 186 cm weakly decomposed peat; Fibric Histosol or Norm-Hochmoor (HHn, AG Boden, 2005)). The water level is kept year round quite constant just below ground level with the aid of a pump. To date, no harvesting took place.

## 2.2 Measurements of site factors

The soil identification (soil horizon, peat substrate, $CaCO_3$ content, pH) was conducted according to AG Boden (2005). The decay degree was determined according to von Post.

Aboveground biomass at WS was sampled (cut by hand) from the measurement plots down to the original peat and separated in green (green biomass) and brown (dead biomass) plant parts as well as in moss and vascular plants. We determined dry matter by drying the samples in a drying oven at a temperature of 105 °C for two days (until constant weight). Fresh and dry biomass was quantified using a laboratory balance.

The dried samples were heated to 550 °C in the drying oven for about three days to ash the biomass, and subsequently analysed in an elemental analyser (Elementar vario plus CNS-analyser) to achieve carbon- and nitrogen-contents.

LM, LE, and WS were equipped with tubes perforated in the peat body, close to the collars. Water levels were manually measured at each gas measurement campaign with an electric contact gauge. In addition, at LE and WS the water levels were continuously (half-hourly) recorded from June 2010 until December 2011 with Schlumberger MiniDiver. The missing time periods were filled by interpolation between the manual measurements.

Meteorological parameters, such as temperatures (air temperature, soil temperature in 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 WS.

In addition, soil temperatures were measured and saved half hourly with a datalogger (DN Messtechnik, Norderstedt) at LM and WS. The data of LM were used for LM, LE and LS.

### 2.3 Measurements and modelling of carbon dioxide exchange

Flux measurements were carried out every four weeks, starting September 2009 and ending 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, a closed cell rubber tube on the bottom side 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), net ecosystem exchange (NEE) with transparent chambers (3 mm strong Plexiglas). The research plots were arranged with boardwalks and 3 collars (3 mm strong PVC, about 20 cm apart).

Air pressure, air temperature, soil temperatures in two, five and ten cm depth (measured with inserting thermometers), and photosynthetic active radiation (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 to 18 measurements with opaque and 12 to 30 measurements with transparent chambers were carried out.

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. To ensure quality and representativeness of the slope the following parameters were tested: (1) linearity of slope, (2) difference of the slope from zero (slopes not different from zero were set to zero), (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 (IPCC, 1996).

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

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 in 2 or 5 cm depth).

GPP was derived from transparent (NEE) and opaque ($R_{eco}$) chamber measurements and modelled using a saturation function (Michaelis and Menten, 1913) and photosynthetic active radiation (PAR) as 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 %.

Fitting of parameters was done using Microsoft excel® Solver.

The half-hourly flux rates for the period between two measurement days were determined as following: firstly, for each time step (i.e. 30 min) of this period $R_{eco}$ and NEE were calculated twice, using the model parameters of the measurement day before and those of the day after this period, respectively. Secondly, the two flux rates at a given time step of the period were weighted and added to get the interpolated flux rate, 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 $F_i$, $t_i$ = flux rate and time at time step $i$ to be modelled, $t_n$, $t_{n+1}$ = time (day) of the campaigns $n$ and $n+1$. $F_n$, $F_{n+1}$ = flux rates calculated with the model parameters of campaigns $n$ and $n+1$.

Finally, monthly and yearly balances were calculated.

### 2.4 Measurements and modelling of methane and nitrous oxide exchange

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

The chambers were identical in construction with the opaque chambers applied for $R_{eco}$ ($CO_2$), but not ventilated. A measuring procedure lasted one hour, 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-and FID-Detectors (Beetz et al., 2013).

During gas exchange measurement, air temperature and soil temperatures in two, five and ten cm depth (measured with 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 zero. Slopes not different from zero were set to zero.

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

### 2.5 Net ecosystem carbon balance and global warming potential

To obtain a complete carbon balance of a peatland, the net ecosystem carbon balance (NECB) was calculated (Chapin et al., 2006). DOC was estimated to 1.7 $\mathrm{g\,C\,m^{-2}\,a^{-1}}$ according to Moore (1987). Values of DIC, CO and VOC were assumed to be negligible and not considered.

Fluxes were expressed in terms of $CO_2$-equivalents using the global warming potential over a time span of 100 years (GWP100) of the respective gases ($CO_2 : CH_4 : N_2O = 1 : 21 : 310$: IPCC, 1996).

### 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. Analogous to the interpolation of the half-hourly gas fluxes, we interpolated the standard errors. The monthly and yearly 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 analogous to the interpolation of the fluxes. The yearly 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, if slopes are significant different from zero, 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 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

LM was entirely built up by highly decomposed peat with a high decay degree (z10), amorphous peat substrate, and had a very low pH (3.4). The uppermost horizons of LE and LS are built up of reduced bog-peat, had a very low decay degree (z1) and a pH of 3.7. The peat of LE consisted mainly of herbs, while at LS we found *Sphagnum* peat. At WS, the uppermost horizon (reduced bog-peat, *Sphagnum* peat) had also a decay degree of z1, but a higher pH (3.9). There was no $CaCO_3$ at the sites.

The vegetation at WS was grown on top of the original peat (consisting of highly decomposed peat) and built up an horizon of 15 cm of little decomposed Sphagnum material since the beginning of Sphagnum cultivation. Analysis of aboveground biomass was conducted in May of the last measurement year at WS (Table 1). The dry mass of the vegetation consisted primarily of *Sphagnum*. The total carbon stock was $715.8 \pm 57.2\,\mathrm{g\,m^{-2}}$.

The water table of LM was subject to fluctuation (Fig. 1). The yearly mean of the water table was 16.1 and 10.8 cm below ground surface in 2010 and 2011, respectively. The summer mean (May–October) was 34 and 21 cm below ground surface in 2010 and 2011, respectively. At LE the water table was higher and more stable in the course of the year (mean of 2010 and 2011: 4.4 and 3.8 cm above ground surface, respectively, summer mean: 4.9 and 2.5 cm below ground surface, respectively). LS was located about ten cm lower than LE, thus the mean was 14.4 and 13.8 cm above ground surface in 2010 and 2011, respectively. WS had a different water regime, because the water table was regulated (yearly mean in 2010 and 2011: 6.1 and 9.2 cm below ground surface, respectively, summer mean: 6.3 cm and 8.5 cm below ground surface, respectively).

The yearly course of temperature and precipitation is presented in Fig. 1.

### 3.2 Carbon dioxide

The regressions between measured and modelled flux rates for $R_{eco}$ and NEE of each measurement campaign at LM (Table 2) were in all cases significant ($P < 0.1$).

At the other three sites, in a few cases, mostly in winter, the span between the lowest and the highest temperature was too small for modelling the $R_{eco}$ (Table 3–5). At LE, this was the case on 25 November 2009, 15 December 2010 and 14 December 2011, and at LS on 31 March 2010, 21 April 2010, 18 August 2010 and 15 December 2010. In these cases $E_0$ was set to 0 and $R_{ref}$ was replaced by the mean value of the measured values. This is a conservative way to get an accurate result. The measurements on 9 February 2011 at LS had to be discarded because the data was not satisfactory. At WS the regressions between measured and modelled flux rates for $R_{eco}$ of the measurements on 29 September 2009 and 27 October 2009 were not significant, on 8 June 2011, gas fluxes at WS did not increase with increasing temperatures, and on 14 December 2010, there was almost no change of the soil temperature, and the air temperature was during the whole day below 0 °C, 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 LM, LE and LS, at WS the long-term influencing factors remained similar between the two pooled measurement campaigns. The measurement campaign-specific regressions between measured and modelled flux rates for the NEE were in all cases significant ($P < 0.1$).

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 followed almost the 1 : 1 line (Fig. 2). The standard errors for the $R_{eco}$ and the NEE at LM were 0.36 and 1.45 $\mu mol\ CO_2\text{-}C\ m^{-2}\ s^{-1}$, respectively. At LE standard errors of 0.70

and 1.32 µmol $CO_2$-C $m^{-2}$ $s^{-1}$, respectively, were determined. The standard errors at LS amounted to 0.39 and 0.83 µmol $CO_2$-C $m^{-2}$ $s^{-1}$, respectively, and at WS to 0.41 and 0.53 µmol $CO_2$-C $m^{-2}$ $s^{-1}$, respectively. The gas fluxes at LM and LE were generally higher than at the other sites, consequently the standard errors were usually higher, at least for the NEE.

The yearly course of $R_{eco}$ showed a strong seasonal pattern at all sites, with high values in summer and low values in winter (Fig. 3). In average over the two 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 LM, LE, LS, and WS, 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). LM and LE demonstrate a similar yearly course for the most part of the year. However, in the beginning of the vegetation period, gas fluxes started to increase much earlier at LE than at the other sites. The yearly pattern of LS and WS differed strongly from the course of LM and LE. LS and WS revealed both much lower $R_{eco}$ and GPP. By comparing the yearly course of the $R_{eco}$ with the course of the temperature it appeared that there is a lagging in the development of the vegetation in spring at all sites with the exception of LE. In late summer and autumn, when temperatures were still high, the $R_{eco}$ dropped already. In July 2010, the GPP at LS was contrary to the general trend, and dropped to lower values. Subsequently, it increased again. By comparing the yearly course of the GPP with the course of the PAR, there is a delay visible, similar to the delay of the $R_{eco}$ (see above).

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 zero or net emissions occurred (Fig. 3). At LE and LS the highest cumulated monthly net uptake of $CO_2$ occurred in average in June (−49.5 ± 20.4 g $CO_2$-C $m^{-2}$ and −47.8 ± 16.2 g $CO_2$-C $m^{-2}$, respectively), whereas at LM the highest averaged uptake of $CO_2$ was detected in July (−74.8 ± 2.4 g $CO_2$-C $m^{-2}$) and at WS in August (−25.0 ± 16.1 g $CO_2$-C $m^{-2}$). There was a gradient from highest net uptake at LM to lowest net uptake at WS during the summer months June until August. During the remaining part of the year, LM emitted net $CO_2$, LE emitted also net $CO_2$, but less than LM. LS and WS sequestrated net $CO_2$, but WS sequestrated more net $CO_2$.

The highest annual $R_{eco}$ was found at LE, followed by LM, LS, and WS (Table 6). In 2011, the annual $R_{eco}$ were higher than in 2010.

The net $CO_2$ sequestration (NEE) at LS and WS were about the same and not significantly different (Table 6). The uptake was higher in 2010 than in 2011. LM and LE were net sinks in 2010 and net sources in 2011. At all sites the yearly NEE balance was significantly different between the two years, caused by a higher $R_{eco}$ in 2011, compared to 2010. In average, a gradient from LM with a smaller uptake to WS with a higher uptake was apparent.

The standard errors were high, compared to the yearly balances, especially at LM and in 2011. In addition, the difference between the two years was high, particularly at LM and LE, where the standard errors were much higher than the mean values. WS showed the most stable values.

### 3.3 Methane

At the sites in the Leegmoor the yearly courses of the methane fluxes showed no seasonal trends, but rather a diffuse pattern (Fig. 4). At WS there was a relation between $CH_4$ fluxes and temperature as well as between $CH_4$ fluxes and water table visible (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. 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 zero, 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 zero.

At LM and WS the yearly $CH_4$ balances were low and not significantly different between the two sites (Table 6). At LE flux rates were higher and at LS highest methane emissions occurred. In 2011, the $CH_4$ emissions of LE and LS were not significantly different.

The $CH_4$ emissions in 2010 and 2011 were not significantly different at all sites.

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

### 3.4 Nitrous oxide

The yearly $N_2O$ balances did not differ significantly between all sites in both years (Table 6). While LS 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 LE.

### 3.5 Net ecosystem carbon balance and global warming potential

The NECB of LM and WS were similar to the annual NEE, because the NECB was mainly determined by the NEE (Table 6). In spite of the higher $CH_4$ emissions at LE and LS, there is still a gradient from LM with the lowest to WS with the highest NECB.

At LE and LS the GWP100 balance revealed a different picture than the NECB, because methane exerted a greater climatic impact (Table 6). LS was a greenhouse gas source (GWP100 balance) in both years and in average the highest source of all sites. LE and LM were sinks (GWP100 balance) in one year and sources in another year; WS was a sink in both years.

Changing the time perspective of the GWP assessment from 100 to 500 years leads to the conversion of LE and LS from a GHG source to a sink (Table 6). WS and LM 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).

# 4 Discussion

## 4.1 Evaluation of the methodology

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, the winter conditions are taken into consideration as good as possible by keeping up a time step of one campaign every four weeks.

Temperatures and PAR were used for the modeling at each measurement campaign, while other influencing factors like soil moisture or vegetation were not considered on a short term (i.e. daily), but only on a long term (i.e. monthly), disregarding that these factors may also change in 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 modeled and measured values of the NEE-model well above $R^2 = 0.5$ (Tables 2–5) underlining that temperature and PAR are the main factors on a short term. Factors having an effect on the long term are accounted for by the repeated measurement campaigns, which result in different model parameters as a consequence of the different field situation. The linear interpolation between measurement campaigns provided that long term influencing factors change also linearly, which is certainly not the case. For this reason we kept the time span between two measurement campaigns as short as possible (Beetz et al., 2013).

## 4.2 Effect of vegetation, water level and weather conditions

At all sites the seasonal pattern of $R_{eco}$ and GPP followed basically the course of the temperature and the PAR, respectively (Figs. 1 and 3). The deviations from these courses 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 raised already, 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 the autotrophic respiration is low and is not outbalance by the 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 LM and LE on the one hand, and LS and WS on the other hand were similar, due to similar types of vegetation, respectively. In comparison to the other sites, at LE the GPP 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 LS 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 LM and LE were not dominated by Sphagnum, but by species like Eriophorum which are less vulnerable to fluctuations of the water table (Tuittila et al., 1999). The clearly visible effect of the dry period on GPP at LS proves the ability of our model to account for such influencing parameters.

A meta-analysis of the data of this paper, 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) revealed that $CO_2$ balances of our sites are in line with those of other bogs. If only published values from German bogs are taken into consideration, it seems that our results fit more to the results of natural bogs than of rewetted bogs: Drösler (2005) and Beetz et al. (2013) found in natural bogs in Germany yearly balances in the range of −157 to −8 g $CO_2$-C $m^{-2}$ $a^{-1}$. Our values ranged from −201.7 ± 126.8 to 29.7 ± 112.7 g $CO_2$-C $m^{-2}$ $a^{-1}$ (Table 6). In contrast, rewetted bogs in Germany reveal annual balances in the range of −148 to 192 g $CO_2$-C $m^{-2}$ $a^{-1}$ (Drösler, 2005; Beetz et al., 2013). WI and vegetation explains the variation in the meta-analysis partly (Fig. 5). However, small differences of mean water level between the sites lead to vanishingly small differences in gas fluxes. Thus, LS and WS were not significantly different, while LE revealed a slightly lower net $CO_2$ uptake due to a different type of vegetation, and LM showed a much lower net accumulation, because of different vegetation and a much lower water level in summer.

The high variation of the yearly $CH_4$ emissions between the sites (Table 6) are 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; own data unpublished), and can be mainly explained by the variation of 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, LE and LS revealed significantly higher annual methane emissions than LM and WS. 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 averaged water level. *E. vaginatum* and *E. angustifolium* are plants with aerenchymous leafs and contribute to the methane emissions because methane is transported through the aerenchym (Joabbson et al., 1999; Joabbson and Christensen, 2001; Drösler, 2005; Couwenberg et al., 2011). One *Ericaceae* dominated site showed unusually high $CH_4$ emissions. 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 on a 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.

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 get the methane emissions of the whole rewetted area, a mapping of mean water tables and/or vegetation type is needed. And the relationship between water table and methane emission can than be used to estimate the overall emission.

On the contrary, 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 zero. A change in weather conditions and water table can easily convert a sink into a source and vice versa. This high inter-annual fluctuation of the $CO_2$ balances in organic soils, with years releasing $CO_2$ and others sequestering $CO_2$ were 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 in average over many years sinks. Therefore, measurements should be conducted over several years.

Rewetted and natural bogs have generally low fluxes of nitrous oxide due to anoxic conditions (Byrne et al., 2004; Drösler, 2005; Beetz et al., 2013), which is confirmed in our study (Table 6).

### 4.3 Net ecosystem carbon balance and global warming potential of rewetted bogs

The *Molinia* dominated LM was a net carbon sink in one year and a source in another year (Table 6: −74.1±91.4 and 11.0±138.9 g $CO_2$-C $m^{-2}$ $a^{-1}$, respectively). Beetz et al. (2013) observed the same in a similar rewetted bog in North Germany. The NECBs of our sites are in the range of similar rewetted and natural sites (Drösler, 2005; Bortoluzzi et al., 2006; Beetz et al., 2013).

All sites in Leegmoor revealed negative NECB in average over the two measurement years (Table 6). Thus, the aim of carbon accumulation is achieved. On the other hand, LE and LS have in average over the two 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; own data unpublished) shows that the GWP100 balances of our sites (Table 6) are in the same range as the balances of other rewetted bogs (Fig. 5). According to the analysis, inundated bogs are generally GHG sources in terms of the GWP100 balance, due to the high methane emissions. At a mean water level between zero and 20 cm below ground level, most rewetted bogs seem to be GHG sinks in terms of the GWP100 balance. 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) show that natural bogs do not have lower emissions or higher accumulation rates of GHG than rewetted bogs. Changing the time perspective from 100 years to 500 years alters the relationship and mean values, because the impact of methane is decreased. This would shift LE and LS from being greenhouse gas sources to being sinks, and the climatic impacts of the sites in the Leegmoor would be very similar. Most of the inundated bogs in the meta-analysis are GHG sources in terms of the GWP100 balance and GHG sinks in terms of the GWP500 balance.

In conclusion, rewetted former peat mining areas may become net carbon sinks and a growing peatland within 30 years after 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 becomes zero. This means that near-natural conditions are established. A high water table (above ground level) lead 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 have always a heterogeneous spatial distribution of areas differing in water level and vegetation. In addition, the water level shows inter annual variation. On one hand, there will always exist zones where the water level is too high and where a positive GWP100 balance due to high $CH_4$ emissions has to be expected. On the other hand there might be always places which have a too low water level and have a positive GWP100 balance due to carbon dioxide emissions. Therefore, the water level should be kept a few centimetres below ground surface in the biggest part of the area and inundation should be avoided, if possible.

### 4.4 Net ecosystem carbon balance and global warming potential of *Sphagnum* Farming sites

WS shows highest accumulation of carbon, compared to the other sites (Table 6). WS and LS have a similar NEE, but the net carbon accumulation (NECB) at WS is higher due to lower methane emissions. The main difference of the site factors between WS and LS are the water level dynamics (Fig. 1). The water level at WS is kept quite constant at a level which is unfavourable for large $CH_4$ emissions.

At WS the carbon stock of the biomass grown on the old peat layers revealed that in average $-102.3 \pm 8.2\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$ was accumulated. This is similar to the yearly 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 analyzed biomass. However, the proportion of vascular plants is low (about 15 % of whole biomass).

WS was a GHG sink in terms of the GWP100 balance in both examination years and was with −295.8 ± 73.8 g $CO_2$-eq. $m^{-2} a^{-1}$ the strongest sink of GHG in average over the two years, compared to Leegmoor (Table 6, Fig. 5). The yearly averaged water level is about six to nine cm below ground surface, which is quite unfavourable for peat mineralization, but obviously deep enough for oxidation of the most part of produced methane.

At WS no biomass was 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, NECB and GWP100 balance will be near neutral, because almost the whole biomass built up during the years of Sphagnum farming is removed. Nevertheless, a commercial Sphagnum farming would be by far the most convenient use of bogs. Conventional commercial uses of bogs like cropland, grassland or peat mining cause high emissions of GHG.

This is the first study on the GHG exchange of bogs used for *Sphagnum* farming. The results indicate that keeping the water table constant year round just a few centimetres below ground level lead to a neutral GWP balance. Providing this, a conversion from conventional farming with deep drainage to *Sphagnum* farming would lead to a great reduction of the climate impact.

## 5 Conclusions

GHG fluxes in rewetted bogs are mainly driven by temperature, PAR, wl and type of vegetation. 30 years after rewetting, bogs became net carbon sinks and, therefore, peat accumulating sites (“growing” bogs) comparable to natural bogs. Because of inter annual variation of weather conditions, rewetted and natural bogs may be net carbon sources in single years, however, on the long term, they function as sinks. Due to methane emissions under inundated conditions, the GWP100 balance is very likely positive and the bog has therefore a small warming impact on climate. In order to promote carbon accumulation, the wl should be high. However, in order to achieve a climate cooling effect inundation should be avoided.

This study indicate that *Sphagnum* farming has a near neutral climate impact and is therefore a climate-friendly alternative land use.

*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.

## 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, 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 Peat, 8, 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.

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

Drösler, M., Freibauer, A., Christensen, T. R., and Friborg, T.: Observation and status of Peatland Greenhouse Gas Emissions in Europe, in: Dolman, A. J., Valentini, R., and Freibauer, A.: The Continental-Scale Greenhouse Gas Balance of Europe, Ecological Studies, vol. 203, Springer, chap. 12, 243–261, 2008.

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

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.

Firestone, M. K. and Davidson, E. A.: Microbial basis of NO and $N_2O$ production and consumption in soil, in: Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere, edited by: Andreae, M. O. and Schimel, D. S., John Wiley & Sons, 7–21, 1989.

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, 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, 37, 85–116, 2007.

Höper, H. and Blankenburg, J.: Emissionen klimarelevanter Gase aus niedersächsischen Mooren und Möglichkeiten der Reduzierung, in: NNA – Berichte Klimaveränderungen und Naturschutz, edited by: Norddeutsche Naturschutzakademie, vol. 13, issue 2, 110–117, 2000.

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, Fresen. Z. Anal. Chem., 319, 379–383, 1984.

IPCC: Climate Change, The Science of Climate Change, 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.

Kasimir Klemedtsson, A., Weslien, P., and Klemedtsson, L.: Methane and nitrous oxide fluxes from a farmed Swedish Histosol, Eur. J. Soil Sci., 60, 321–331, 2009.

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.

KTBL: Faustzahlen für die Landwirtschaft, 14th edn., Yara, 2005.

Kreyszig, E.: Statistische Methoden und ihre Anwendung, 7th edn., Vandenhoeck & Ruprecht, Göttingen, 1979.

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.

Meyer, K.: Die Flüsse der klimarelevanten Gase $CO_2$, $CH_4$ und $N_2O$ eines nordwestdeutschen Niedermoores unter dem Einfluss der Wiedervernässung, Göttinger Bodenkundliche Berichte 111, Institut für Bodenwissenschaft, Universität Göttingen, 1999.

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

Moore, T. R.: Patterns of dissolved organic matter in subarctic peatlands, Earth Surf. Proc. Land., 12, 387–397, 1987.

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.

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.

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.

Scheffer, B.: Zur Stoffdynamik von Niedermoorböden, in: NNA – Berichte Entwicklung der Moore, edited by: Norddeutsche Naturschutzakademie, 7, 67–73, 1994.

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.

Schlesinger, W. H.: Biogeochemistry: an analysis of global change, 2nd edn., Academic Press, 1997.

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.

Van den Bos, R.: Summary, discussion and conclusions, Ph.D. thesis, chap. 7, 119–129, 2003.

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 revegetated cut-away peatland five decades after abandonment, Boreal Environ. Res., 12, 177–190, 2007.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

**Table 1.** Dry mass, total nitrogen content and total carbon content of moss, grass and total biomass at WS. Mean and Standard error.

| | | moss | | vascular plants | | total biomass | |
|---|---|---|---|---|---|---|---|
| | | m | s.e. | m | s.e. | m | s.e. |
| dry mass | [$\text{g m}^{-2}$] | 1288.0 | ±71.0 | 183.8 | ±49.6 | 1471.1 | ±88.8 |
| total N | [%] | 1.0 | ±0.04 | 0.2[a] | | | |
| total C | [%] | 49.2 | ±0.2 | 45[a] | | | |
| total N | [$\text{g m}^{-2}$] | 12.6 | ±0.7 | 0.4 | ±0.1 | 12.9 | ±0.8 |
| total C | [$\text{g m}^{-2}$] | 633.0 | ±34.9 | 82.7 | ±22.3 | 715.8 | ±57.2 |

[a] According to KTBL (2005).

**Table 2.** Parameters for the $R_{eco}$ and NEE models of LM: $E_0$: 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 $m^{-2}$ $s^{-1}$)$^{-1}$], $R^2$: coefficient of determination (Pearson) between modelled and measured values. s.e.: 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 | $E_0$ | $R_{ref}$ | $R^2$ | s.e. | *n* | temp | $GP_{max}$ | alpha | $R^2$ | s.e. | *n* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 30 Sep 2009 | 850.5 | 2.34 | $0.59^{c}$ | 0.41 | 12 | soil5 | −13.09 | −0.0203 | $0.59^{d}$ | 0.98 | 23 |
| 29 Oct 2009 | 748.1 | 2.04 | $0.32^{b}$ | 0.41 | 13 | soil5 | −6.25 | −0.0057 | $0.19^{b}$ | 0.34 | 21 |
| 25 Nov 2009 | **1106.8** | 0.35 | $0.46^{b}$ | 0.04 | 10 | soil2 | −0.89 | −0.0052 | $0.45^{c}$ | 0.09 | 21 |
| 03 Mar 2010 | 68.2 | 0.36 | $0.45^{c}$ | 0.03 | 15 | air | −0.59 | −0.0053 | $0.67^{d}$ | 0.09 | 25 |
| 31 Mar 2010 | 55.2 | 0.67 | $0.84^{d}$ | 0.02 | 15 | air | −1.73 | −0.0027 | $0.79^{d}$ | 0.19 | 26 |
| 21 Apr 2010 | 723.9 | 0.68 | $0.60^{d}$ | 0.05 | 14 | soil5 | −0.78 | −0.0014 | $0.55^{d}$ | 0.13 | 28 |
| 27 May 2010 | 175.4 | 2.32 | $0.30^{b}$ | 0.28 | 14 | soil2 | −5.18 | −0.0089 | $0.87^{d}$ | 0.41 | 30 |
| 23 Jun 2010 | 49.1 | 4.52 | $0.68^{d}$ | 0.38 | 18 | air | −15.39 | −0.0441 | $0.94^{d}$ | 1.02 | 30 |
| 21 Jul 2010 | 330.9 | 3.29 | $0.71^{d}$ | 0.69 | 16 | soil2 | −24.08 | −0.0659 | $0.90^{d}$ | 2.15 | 30 |
| 18 Aug 2010 | 332.3 | 1.69 | $0.28^{b}$ | 0.58 | 15 | soil2 | −29.19 | −0.0261 | $0.87^{d}$ | 1.68 | 21 |
| 15 Sep 2010 | 92.4 | 1.63 | $0.44^{c}$ | 0.14 | 15 | air | −27.50 | −0.0195 | $0.95^{d}$ | 1.11 | 27 |
| 13 Oct 2010 | 632.2 | 2.23 | $0.24^{a}$ | 0.21 | 15 | soil5 | −8.92 | −0.0393 | $0.94^{d}$ | 0.73 | 21 |
| 09 Nov 2010 | 332.7 | 1.99 | $0.58^{c}$ | 0.10 | 12 | air | −2.77 | −0.0063 | $0.77^{d}$ | 0.20 | 21 |
| 15 Dec 2010 | 565.6 | 2.14 | $0.52^{b}$ | 0.06 | 11 | air | −0.51 | −0.0014 | $0.29^{b}$ | 0.07 | 21 |
| 09 Feb 2011 | 63.4 | 0.57 | $0.95^{d}$ | 0.03 | 12 | air | −3.75 | −0.0015 | $0.59^{d}$ | 0.15 | 21 |
| 09 Mar 2011 | 220.6 | **0.32** | $0.46^{b}$ | 0.06 | 12 | air | −1.20 | **−0.0013** | $0.64^{d}$ | 0.08 | 21 |
| 14 Apr 2011 | **19.1** | 1.07 | $0.29^{b}$ | 0.09 | 15 | air | −1.40 | −0.0032 | $0.51^{d}$ | 0.23 | 27 |
| 03 May 2011 | 131.3 | 1.43 | $0.88^{d}$ | 0.14 | 15 | air | −2.69 | −0.0038 | $0.56^{d}$ | 0.27 | 24 |
| 07 Jun 2011 | 216.8 | 4.19 | $0.63^{c}$ | 0.03 | 12 | soil5 | −37.12 | −0.0282 | $0.83^{d}$ | 3.11 | 27 |
| 29 Jun 2011 | 273.1 | 2.33 | $0.48^{b}$ | 1.43 | 11 | air | **−61.46** | −0.0312 | $0.952^{d}$ | 2.18 | 23 |
| 27 Jul 2011 | 62.6 | 5.77 | $0.70^{d}$ | 0.52 | 15 | air | −42.03 | −0.0412 | $0.94^{d}$ | 2.04 | 30 |
| 24 Aug 2011 | 43.9 | **6.98** | $0.30^{b}$ | 0.40 | 14 | air | −30.56 | −0.0459 | $0.81^{d}$ | 2.69 | 24 |
| 21 Sep 2011 | 33.0 | 3.58 | $0.60^{b}$ | 0.05 | 9 | air | −31.69 | −0.0529 | $0.99^{d}$ | 0.64 | 21 |
| 20 Oct 2011 | 789.1 | 2.06 | $0.93^{d}$ | 0.08 | 12 | soil2 | −15.33 | −0.0069 | $0.88^{d}$ | 0.59 | 21 |
| 16 Nov 2011 | 533.8 | 1.40 | $0.59^{c}$ | 0.02 | 10 | soil2 | −0.71 | −0.0282 | $0.46^{d}$ | 0.16 | 21 |
| 14 Dec 2011 | 574.9 | 1.29 | $0.41^{b}$ | 0.06 | 12 | soil2 | **−0.50** | **−0.8479** | $0.80^{d}$ | 0.11 | 15 |

[a] $P < 0.1$;
[b] $P < 0.05$;
[c] $P < 0.01$;
[d] $P < 0.001$.

**Table 3.** Parameters for the $R_{\text{eco}}$ and NEE models of LE: $E_0$: activation energy like parameter [K], $R_{\text{ref}}$: respiration at the reference temperature [µmol $CO_2$-C m$^{-2}$ s$^{-1}$], temp: best fit temperature for $R_{\text{eco}}$ model. $GP_{\text{max}}$: 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$^{-1}$)$^{-1}$], $R^2$: coefficient of determination (Pearson) between modelled and measured values. s.e.: 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 | $E_0$ | $R_{\text{ref}}$ | $R^2$ | s.e. | *n* | temp | $GP_{\text{max}}$ | alpha | $R^2$ | s.e. | *n* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 30 Sep 2009 | **799.8** | 1.93 | 0.40[b] | 0.40 | 11 | soil5 | −42.75 | −0.0144 | 0.63[d] | 0.85 | 20 |
| 29 Oct 2009 | 222.0 | 2.88 | 0.28[b] | 0.09 | 15 | soil5 | −22.28 | −0.0107 | 0.64[d] | 0.56 | 24 |
| 25 Nov 2009 | 0.0 | 1.06 | 0.10 | 0.23 | 12 | | −55.97 | −0.0127 | 0.90[d] | 0.16 | 21 |
| 3 Mar 2010 | 442.0 | 2.72 | 0.60[d] | 0.10 | 15 | soil5 | −1.99 | −0.0039 | 0.64[d] | 0.22 | 25 |
| 31 Mar 2010 | 36.6 | 2.29 | 0.27[a] | 0.22 | 13 | air | −7.02 | −0.0089 | 0.77[d] | 0.65 | 29 |
| 21 Apr 2010 | 472.2 | 2.37 | 0.30[a] | 0.42 | 15 | soil2 | −9.78 | −0.0301 | 0.87[d] | 0.94 | 30 |
| 27 May 2010 | 132.5 | 2.60 | 0.48[c] | 0.51 | 15 | air | −20.40 | −0.0302 | 0.90[d] | 1.22 | 30 |
| 23 Jun 2010 | 170.9 | 3.12 | 0.78[d] | 0.88 | 18 | air | −15.56 | −0.0394 | 0.91[d] | 0.93 | 30 |
| 21 Jul 2010 | 110.3 | **4.62** | 0.24[b] | 2.04 | 18 | air | −18.26 | −0.0427 | 0.85[d] | 1.65 | 30 |
| 18 Aug 2010 | 169.9 | 2.85 | 0.21[a] | 0.55 | 15 | soil2 | −21.52 | **−0.0513** | 0.86[d] | 1.77 | 24 |
| 15 Sep 2010 | 152.7 | 1.82 | 0.41[b] | 0.13 | 10 | soil2 | −29.23 | −0.0227 | 0.81[d] | 2.17 | 26 |
| 13 Oct 2010 | 389.5 | 1.69 | 0.32[b] | 0.42 | 14 | soil2 | −37.51 | −0.0223 | 0.74[d] | 2.38 | 18 |
| 9 Nov 2010 | 440.8 | 1.53 | 0.34[b] | 0.09 | 12 | soil2 | −6.82 | −0.0180 | 0.97[d] | 0.16 | 18 |
| 15 Dec 2010 | 0.0 | 0.28 | 0.04 | 0.13 | 12 | | **−1.25** | −0.0126 | 0.84[d] | 0.14 | 21 |
| 9 Feb 2011 | **23.4** | **1.39** | 0.47[b] | 0.07 | 12 | air | −54.19 | **−0.0022** | 0.82[d] | 0.20 | 18 |
| 9 Mar 2011 | 250.8 | 2.12 | 0.25[a] | 0.47 | 12 | air | −4.80 | −0.0045 | 0.23[b] | 0.33 | 19 |
| 14 Apr 2011 | 115.1 | 2.33 | 0.47[c] | 0.77 | 15 | air | −19.20 | −0.0089 | 0.88[d] | 0.86 | 24 |
| 3 May 2011 | 500.6 | 2.18 | 0.73[d] | 0.45 | 12 | soil2 | −19.65 | −0.0151 | 0.92[d] | 1.03 | 24 |
| 7 Jun 2011 | 145.9 | 4.53 | 0.28[a] | 0.71 | 13 | air | −17.95 | −0.0334 | 0.82[d] | 1.98 | 27 |
| 29 Jun 2011 | 147.8 | 4.32 | 0.21[a] | 0.83 | 14 | air | **−72.79** | −0.0283 | 0.94[d] | 1.44 | 23 |
| 27 Jul 2011 | 259.6 | 3.08 | 0.75[d] | 0.97 | 15 | soil2 | −33.18 | −0.0286 | 0.90[d] | 1.50 | 30 |
| 24 Aug 2011 | 483.1 | 1.74 | 0.55[c] | 1.08 | 15 | soil2 | −29.23 | −0.0356 | 0.93[d] | 1.24 | 24 |
| 21 Sep 2011 | 625.0 | **1.39** | 0.25[a] | 0.53 | 12 | soil2 | −32.84 | −0.0436 | 0.95[d] | 1.30 | 24 |
| 20 Oct 2011 | 391.1 | 1.96 | 0.59[c] | 0.29 | 12 | soil2 | −21.47 | −0.0265 | 0.84[d] | 1.59 | 24 |
| 16 Nov 2011 | 308.4 | 2.23 | 0.31[a] | 0.20 | 12 | air | −39.93 | −0.0142 | 0.93[d] | 0.25 | 21 |
| 14 Dec 2011 | 0.0 | 1.40 | 0.02 | 0.56 | 24 | | −7.09 | −0.0064 | 0.73[d] | 0.38 | 12 |

[a] $P < 0.1$;
[b] $P < 0.05$;
[c] $P < 0.01$;
[d] $P < 0.001$.

**Table 4.** Parameters for the $R_{eco}$ and NEE models of LS: $E_0$: activation energy like 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 $m^{-2}$ $s^{-1}$)$^{-1}$], $R^2$: coefficient of determination (Pearson) between modelled and measured values. s.e.: 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 | $E_0$ | $R_{ref}$ | $R^2$ | s.e. | *n* | temp | $GP_{max}$ | alpha | $R^2$ | s.e. | *n* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 30 Sep 2009 | 136.4 | **2.33** | $0.43^a$ | 0.27 | 9 | air | **−17.89** | −0.0157 | $0.74^d$ | 0.68 | 23 |
| 29 Oct 2009 | 425.3 | 1.17 | $0.20^a$ | 0.15 | 15 | soil5 | −13.91 | −0.0178 | $0.95^d$ | 0.29 | 24 |
| 25 Nov 2009 | **29.4** | 0.51 | $0.43^a$ | 0.01 | 9 | air | −4.64 | −0.0161 | $0.90^d$ | 0.17 | 24 |
| 3 Mar 2010 | 247.7 | 0.53 | $0.26^a$ | 0.04 | 12 | soil2 | −4.89 | **−0.0001** | $0.21^b$ | 0.03 | 25 |
| 31 Mar 2010 | 0.0 | 0.42 | 0.00 | 0.27 | 15 |  | −17.35 | −0.0003 | $0.55^d$ | 0.10 | 27 |
| 21 Apr 2010 | 0.0 | 0.42 | 0.00 | 0.27 | 15 |  | −2.83 | −0.0045 | $0.94^d$ | 0.18 | 28 |
| 27 May 2010 | 183.7 | 0.98 | $0.44^c$ | 0.15 | 15 | soil2 | −9.46 | −0.0253 | $0.95^d$ | 0.50 | 30 |
| 23 Jun 2010 | 231.8 | 1.74 | $0.86^d$ | 0.53 | 18 | air | −13.46 | −0.0224 | $0.91^d$ | 0.72 | 30 |
| 21 Jul 2010 | 247.5 | 1.64 | $0.17^a$ | 0.47 | 18 | soil5 | −4.39 | −0.0130 | $0.65^d$ | 0.67 | 30 |
| 18 Aug 2010 | 0.0 | 2.49 | 0.02 | 0.57 | 15 |  | −11.82 | −0.0195 | $0.86^d$ | 0.94 | 24 |
| 15 Sep 2010 | 175.8 | 1.04 | $0.47^b$ | 0.21 | 12 | air | −13.80 | −0.0170 | $0.74^d$ | 1.32 | 27 |
| 13 Oct 2010 | 297.1 | 1.09 | $0.25^a$ | 0.26 | 15 | soil2 | −9.80 | **−0.0360** | $0.92^d$ | 0.74 | 21 |
| 9 Nov 2010 | 404.8 | 1.23 | $0.66^b$ | 0.07 | 8 | soil2 | −3.19 | −0.0190 | $0.66^d$ | 0.39 | 18 |
| 15 Dec 2010 | 0.0 | 0.08 | 0.16 | 0.02 | 12 |  | **−0.58** | −0.0026 | $0.71^d$ | 0.08 | 18 |
| 9 Mar 2011 | 100.7 | 0.45 | $0.56^b$ | 0.03 | 8 | air | −0.66 | −0.0010 | $0.29^b$ | 0.07 | 21 |
| 14 Apr 2011 | 110.0 | 1.23 | $0.40^b$ | 0.45 | 15 | air | −9.80 | −0.0047 | $0.74^d$ | 0.70 | 24 |
| 3 May 2011 | 217.7 | 1.52 | $0.68^d$ | 0.56 | 15 | air | −10.33 | −0.0131 | $0.65^d$ | 1.21 | 24 |
| 7 Jun 2011 | 267.6 | 2.25 | $0.39^b$ | 0.62 | 15 | air | −12.20 | −0.0237 | $0.88^d$ | 1.01 | 27 |
| 29 Jun 2011 | 213.8 | 2.00 | $0.35^b$ | 0.64 | 14 | air | −15.02 | −0.0344 | $0.89^d$ | 1.18 | 24 |
| 27 Jul 2011 | 197.9 | 1.99 | $0.68^d$ | 0.80 | 15 | air | −13.62 | −0.0269 | $0.80^d$ | 1.01 | 30 |
| 24 Aug 2011 | 335.1 | 1.43 | $0.74^d$ | 0.52 | 13 | soil5 | −17.71 | −0.0282 | $0.74^d$ | 1.23 | 24 |
| 21 Sep 2011 | **1069.0** | **0.39** | $0.41^b$ | 0.36 | 12 | soil5 | −15.98 | −0.0294 | $0.90^d$ | 0.81 | 24 |
| 20 Oct 2011 | 253.1 | 0.84 | $0.62^c$ | 0.20 | 12 | air | −9.14 | −0.0180 | $0.86^d$ | 0.72 | 24 |
| 16 Nov 2011 | 396.5 | 1.33 | $0.42^b$ | 0.08 | 12 | air | −5.46 | −0.0168 | $0.96^d$ | 0.14 | 21 |
| 14 Dec 2011 | 308.6 | 2.29 | $0.56^b$ | 0.16 | 12 | air | −3.45 | −0.0032 | $0.82^d$ | 0.13 | 12 |

[a] $P < 0.1$;
[b] $P < 0.05$;
[c] $P < 0.01$;
[d] $P < 0.001$.

**Table 5.** Parameters for the $R_{eco}$ and NEE models of WS: $E_0$: 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 $m^{-2}$ $s^{-1}$)$^{-1}$], $R^2$: coefficient of determination (Pearson) between modelled and measured values. s.e.: 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 | $E_0$ | $R_{ref}$ | $R^2$ | s.e. | $n$ | temp | $GP_{max}$ | alpha | $R^2$ | s.e. | $n$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 29 Sep 2009 | 277.8 | 0.91 | $0.43^d$ | 0.41 | 26 | soil5 | −6.12 | −0.0194 | $0.86^d$ | 0.46 | 36 |
| 27 Oct 2009 | | | | | | | −4.73 | −0.0114 | $0.79^d$ | 0.29 | 39 |
| 24 Nov 2009 | 969.8 | 0.39 | $0.40^a6$ | 0.07 | 9 | soil5 | −2.16 | −0.0231 | $0.83^d$ | 0.20 | 27 |
| 2 Mar 2010 | 772.4 | 0.66 | $0.34^b$ | 0.05 | 12 | soil2 | −4.59 | **−0.0014** | $0.62^d$ | 0.24 | 41 |
| 30 Mar 2010 | 264.9 | 0.48 | $0.61^d$ | 0.15 | 18 | air | −3.46 | −0.0102 | $0.96^d$ | 0.12 | 45 |
| 20 Apr 2010 | 97.3 | 1.04 | $0.34^b$ | 0.22 | 18 | air | −4.10 | −0.0125 | $0.95^d$ | 0.21 | 47 |
| 26 May 2010 | 144.6 | 1.70 | $0.19^a$ | 0.52 | 17 | soil5 | −12.56 | −0.0051 | $0.87^d$ | 0.43 | 50 |
| 22 Jun 2010 | 300.7 | 1.45 | $0.73^d$ | 0.70 | 18 | soil2 | −11.89 | −0.0116 | $0.84^d$ | 0.66 | 57 |
| 20 Jul 2010 | 301.3 | 1.29 | $0.26^b$ | 1.08 | 18 | soil5 | −9.72 | −0.0190 | $0.67^d$ | 0.86 | 57 |
| 17 Aug 2010 | 930.2 | **0.26** | $0.54^d$ | 0.82 | 18 | soil5 | −10.81 | −0.0273 | $0.83^d$ | 0.81 | 48 |
| 14 Sep 2010 | 430.2 | 0.84 | $0.18^a$ | 0.62 | 18 | soil5 | **−15.20** | −0.0262 | $0.88^d$ | 0.43 | 33 |
| 12 Oct 2010 | 694.6 | 0.70 | $0.48^c$ | 0.25 | 15 | soil5 | −7.70 | −0.0219 | $0.94^d$ | 0.46 | 42 |
| 10 Nov 2010 | 240.1 | 0.35 | $0.64^d$ | 0.05 | 27 | soil2 | −3.03 | −0.0317 | $0.90^d$ | 0.21 | 42 |
| 14 Dec 2010 | | | | | | | **−0.37** | −0.0028 | $0.74^d$ | 0.04 | 27 |
| 8 Feb 2011 | 406.5 | 0.65 | $0.50^c$ | 0.09 | 15 | soil2 | −3.05 | −0.0146 | $0.92^d$ | 0.18 | 35 |
| 8 Mar 2011 | 648.1 | 2.20 | $0.21^a$ | 0.09 | 15 | soil5 | −1.65 | −0.0193 | $0.86^d$ | 0.18 | 24 |
| 12 Apr 2011 | 94.0 | 0.76 | $0.24^b$ | 0.08 | 18 | soil2 | −3.41 | −0.0142 | $0.89^d$ | 0.30 | 46 |
| 8 Jun 2011 | **67.2** | **2.30** | $0.33^c$ | 0.44 | 30 | air | −6.78 | −0.0286 | $0.93^d$ | 0.31 | 33 |
| 28 Jun 2011 | | | | | | | −11.15 | −0.0212 | $0.91^d$ | 0.69 | 57 |
| 26 Jul 2011 | 322.6 | 1.22 | $0.67^d$ | 0.29 | 18 | soil2 | −13.84 | −0.0304 | $0.98^d$ | 0.49 | 57 |
| 23 Aug 2011 | 225.0 | 1.57 | $0.44^c$ | 0.20 | 14 | soil2 | −13.78 | −0.0275 | $0.97^d$ | 0.58 | 44 |
| 20 Sep 2011 | 229.5 | 1.43 | $0.89^d$ | 0.23 | 18 | soil2 | −14.17 | −0.0294 | $0.95^d$ | 0.58 | 45 |
| 19 Oct 2011 | 88.2 | 1.11 | $0.50^c$ | 0.16 | 12 | air | −6.44 | −0.0237 | $0.94^d$ | 0.31 | 30 |
| 15 Nov 2011 | 114.4 | 0.62 | $0.23^a$ | 0.04 | 15 | air | −2.57 | −0.0244 | $0.95^d$ | 0.10 | 33 |
| 13 Dec 2011 | **1015.1** | 1.81 | $0.51^b$ | 0.07 | 11 | soil5 | −1.43 | **−0.0624** | $0.93^d$ | 0.09 | 27 |

[a] $P < 0.1$;
[b] $P < 0.05$;
[c] $P < 0.01$;
[d] $P < 0.001$.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

**Table 6.** Annual and average balances for $R_{\mathrm{eco}}$, NEE, $CH_4$-C, $N_2O$-N exchange, NECB (net ecosystem carbon balances) and GWP (global warming potentials for the time spans of 100 and 500 years) balances. *m*: mean, s.e.: standard error. Letters indicate that balances are not significantly different.

| year | balances | | 2010 | | 2011 | | average | |
|---|---|---|---|---|---|---|---|---|
| | | | *m* | s.e. | *m* | s.e. | *m* | s.e. |
| LM | $R_{\mathrm{eco}}$ $CO_2$ | [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$^{-1}$] | −74.1 | 91.4 | 11.0 | 138.9 | −31.5 | 42.5 |
| | GWP 100 | [g $CO_2$-eq. m$^{-2}$ a$^{-1}$] | −234.2 | 335.3 | 24.4 | 509.4 | −104.9 | 156.0 |
| | GWP 500 | [g $CO_2$-eq. m$^{-2}$ a$^{-1}$] | −254.4 | 335.3 | 27.9 | 509.4 | −113.3 | 156.0 |
| LE | $R_{\mathrm{eco}}$ $CO_2$ | [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$^{-1}$] | −183.8 | 126.9 | 51.6 | 112.8 | −66.1 | 115.7 |
| | GWP 100 | [g $CO_2$-eq. m$^{-2}$ a$^{-1}$] | −280.5 | 465.2 | 644.5 | 413.6 | 182.0 | 424.3 |
| | GWP 500 | [g $CO_2$-eq. m$^{-2}$ a$^{-1}$] | −610.9 | 465.1 | 248.7 | 413.4 | −181.1 | 424.2 |
| LS | $R_{\mathrm{eco}}$ $CO_2$ | [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$^{-1}$] | −89.5 | 61.4 | −50.3 | 79.9 | −69.9 | 18.7 |
| | GWP 100 | [g $CO_2$-eq. m$^{-2}$ a$^{-1}$] | 167.0 | 225.7 | 368.4 | 293.8 | 267.7 | 68.6 |
| | GWP 500 | [g $CO_2$-eq. m$^{-2}$ a$^{-1}$] | −266.7 | 225.0 | −108.0 | 292.7 | −187.3 | 68.6 |
| WS | $R_{\mathrm{eco}}$ $CO_2$ | [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$^{-1}$] | −114.1 | 48.1 | −75.3 | 39.8 | −94.7 | 20.1 |
| | GWP 100 | [g $CO_2$-eq. m$^{-2}$ a$^{-1}$] | −356.8 | 176.5 | −234.9 | 145.9 | −295.8 | 73.8 |
| | GWP 500 | [g $CO_2$-eq. m$^{-2}$ a$^{-1}$] | −415.8 | 176.5 | −271.4 | 145.9 | −343.6 | 73.7 |

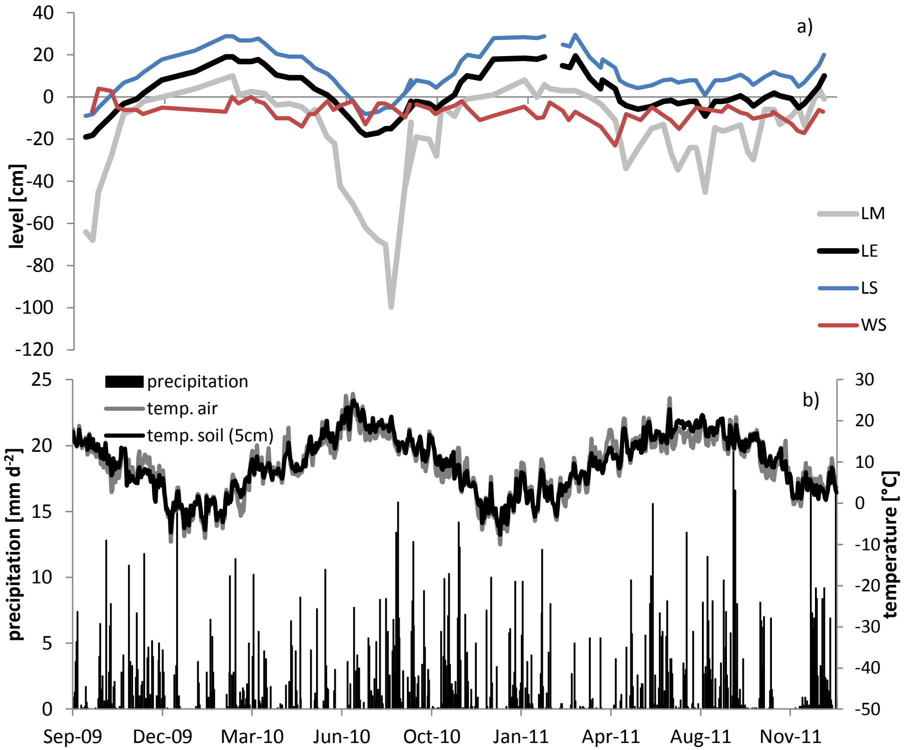

**Fig. 1.** **(a)** Water level of the examination sites, **(b)** yearly course of temperatures and precipitation at the weather station near WS. September 2009 until December 2011.

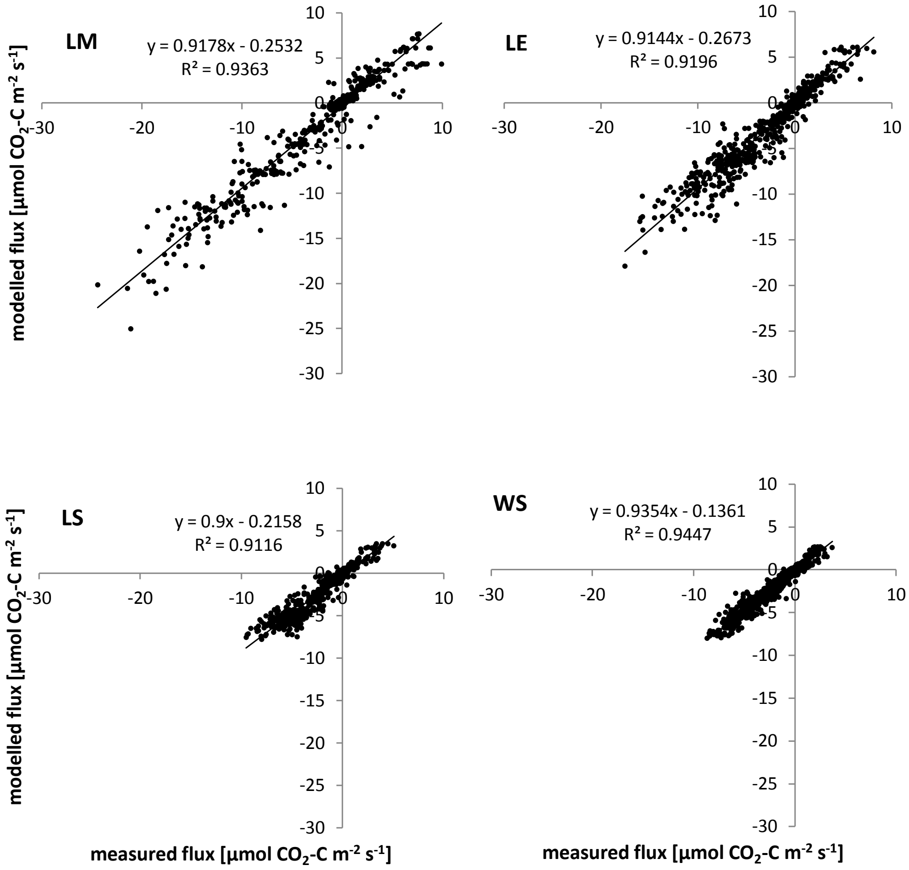

**Fig. 2.** Modelled vs. measured fluxes of NEE at the measurement sites. Regression equations and coefficients of determination (Pearson) ($R^2$).

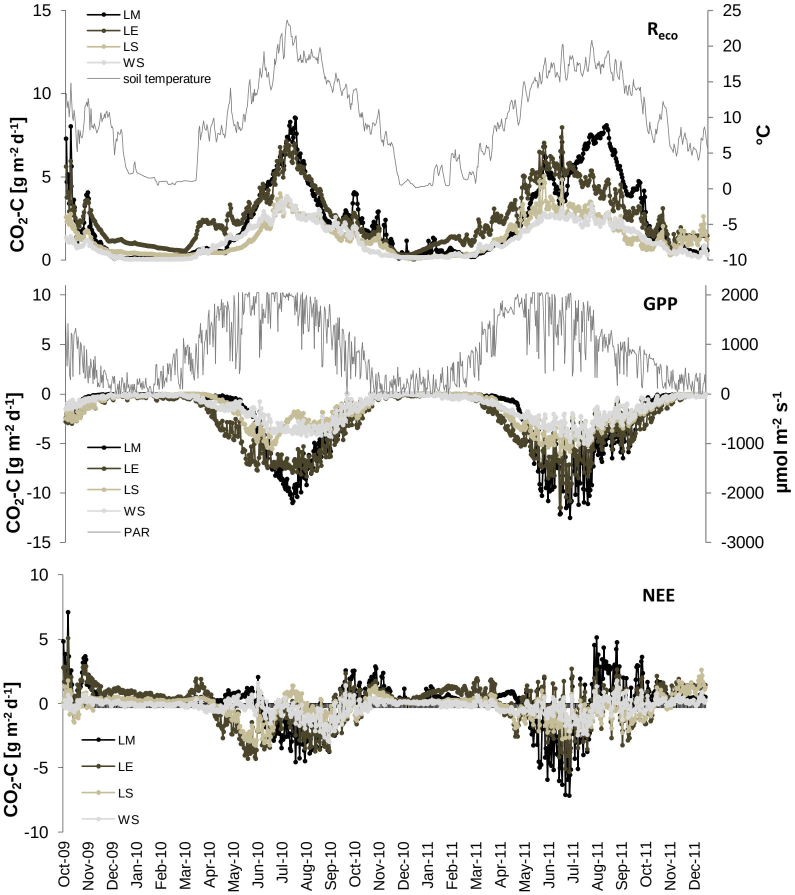

**Fig. 3.** Yearly courses of daily $R_{eco}$, GPP and NEE of the measurement sites (left axis). Soil temperature and PAR of the measurement sites (right axis).

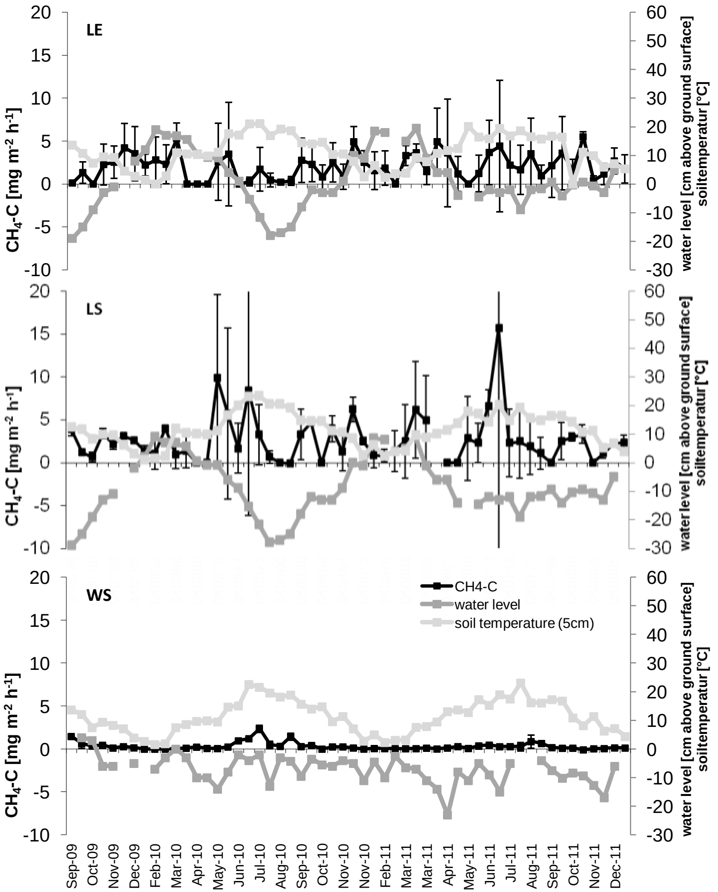

**Fig. 4.** Yearly course of CH$_4$ flux at LE, LS and WS (left axis). Mean of the 3 collars, error bars are standard errors. Yearly courses of water level and soil temperature in 5 cm depth (right axis).

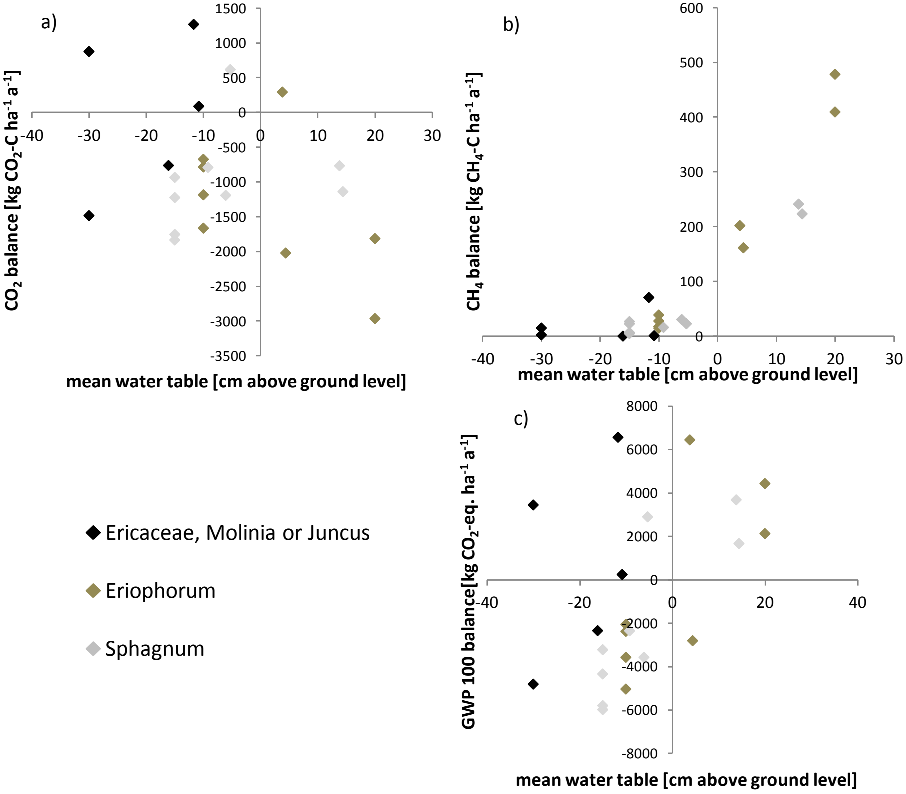

**Fig. 5.** Yearly gas exchange balances vs. mean water level of rewetted bogs in temperate zone: categories according to dominant vegetation (*Ericaceae*- *Molinia*- or *Juncus*-dominated, *Eriophorum*-dominated, *Sphagnum*-dominated). **(a)** Yearly NEE-balance vs. mean water level, **(b)** yearly CH$_4$-balance vs. mean water level, **(c)** yearly GWP100-balance vs. mean water level. Mean water level at some sites is estimated from figures.