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Can a bog drained for forestry be a stronger carbon sink than a natural bog forest?

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Abstract

This study compares the CO_2 exchange of a natural bog forest, and of a bog drained for forestry in the pre-alpine region of southern Germany. The sites are separated by only ten kilometers, they share the same formation history and are exposed to the same climate and weather conditions. In contrast, they differ in land use history: at the Schechenfilz site a natural bog-pine forest (*Pinus mugo rotundata*) grows on an undisturbed, about 5 m thick peat layer; at Mooseurach a planted spruce forest (*Picea abies*) grows on drained and degraded peat (3.4 m). The net ecosystem exchange of CO_2 (NEE) at both sites has been investigated for two years (July 2010 to June 2012), using the eddy covariance technique. Our results indicate that the drained, forested bog at Mooseurach is a much stronger carbon dioxide sink (-130 ± 31 and $-300 \pm 66\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$ in the first and second year respectively) than the natural bog forest at Schechenfilz (-53 ± 28 and $-73 \pm 38\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$). The strong net CO_2 uptake can be explained by the high gross primary productivity of the spruces that overcompensates the two times stronger ecosystem respiration at the drained site. The larger productivity of the spruces can be clearly attributed to the larger LAI of the spruce site. However, even though current flux measurements indicate strong CO_2 uptake of the drained spruce forest, the site is a strong net CO_2 source, if the whole life-cycle, since forest planting is considered. We determined the difference between carbon fixation by the spruces and the carbon loss from the peat due to drainage since forest planting. The estimate resulted in a strong carbon release of $+156\,\mathrm{t\,C\,ha^{-1}}$ within the last 44 yr, means the spruces would need to grow for another 100 yr, at the current rate, to compensate the peat loss of the former years. In contrast, the natural bog-pine ecosystem has likely been a small but consistent carbon sink for decades, which our results suggest is very robust regarding short-term changes of environmental factors.

1 Introduction

On a global scale peatlands play a major role with respect to carbon exchange, although they cover only 3 % of the Earth's land-surface area (Post et al., 1982). It has been estimated that northern peatlands have accumulated between 270 and 455 Pg of carbon (Gorham, 1991; Turunen et al., 2002) since the last ice age (i.e., over the last 10^4 yr). This corresponds to 20–30 % of the world's estimated soil carbon pool (Gorham, 1991) and 50 % of atmospheric carbon (Houghton et. al., 1990). Furthermore, an annual carbon accumulation of 15–30 $\mathrm{g\,C\,m^{-2}\,a^{-1}}$ in boreal peatlands has been estimated by Tolonen and Turunen (1996). It is generally accepted that undisturbed peatlands are the only terrestrial ecosystems that accumulate carbon continuously and over long time scales (Clymo, 1984). The importance of peatlands for the global carbon balance has been established by numerous studies carried out in the last 15 yr (e.g. Erwin, 2009; Frolking and Roulet, 2007; Moore et al., 1998). However, this carbon storage pool is threatened, as many natural peatlands are disturbed by human interference, such as peat cutting and land use change for agricultural use (Alm et al., 1999; Droesler et al., 2008). In addition the carbon storage potential of peatlands is threatened by climate change induced drought, as lower water tables lead to marked CO_2 emissions in peatland ecosystems (e.g. Alm et al., 1999; Arneth et al., 2002; Aurela et al., 2007).

If peatlands are drained, such that the peat layer is no longer water-logged, they lose their carbon accumulation capability. The organic soil carbon of the drained peat is oxidized to CO_2 and emitted to the atmosphere. To date, a number of studies have investigated the CO_2 exchange of peatlands, and the environmental factors that control it, by eddy covariance (e.g. Aurela et al., 2009; Lafleur et al., 2005; Sottocornola and Kiely, 2005), or chamber measurements (e.g. Bubier et al., 2003a; Goulden and Crill, 1997). The resulting carbon budgets depend on land use and peatland type. Generally ombrotrophic bogs are stronger carbon sinks than more nutrient-rich fens (Byrne et. al., 2004), while intensive land use (e.g. cropland) leads to stronger CO_2 emissions than extensive land use (Byrne et. al., 2004; Droesler et al., 2008). Most studies have focused on the greenhouse gas exchange of natural and agriculturally used peatlands in the boreal climate zone, where they cover large areas (e.g. Aurela et al., 2007; Bubier et al., 2003b; Lafleur et al., 2003; Lohila et al., 2007). However, studies about peatland forests are still rare, e.g. Maljanen et al. (2010) emphasize the lack of knowledge about the carbon budget of peatland forests, even in the boreal climate zone.

The objective of this study is to compare the CO_2 budget of a natural and a drained peatland forest in the pre-alpine region of southern Germany. The key issue to be addressed centers on the magnitude of the CO_2 budgets at these sites and the critical factors that account for the differences between them. To our knowledge this is the first direct comparison of the CO_2 exchange between natural and managed peatland forests in the temperate climate zone. Although, methane is likely also important for full greenhouse gas estimates in peatland ecosystems, this study focuses on CO_2 exchange, as comparable data of methane fluxes are not available.

2 Materials and methods

We report on CO_2 exchange measurements made over two years, from 01 July 2010 to 30 June 2012.

2.1 Site description

Measurements took place at two bog forests located within the pre-alpine region of southern Germany (Fig. 1), approximately 40 km south of Munich (Fig. 1c): Mooseurach (drained): 47°48′34″ N, 11°27′28″ E, 598 m a.s.l. and Schechenfilz (natural): 47°48′23″ N; 11°19′39″ E, 590 m a.s.l.

The sites are separated by 10 km, thus sharing the same glacial history and weather conditions. The lakes and peatlands in this pre-alpine region including both sites were formed on the ground moraine upon the retreat of the Isar-piedmont glacier (Isar-

Vorlandgletscher) at the end of the last ice age. Peatlands in this region extend over the lowlands an area south of lakes Ammer and Starnberg that reaches far beyond the two present study sites (Fig. 1c). The climate can be characterized as cool-temperate and humid with an average annual temperature of 8.6 °C and an average annual precipitation of 1127 mm (Table 1). The maximum precipitation occurs during the summer months.

While the general atmospheric conditions are the same, the sites clearly distinct by their land use history.

2.1.1 Schechenfilz (natural)

The near-natural ombrotrophic bog Schechenfilz (111 ha) (Fig. 1a) is part of the conservation area “Osterseen”. The northern part of the bog complex Schechenfilz was affected by peat cutting until the 1950s and was restored in 2001. However, in the present observation area the peat layer is still pristine. This vegetation is structured in open sedge-, heather meadows and wooded areas. The study site is situated in a woody area, dominated by slow growing bog-pines (*Pinus mugo rotundata* [Link] TURRA) that reach an average height of 2 m. The age of the trees varies from sapling up to 150 yr. The average leaf area index (LAI) of the bog pines is 2.3 (±0.8). The ground layer vegetation is dominantly formed by peat mosses (*Sphagnum spp.*) in addition with heather (*Calluna vulgaris* (L.)), bog bilberry scrubs (*Vaccinium uliginosum* (L.s.I)) and several species of the sedge-family (*Cyperacaea,* mainly *Eriophorum vaginatum* (L.), hare’s-tail cottongrass). As in all such bog forests, the distribution of vegetation is quite heterogeneous, but the heterogeneity occurs at scales much smaller than the expected flux measurement footprint (see also Sect. 2.3).

The analyses of one soil profile indicate pristine peat conditions at this site (N. Rosskopf, personal communication, 2012, Fig. 2). The upper 12 cm are only temporarily water saturated, and plants are only very weakly decomposed so that their structure is easily discernible. The underlying continuously water saturated layer extents to a thickness of almost 5 m (from 0.12–5.10 m below surface level). Elemental analyses of soil profiles show a high carbon content of about 50 % and pH-values of about 4, indicating the very acid environment typical for peat bogs. The C/N ratio varies within the different layers but shows a consistently low nutrient supply. Peat conditions, as well as vegetation composition, corresponds to typical pristine bog characteristics, so we consider the site at Schechenfilz to be a natural bog forest.

2.1.2 Mooseurach (drained)

The Mooseurach site (70 ha) is part of the large bog complex Weidfilz (250 ha, Fig. 1b) that was drained at the beginning of the 20th century; first for peat cutting, and a few years later to prepare it for agricultural use. Because of unfavorable agricultural site conditions, such as nutrient deficiency and still high water table, forestry became more important. The research area was afforested in 1967; the dominant species is Norway spruce (*Picea abies* [L.] KARST) with additions of Scots pine (*Pinus sylvestris* [L.]). Presently, the forest has an average canopy height of 21 m and an average LAI of 5.9 (±2.0). The peat is moderately drained, and although the drainage system is no longer maintained, it is still effective. Analyses of the soil at Mooseurach (N. Rosskopf, personal communication, 2012, Fig. 2) demonstrate the effects of drainage: in the upper 20 cm humification of the peat is well advanced and plant structures are no longer identifiable (humification degree 10 out of 10 after von Post, 1922). Between 20 and 35 cm beneath the surface the peat is occasionally water saturated in the course of the year, and below this is an almost 3 m thick continuously water saturated peat layer. Below 3.4 m the soil is mineral. It should be noted that the fraction of nitrogen (N) is greater at the drained site, implying a better availability of nutrients which is supported by the lower C/N ratio (Fig. 2). The drained site is also characterized by stronger humification and mineralization of the peat.

An old map of the drained site at Mooseurach, created in the 1940s, indicate a peat thickness of 4.4 m at the research area, about one meter thicker than today, illustrating the peat loss due to anthropogenic activity in the last 70 yr.

2.2 Instrumentation

CO_2 exchange was measured at the two study sites using the eddy covariance technique (e.g. Baldocchi et al., 1988; Foken et al., 2012). Due to differences in vegetation height, a 30 m radio-antenna-type tower was installed at the 21 m high drained spruce forest at Mooseurach and a 6 m tower in the bog-pine forest (canopy height about 2 m) at Schechenfilz. The towers were equipped with eddy covariance systems complemented by instruments to measure relevant auxiliary parameters. A 3-D sonic anemometer (CSAT-3, Campbell Scientific, Inc., Logan, Utah, USA) was used at each site. Carbon dioxide and water vapor were measured at Schechenfilz by an open path infrared gas analyzer (IRGA, LI7500, Li-Cor, Inc., Lincoln, Nebraska, USA), while at Mooseurach a closed path infrared gas analyzer (LI7200, Li-Cor) was installed. The intake tube was a 1 m insulated steel line with 3/8″ inner diameter and a flow rate of $15\,\mathrm{L\,min^{-1}}$.

Air temperature and relative humidity were measured by the HMP45C (Vaisala, Helsinki, Finland), photosynthetic active radiation by the LI 190SL (Li-Cor), the net radiation by the CNR4 (Kipp and Zonen, Delft, the Netherlands) and precipitation was detected by a tipping bucket raingauge 52 202 (Campbell Scientific) at both sites. Ground water table fluctuations were measured continuously by several mini-diver gauges (Schlumberger Water Services, Delft, the Netherlands; eight gauges in Schechenfilz and four in Mooseurach). The water content was detected by three water content reflectometers CS616 (Campbell Scientific), integrating the water content of the first 30 cm. The surface temperature was measured by an infra-red remote sensor IR100 (Campbell Scientific). The LAI of the trees is the mean of 100 individual measurements with the SunScan Canopy Analysis System SS1 (Delta-T, Cambridge, UK). At Schechenfilz the soil temperature in 10 cm depth was measured by T107-probes (Campbell Scientific) and in Mooseurach by soil temperature profiles STP01SC (Hukseflux, Delft, the Netherlands) in five different depths (0.02, 0.05, 0.1, 0.2, 0.5 m).

2.3 Data handling

The calculation and correction of the turbulent half-hourly CO_2-fluxes were performed with the software package TK3 (Mauder and Foken, 2011) that includes adjustments accounting for density fluctuations for the open-path flux measurements (WPL-adjustment after Webb et al., 1980) and spectral loss (high frequency) following Moore (1986). Furthermore, we applied the planar fit method after Wilczak et al. (2001) to ensure zero mean vertical wind speed.

Eddy covariance measurements allow the detection of continuous time series although data gaps occur for various reasons. Short gaps occurred sporadically, due to sensor malfunction and instrument diagnostic, in particular to the open path CO_2/H_2O analyzer during wet and foggy conditions. At Mooseurach, four long data gaps occurred on 12 April–19 April 2011, 10 July–25 July 2011, 15 November–26 November 2011 and 23 February–27 March 2012. In Schechenfilz three long gaps happened on 23 October–26 October 2010, 28 April–04 May 2011 and 22 May–27 May 2011. These longer data gaps were caused by power failure or problems of data storage. The raw data coverage of half-hourly flux measurements was 91 % at Mooseurach and 71 % at Schechenfilz. Subsequently, these data were screened to ensure good quality according to three rejection criteria.

First we applied the analytical footprint model (Kormann and Meixner, 2001) to estimate how well the measured fluxes captured the sources and sinks of the bog forest. If more than 70 % of the 30 min flux footprint overlapped with the area of interest, the data were used for further analysis; otherwise the data were rejected. At Mooseurach 21 % of the flux measurements did not originate from the area of interest. At Schechenfilz the target area is large relative to the measurement height and thus the footprint size matches the area of interest. It was therefore not necessary to apply a footprint criterion at the natural bog-pine site.

Second, an important source of error in the calculation of NEE is the underestimation of nighttime fluxes, due to low turbulence conditions. During such situations, emitted

CO_2 can accumulate near the surface and be advected away from the ecosystem without reaching the measurement system. Following standard practice (e.g. Aubinet et al., 2012; Goulden et al., 1996; Schmid et al., 2003), the friction velocity (u_*) was used to determine time periods when flux measurements were likely to be unreliable as a result of limited atmospheric mixing. The limiting value of friction velocity that indicates sufficient turbulence depends on surface roughness and therefore on vegetation type. We determined a lower u_*-limit of $0.225\,\mathrm{m\,s^{-1}}$ and of $0.125\,\mathrm{m\,s^{-1}}$ at Mooseurach and Schechenfilz respectively, following the method of Goulden et al. (1996). Above these thresholds the flux measurements no longer showed a dependence on friction velocity. Based on this criterion 30 % of all data had to be rejected at each of the sites, particularly at night.

Finally, an outlier test was applied to filter out unrealistic singular values. We separated the dataset into daytime ($> 20\,\mathrm{W\,m^{-2}}$ global radiation) and nighttime values ($< 20\,\mathrm{W\,m^{-2}}$ global radiation) and used a moving window with a width of ±14 half-hourly values. Each 30 min flux value within the window had to be within the 99 % confidence interval otherwise the value was excluded from further calculations. This conservative outlier test rejected only 1 % of the data at Mooseurach and 2 % at Schechenfilz. Considering missing values (28 % and 30 % in Schechenfilz and Mooseurach, respectively) and data rejection based on strict criteria (32 % and 31 %) leads to a high quality dataset covering 40 % of the total measurement period. An overview on missing and rejected data is given in Table 2.

2.4 Gap-filling method

The net ecosystem exchange of CO_2 (NEE) is the sum of two components driven by nearly independent processes that cause fluxes of approximately the same magnitude, but opposite directions (Moncrieff et al., 1996): the upward directed ecosystem respiration (R_{eco}) and the downward directed gross primary production (GPP). Therefore, a negative NEE indicates dominant CO_2 uptake and a positive NEE dominant CO_2 release.

In order to enable an analysis of the seasonal patterns of NEE or differences in the CO_2 balance between the sites, a gap-filling strategy was required, to replace the missing data. We used a non-linear regression method according to Falge et al. (2001) and Moffat et al. (2007) to model the GPP and R_{eco} components individually.

The respiration model is based on an Arrhenius-type exponential relation between (nighttime) data and temperature. Nighttime data were identified using a global radiation threshold of $20\,\mathrm{W\,m^{-2}}$ (Reichstein et al., 2005), and the temperatures used were those that provided the best fit, and consequently the lowest uncertainty of gap-filling, at each site. The temperatures selected were the soil temperature at a depth of 10 cm for Schechenfilz and the surface temperature at Mooseurach. The relation used was described by Lloyd and Taylor (1994) as:

$$R_{eco} = R_{ref} \times \mathrm{EXP}^{\left[E_0\left(\frac{1}{T_{ref}-T_0} - \frac{1}{T-T_0}\right)\right]}. \quad (1)$$

Where R_{ref} is defined as the ecosystem respiration at a reference temperature of 283.15 K (T_{ref}), E_0 is a fitting parameter called the activation energy (K), T_0 is a constant temperature of 223.8 K and T (°C) the temperature providing the best fit. To ensure realistic relationships we fitted the data over a wide temperature range choosing a fitting period of 6 months. As the respiration–temperature relationship showed no response to the phenology of the vegetation the fitting period is taken to be of acceptable length.

During the daytime (global radiation $> 20\,\mathrm{W\,m^{-2}}$), the respiration was estimated by the same correlation coefficients, determined by the nighttime respiration-temperature-relation. The GPP was modeled with a rectangular hyperbolic Michaelis–Menten-type function (Falge et al., 2001):

$$\mathrm{GPP} = \alpha' \times \mathrm{PAR} \times \mathrm{GPP}_{max} / (\mathrm{GPP}_{max} + \alpha' \times \mathrm{PAR}), \quad (2)$$

where α' is the apparent quantum yield, interpreted as the ecosystem light use efficiency ($\mathrm{\mu mol\,m^{-2}\,s^{-1}/\mu mol\,m^{-2}\,s^{-1}}$). In this case the carbon uptake per photon of photosynthetic active radiation (PAR). The fitting parameter GPP_{max} is the maximum carbon fixation rate at unlimited PAR. The annual growing cycle of vegetation activity is strongly related to radiation and temperature variation. Based on this scheme, GPP was calculated for 13 different periods, whose lengths depended on the mean daily soil temperature in 10 cm depth. During transition periods in spring and autumn we used a temperature range of 2 °C, and during more constant periods in midsummer and winter 4 °C. For the estimate of uncertainty please refer to the appendix.

3 Results and discussion

3.1 Meteorological site characteristics during the measurement period

As expected, atmospheric parameters, such as global radiation and precipitation, were essentially the same at the two sites. The correlation coefficient (R^2) of the linear regressions of half hourly meteorological values at the sites indicate a correlation of better than 0.97.

However, site-related environmental factors such as soil temperature and water table depth (WTD) were different (Fig. 3c–e). Following Couwenberg's classification (2012), the natural bog Schechenfilz belongs to the class of wet peatlands, where the mean annual water table depth during the two years measurement period is above −0.2 m (−0.06 ± 0.04 m). At the drained bog Mooseurach, the mean annual water table is just below −0.2 m (−0.21 ± 0.08 m), thus making Mooseurach a dry peatland site. The water table was consistently higher at the natural site; in addition, water content was more stable than at the drained bog Mooseurach. Due to its intact drainage system, the water table at Mooseurach reacted more rapidly to low precipitation periods. The water holding capacity of the pristine soil is much larger than that of the drained soil (Fig. 3d and e).

Overall, the first measurement year was slightly cooler and wetter than the second measurement year. Within the two years, five periods of considerable water table drawdown were recorded, more prominently at Mooseurach (Fig. 3e); at the beginning of July 2010, during the warm and sunny spring of 2011, during the warm and relatively dry period in August and September 2011, and in November 2011 when there was no precipitation and it was sunny (50 % more sunshine hours compared to the long-term) but about 1 °C cooler than the long-term average. The period in November led to the strongest water table drawdown at the drained site. Another strong water table drawdown was recorded during the extraordinary cold period in January and February 2012. At this time, the monthly air temperature was about −4 °C lower than the long-term average and we measured half hourly temperature extremes of below −20 °C. Unfortunately, temperatures were below the operation range of the gauges, hence the extent of the detected strong water table drawdown in February 2012 remains uncertain and will not be considered in further discussions.

3.2 Factors affecting CO_2 exchange

The individual component fluxes, R_{eco} and GPP, which form the NEE, depend on different environmental factors that vary throughout the year.

GPP is mainly controlled by photosynthetically active radiation (PAR). As expected, we detected a strong hyperbolic relationship between PAR and GPP (Fig. 4a) at both sites. Light use efficiency as well as maximum carbon uptake (i.e. at infinite PAR) was larger at Mooseurach (drained) than at Schechenfilz (natural), resulting in a two times larger carbon uptake at the drained site. However, after normalizing the GPP with the corresponding LAI (5.9 at the drained site and 2.3 at the natural site) we found very similar light use efficiencies and almost equal GPPs (−387 and −434 $\mathrm{g\,C\,m^{-2}\,a^{-1}}$ at Schechenfilz and −305 and −350 $\mathrm{g\,C\,m^{-2}\,a^{-1}}$ at Mooseurach, respectively) at both sites.

Respiration increases with increasing temperature (Fig. 4b). For the whole temperature range, respiration was greater at Mooseurach than at Schechenfilz. At the reference temperature of 10 °C, the respiration of the drained ecosystem was about two-times larger. Normalization of R_{eco} with LAI result in very similar emission rates (+364 and +403 $\mathrm{g\,C\,m^{-2}\,a^{-1}}$ at Schechenfilz and +283 and +299 $\mathrm{g\,C\,m^{-2}\,a^{-1}}$ at Mooseurach, respectively) between the sites. Nevertheless, respiration processes are very complex and cannot be solely attributed to LAI.

We further investigated any dependence between changes in volumetric water content (VWC) and nighttime respiration (Fig. 5) for Mooseurach. The slope of R_{eco} in Fig. 5a suggests a moderate exponential relationship between R_{eco} and volumetric water content ($R^2 = 0.79$). However, VWC is also linked to air temperature. After normalization of R_{eco} with air temperature using the relations on Fig. 4b, to exclude the influence of air temperature on R_{eco}, the dependence between R_{eco} and water content disappeared (Fig. 5c). The same applies to the Schechenfilz data. Differences in VWC resulted in marked differences in respiration at the two sites, but short-term fluctuations could be explained by the air temperature dependence.

3.3 Annual variation of CO_2 exchange

Annual budgets of NEE, GPP and R_{eco} were calculated for the observation periods from July 2010 to June 2011 and July 2011 to June 2012. Despite similarities in weather conditions and geological origin, the carbon budgets of the drained and the natural peatland were considerably different. The individual budgets of GPP and R_{eco} for the whole annual cycle show that respiration, as well as GPP, was approximately two times larger at Mooseurach (drained) than at Schechenfilz (natural) (Fig. 6).

The NEE indicates stronger CO_2 uptake at the drained site. At both sites the uptake was smaller in the first, slightly wetter and colder, measurement year from July 2010 to June 2011 ($-130 \pm 31\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$ at Mooseurach and $-53 \pm 28\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$ at Schechenfilz, see Appendix for methods to determine uncertainty) than in the second measurement year July 2011 to June 2012 ($-300 \pm 66\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$ at Mooseurach and $-73 \pm 38\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$ at Schechenfilz). Depending on the start of the annual averaging period, the annual NEE is highly variable. This is more pronounced at the drained spruce forest Mooseurach (range between -80 and $-300\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$, Fig. 7a). At the natural site the range of NEE is noticeably smaller; it ranges between -33 and $-73\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$. On average, the observed CO_2 uptake at the drained site ($-157 \pm 36\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$) was three times larger than at the natural site ($-55 \pm 23\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$, Fig. 7b).

The mean annual uptake at the natural bog-pine site Schechenfilz is very similar to annual NEE budgets of other temperate and boreal natural, non-forested bog sites reported in the literature. For example, Lund et al. (2007) determined an NEE of $-21\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$ for a southern Swedish temperate bog site. In a temperate Canadian bog, Lafleur et al. (2003) found an NEE of between +10 and $-76\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$, depending on snow coverage in winter and water availability during the growing season. For an Irish blanket bog, an NEE within a very similar range (-49 and $-61\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$) was reported by Sottocornola and Kiely (2005). This comparison implies that the presence of the bog-pines does not enhance the annual CO_2 uptake compared to non-forested bog sites, with their corresponding larger coverage of grass species.

Studies of the CO_2 exchange of drained and afforested peatland sites are very rare and the annual budgets reported are highly variable. For example, Dunn et al. (2007) found annual NEE to range between +84 and $-58\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$ for ten consecutive measurement years. Hargreaves et al. (2003) estimated a strong CO_2 uptake of between -200 to $-500\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$ for an 8 to 26 yr old forest on formerly ploughed peatland in Scotland. In a more recent study, the annual CO_2 uptake of a Finnish spruce forest growing on moderately drained peat was estimated to be $-237\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$ (Lohila et al., 2011). The site conditions, as well as the strength of CO_2 uptake, are similar to the presented results for the Mooseurach site.

3.4 Seasonal variation of CO_2 exchange

Over the whole two years measurement period, the drained ecosystem at Mooseurach stored $-429 \pm 73\,\mathrm{g\,C\,m^{-2}}$ and the natural ecosystem at Schechenfilz $-126 \pm 45\,\mathrm{g\,C\,m^{-2}}$ (Fig. 8).

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Seasonal and short-term patterns were very similar at the two sites; the differences in the cumulative CO_2 exchange curves are mostly a result of the generally larger component fluxes in Mooseurach.

In spring, both ecosystems were strong CO_2 sinks in both years, in spite of the considerable water table drawdown in March and April 2011. The strong and consistent CO_2 uptake in spring is due to the phase-shift in the annual cycle of soil temperatures which are still low in spring and thus limit soil respiration while high radiation levels lead to moderately high photosynthetic activity (Dunn et al., 2007; Griffis et al., 2003). However, the carbon uptake rate was markedly stronger at the drained site.

The start of the net uptake season at the Schechenfilz site was very similar in spring 2011 and 2012 (mid-March), but due to a four-week data gap, the beginning of the growing season at Mooseurach could not be detected precisely in 2012.

During dry and warm conditions in summer (July 2010 and August to September 2011) we observed reduced CO_2 uptake, which again was more pronounced at the drained site (Fig. 8). At this time soil respiration reaches its maximum because of maximal soil temperature. Additionally, the photoperiod shortens and, in spite of the sunny conditions, vegetation senescence starts leading to lower photosynthetic activity. In this period, the CO_2 exchange at Mooseurach fluctuates considerably between the two years. In 2010 we observed continuous CO_2 uptake until early October, while in 2011 the CO_2 uptake was discontinuous during the warm and dry period between mid-August and mid-October.

Finally, during the unusual sunny and rainfree weather conditions in November 2011 (compare Fig. 3) we observed an extended secondary net uptake period, while the natural bog-pine system stopped carbon uptake in October, similarly to the previous year (Fig. 8). The different NEE response of the two sites can be attributed to differences in tree physiology. The light-dependent photosynthesis of bog-pines is highly sensitive to low temperatures, whereas the photosynthesis of the Norway spruces is more robust in low temperatures (von Sengbusch, 2002). Thus, the extended period of sunshine at Schechenfilz in November 2011 had no notable influence, as the bog-pines had already ceased photosynthetic activity in response to the drop in temperature. In contrast, photosynthesis by the spruces in Mooseurach continued in spite of the relatively low temperatures. Moreover, the combination of a strong water table drawdown (which makes growing conditions more favorable for the spruces), and low soil temperatures (which reduce soil respiration), further enhanced the net carbon uptake at the drained site in late autumn 2011.

A comparison of the pattern of cumulative NEE over the two years of measurements illustrates the different response of the CO_2 exchange of the drained and the natural peatland ecosystem to changing environmental factors. At Schechenfilz, the annual cycles of cumulative NEE was very similar for both years, despite differences in e.g. drought periods between the two years. At this site the CO_2 exchange is more in balance, due to the low growing activity of the bog pines on one side and the suppressed soil emissions, caused by high soil water level, on the other side. In contrast, at Mooseurach the cycle of CO_2 exchange varied considerably between the two years. However, whether warm and dry anomaly periods increase or reduce carbon uptake at the drained site depends on the season.

3.5 Long-term CO_2 exchange

The results of the two years of eddy covariance measurement presented in this study indicate stronger CO_2 uptake of the drained bog forest than of the natural bog forest. However, meaningful comparisons between peatland forests and full evaluation of the climate impact of different land uses requires a longer-term perspective.

To validate the impact of drainage and spruce afforestation on the long term carbon balance at the Mooseurach site, we have to consider the peat loss induced carbon emissions, as well as the carbon fixation within the spruce life-cycle.

Our estimation of the peat loss is based on a historic map from the 1940s which present a peat thickness of 4.4 m. Thus the peat thickness was reduced approximately by one meter down to today's 3.4 m thickness over the last 70 yr, resulting in a loss-rate of about 1.4 cm a^{-1}. The oxidative contribution to the overall subsidence is estimated to be almost 50 % (Armentano and Menges, 1986; Gronlund et al., 2008; Leifeld et al., 2011b), the rest is being accounted to peat compaction and consolidation. Considering a carbon content of 49.7 % (Fig. 2) and the dry bulk density of $0.15\,\mathrm{g\,cm^{-3}}$ (N. Rosskopf, personal communication, 2012) of the first 20 cm top soil layer, we determine a mean annual carbon loss to the atmosphere of about $+550\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$. This value is close to the annual carbon loss estimate of $+500\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$ of a drained mountain bog in the Swiss Alps, already drained 119 yr ago (Rogiers et al., 2008). This estimate of Rogiers et al. based on differences in ash content after combustion of the peat-profile. A similar approach was used by Leifeld et al. (2011a) who estimated mean carbon loss rates ranging from +140 to $+490\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$ for two drained pre-alpine mountain bogs. Kluge et al. (2008) modeled a larger mean annual carbon loss from the peat of about $+700\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$ for a peatland in northeast Germany.

The carbon fixation of the spruces in Mooseurach was determined by biometry and forest growth modeling (one-dimensional inventory model FORSTAND), as an overall carbon uptake of $-86\,\mathrm{t\,C\,ha^{-1}}$ by the spruces in the last 44 yr (Roehling et al., 2013).

In comparison, the estimated carbon loss from peat degradation is approximately $+242\,\mathrm{t\,ha^{-1}}$ within the same period of 44 yr, resulting in a total net emission of $+156\,\mathrm{t\,C\,ha^{-1}}$. These quantities should be considered as rough estimates. Currently, the eddy covariance measurements present an average annual CO_2 uptake of $-157 \pm 36\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$ ($=1.57\,\mathrm{t\,C\,ha^{-1}\,a^{-1}}$). Thus, the forest would need another 100 yr of carbon assimilation on the current rate, to offset the net carbon loss of the last 44 yr. Because the expected life-cycle of the spruces at the Mooseurach site is only 60 yr, we can conclude that the drained bog forest is a strong net overall CO_2 source even if the current eddy-covariance measurements indicate strong CO_2 uptake.

In contrast, at the natural bog site Schechenfilz the peat layer as well as the water level was not affected by human interference in the past, and the soil conditions are still pristine. Therefore, CO_2 budgets of previous periods were likely of a similar magnitude as the currently observed annual CO_2 exchange variations in environmental factors permitting. Furthermore, the forest is no plantation and the age structure of the trees covers a wide range. Hence, it is likely that the carbon exchange of the natural bog forest is close to the long-term balance with small net accumulation rate. However, due to the high water level at natural bog sites we have to expect methane emissions which would reduce the carbon uptake budget and due to their larger global warming potential considerably reduce the climate mitigation effect.

According to the literature review of Saarino et al. (2007) the methane budget of boreal ombrotrophic mires ranges between +1 and $+16\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$. For example Roulet et al. (1992) determined a budget between +4.3 and $+15.45\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$ measured in a wooded bog (*Picea marina*) between April and November. At the bog-pine site Schechenfilz the groundwater level is never above the surface, which would enhance methane production. Moreover, the coverage of sedges, which are known to serve as conduits for the methane fluxes from the soil, is low in comparison to non-forested bog-sites. Therefore, we expect only small emission rates which will not totally outweigh the climate mitigation potential of the carbon uptake. Thus the natural bog-pine site was a small but consistent net carbon sink during the observation period.

4 Summary and conclusions

Eddy covariance measurements of NEE over two complete annual cycles (July 2010-June 2012) indicate a stronger uptake of CO_2 at a drained spruce forest ecosystem at Mooseurach compared to a natural bog–pine site at Schechenfilz (-130 ± 31 and $-300 \pm 66\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$ in Mooseurach and -53 ± 28 and $-73 \pm 38\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$ in Schechenfilz, respectively). Due to the small distance of 10 km between the sites, differences in the CO_2 exchange can be attributed solely to site-specific factors, such as land use history, soil conditions and vegetation composition, rather than to different atmospheric conditions.

At Mooseurach, the budgets of both component fluxes, GPP and R_{eco}, are about twice as large as in Schechenfilz. The stronger CO_2 uptake at the drained site can be attributed to the larger LAI. Furthermore, the response of the CO_2 flux at the drained spruce forest is much more sensitive to environmental forcing and therefore any variability of the driving factors has a greater impact on the NEE. Whether water table drawdown promotes or reduces net carbon uptake depends on the state of phenology of the spruces and the level of soil respiration, which is strongly related to soil temperature and thus to the season.

Estimates of carbon loss due to drainage and peat degradation resulted in an annual carbon loss of +550 $\mathrm{g\,C\,m^{-2}\,a^{-1}}$. Comparing carbon fixation by the spruces, and carbon loss from the peat since forest planting, 44 yr ago, we roughly determined a total carbon loss of +156 $\mathrm{t\,C\,ha^{-1}}$. The presented eddy covariance measurements can just represent the current state of forest and soil conditions, but CO_2 exchange studies of managed peat forest ecosystems need to consider the different stages of ecosystem development. Consequently, the spruce forest in Mooseurach would need to grow further 100 yr at the present rate to compensate the carbon loss of peat degradation in former years.

In contrast, the natural bog forest in Schechenfilz is a robust and consistently small CO_2 sink. We thus have to conclude that the natural bog-pine forest is a more effective CO_2 sink in the long-term in spite lower uptake rate during the observation period.

This study serves to underline the potential climate benefits provided by peatland restoration. Overall, 13 % of peatlands in Germany are currently drained for forestry. If the present results turn out to be representative of other drained peatlands in Germany, our results indicate that forested peatland restoration may be an important long-term climate change mitigation measure.

Appendix A

Uncertainty of the annual sums

We distinguish between random (ϵ) and systematic errors or bias (δ). The systematic errors need to be further differentiated into full systematic bias and selective bias

(Moncrieff et al., 1996). Selective bias affects solely carbon uptake or carbon release and increases when the measurement period is extended. Causes of systematic errors include underestimation of nighttime respiration, high frequency loss, variations of footprint size and orientation (Massman and Lee, 2002; Richardson et al., 2012; Schmid and Lloyd, 1999). Generally, systematic errors cannot be identified by statistical analysis, but known systematic errors are often minimized by correction terms such as the u_* criterion to eliminate non-turbulent fluxes, corrections of spectral loss (Moncrieff et al., 2004; Moncrieff et al., 1997) or the rejection of data not presenting the target area. However, we are not able to prevent all systematic errors, particularly those whose origin or behavior are not known sufficiently. Concerning the site comparison we can assume that the impact of systematic errors is relatively small, as flux calculation, post-processing (rejection criteria) and gap-filling were conducted in the same way (with the exception of the footprint analysis at the natural site). Thus, any bias due to data processing is expected to be very similar at both sites.

Random errors cannot be corrected for, but identified by statistical analysis and they often decrease with extended datasets. We estimated the gap-filling uncertainty using 10 000 bootstrap samples for R_{eco} and GPP estimation, resulting in a gap-filling uncertainty of ±30.7 $\text{g C m}^{-2}\,\text{a}^{-1}$ in the first measurement year and ±65.9 $\text{g C m}^{-2}\,\text{a}^{-1}$ in the second year in Mooseurach. The gap-filling uncertainty based on Schechenfilz data is ±27.8 $\text{g C m}^{-2}\,\text{a}^{-1}$ and ±38.1 $\text{g C m}^{-2}\,\text{a}^{-1}$.

Random errors of measured fluxes are caused by footprint variability, errors of turbulence sampling and instrument errors (Richardson et al., 2012). The errors of turbulent sampling can be determined by the variance of the covariance, including auto- and cross-covariance terms, following Finkelstein and Sims (2001). This error estimation is implemented in some eddy covariance flux processing software packages e.g. EddyPro (EddyPro, last access: 23 November 2013) and TK3 (Mauder et al., 2013).

The mean error of turbulence sampling as derived by EddyPro is ±2.6 $\text{g C m}^{-2}\,\text{a}^{-1}$ in the first, and ±3.1 $\text{g C m}^{-2}\,\text{a}^{-1}$ in the second year in Mooseurach, and ±1.5 $\text{g C m}^{-2}\,\text{a}^{-1}$ and ±2.5 $\text{g C m}^{-2}\,\text{a}^{-1}$ in Schechenfilz. The uncertainty due to footprint variation and instrument errors could not be estimated accurately in the present project, but based on comparative estimates in the literature (e.g. Dragoni et al., 2007) we expect them to be small in comparison to the gap-filling error.

The random error of measured and gap-filled fluxes were combined by quadrative error propagation (e.g. Richardson et al., 2012; Richardson and Hollinger, 2007), resulting in a negligible contribution of the error induced by turbulent sampling. Thus random uncertainty of the cumulative NEE in Mooseurach was determined as ±30.7 $\mathrm{g\,C\,m^{-2}\,a^{-1}}$ in the first and ±65.6 $\mathrm{g\,C\,m^{-2}\,a^{-1}}$ in the second year, and amounted to 40 % and 22 % of the total annual NEE. At Schechenfilz, the random uncertainty of annual NEE is ±27.8 $\mathrm{g\,C\,m^{-2}\,a^{-1}}$ and ±38.1 $\mathrm{g\,C\,m^{-2}\,a^{-1}}$, and or 47 % and 52 % of the total budgets.

Even if an overall uncertainty of about 50 % were assumed at both sites, the annual $\mathrm{CO_2}$ uptake is invariably stronger at the drained site.

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Table 1. Long-term averages of meteorological parameters (sum of precipitation, mean of air temperature, mean relative humidity and the sum of sunshine duration), provided by the nearby (distance of 8.5 km and 10.5 km to Schechenfilz and Mooseurach, respectively) weather-station Attenkam, run by the German Weather Service (DWD).

Period	Precipitation $\mathrm{mm\,a^{-1}}$	Air temperature °C	rH %	Sunshine hours h
1971–2011	1127	8.6	77.9	1817
2011	1092	9.6	78.4	2114

Table 2. Reasons for data loss and their percentage for both sites.

Data loss due to:	Schechenfilz natural Percentage (%)	Mooseurach drained Percentage (%)
Maintenance, power failure, sensor failure	28	9
Footprint outside target area	–	21
Insufficient turbulence	30	30
Declared as outliers	2	1
Remaining data	40	39

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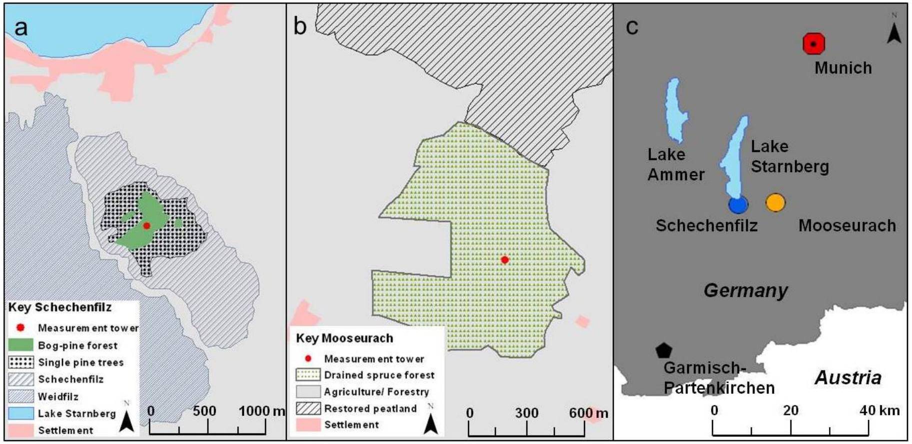

Fig. 1. (a) Schematic map of Schechenfilz site (grey line-filled area), **(b)** Schematic map of Mooseurach site (area with green triangles) and **(c)** location of the research sites in southern Bavaria, Germany. All maps are in a different scale.

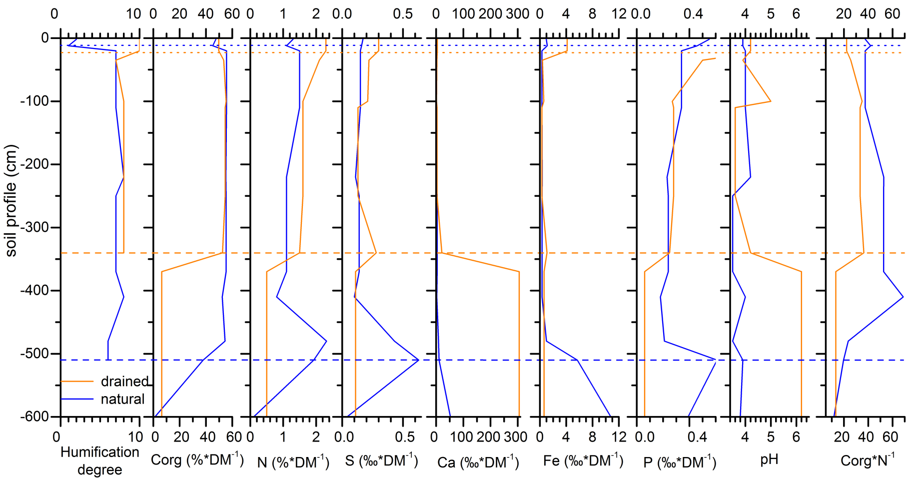

Fig. 2. Soil characteristics and element concentrations of the different peat layer at the natural and the drained site (Corg: organic carbon, N: nitrogen, S: sulfur, Ca: calcium, Fe: iron, P: phosphor, DM = dry matter). Dotted line indicate threshold between frequently water saturated layer and permanent water saturated layer. Dashed line indicate threshold between peat and mineral soil layer. Data are provided by the analysis of one soil profile each site.

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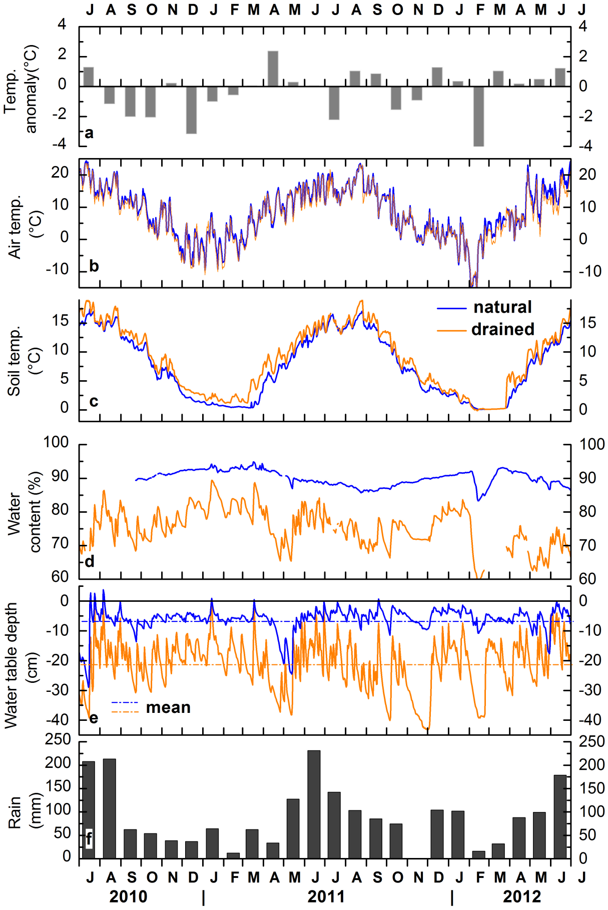

Fig. 3. Time series of daily means **(b–e)** and monthly values (**a** and **f**) of environmental parameters from 01 July 2010 to 30.06.2012. The temperature anomaly is based on 40 yr of long-term data, provided by German weather service (DWD).

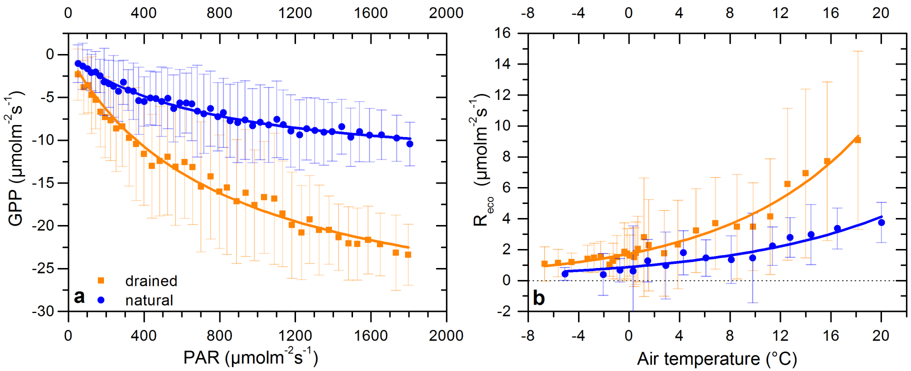

Fig. 4. (a) Gross primary production (GPP: daytime fluxes $-R_{\mathrm{eco}}$) vs. photosynthetic active radiation (PAR); **(b)** Ecosystem respiration (R_{eco}, nighttime fluxes) vs. air temperature. Each point is the average of 100 non-gap-filled half-hourly measurements. The bars denote the standard deviations. Plots show binned data from 2011.

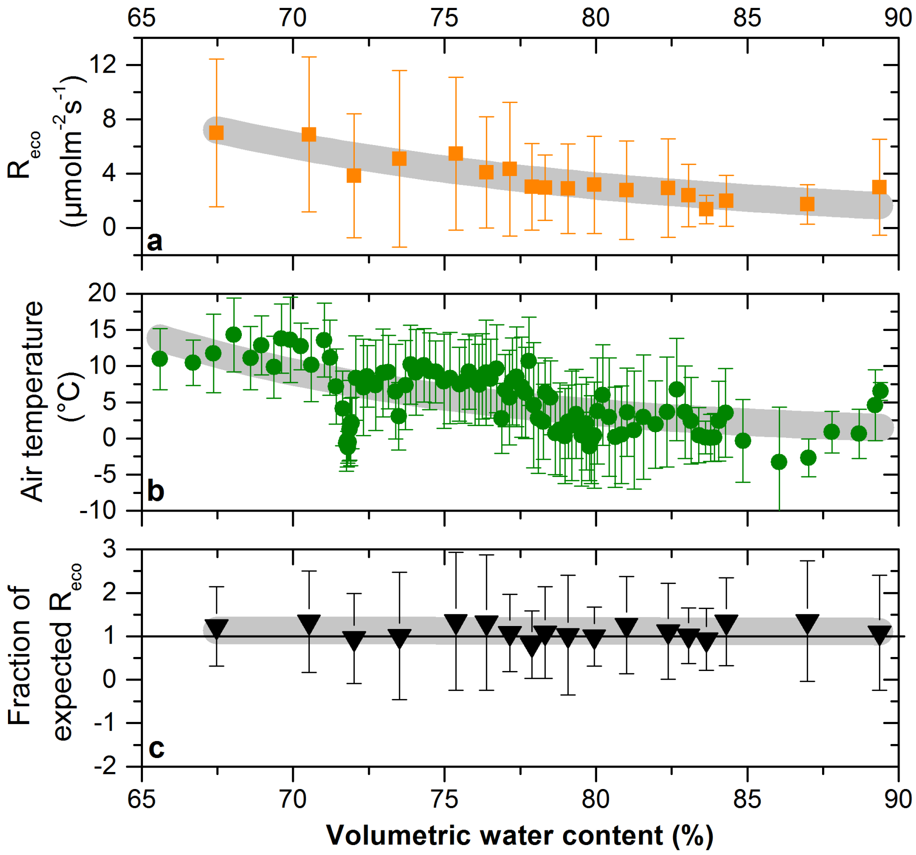

Fig. 5. Relationship between VWC and R_{eco} (non-gap-filled), air temperature and the fraction of expected R_{eco}. Each point is the average of 100 non-gap-filled half-hourly measurements. The bars denote the standard deviations. The grey line represents an exponential dependence. Plots show binned data from 2011 at Mooseurach.

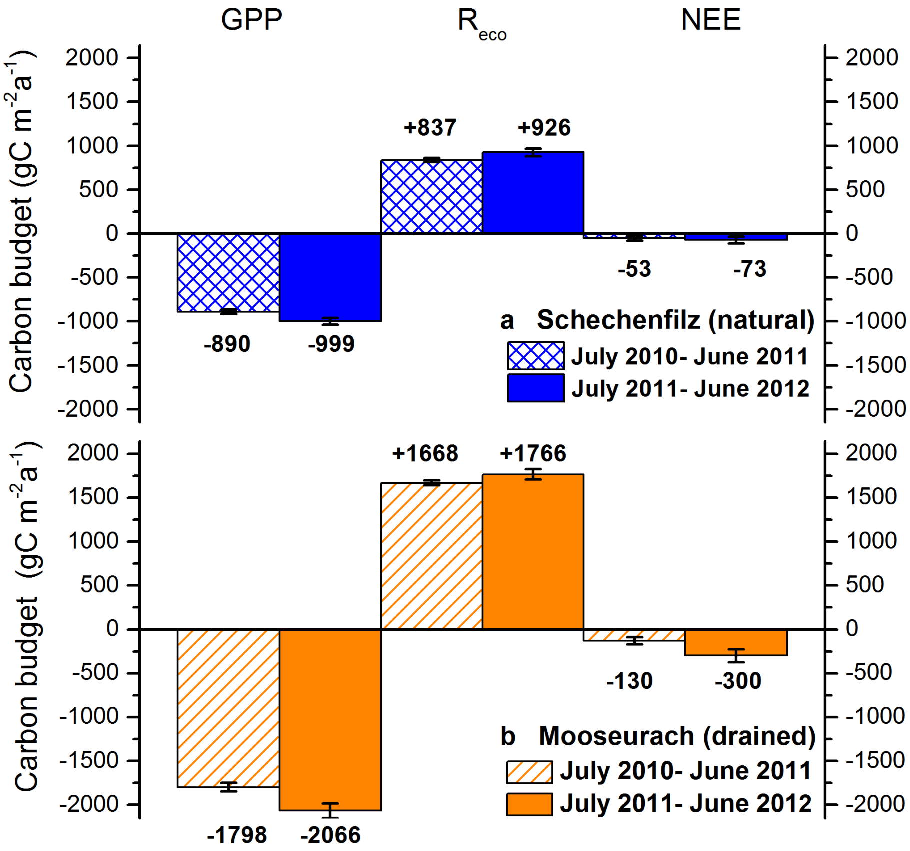

Fig. 6. Annual sums of NEE, R_{eco} and GPP at **(a)** Schechenfilz and **(b)** Mooseurach for the two measurement years. Error bars indicate the variance of the budgets (see Appendix).

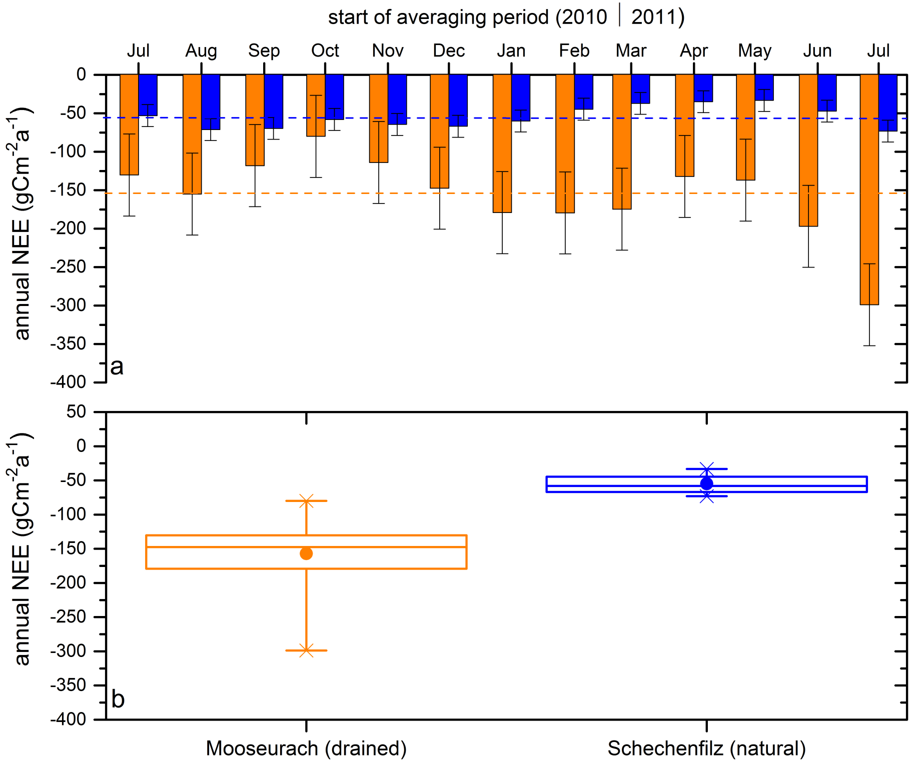

Fig. 7. (a) annual NEE depending on start of averaging period, dashed line illustrate the mean of 13 different averaging periods, the error bars present the standard deviation **(b)** box plot illustrate the range (–) of detected annual sums of NEE, their mean (•). The box indicates the 25th, 75th and 50th percentile.

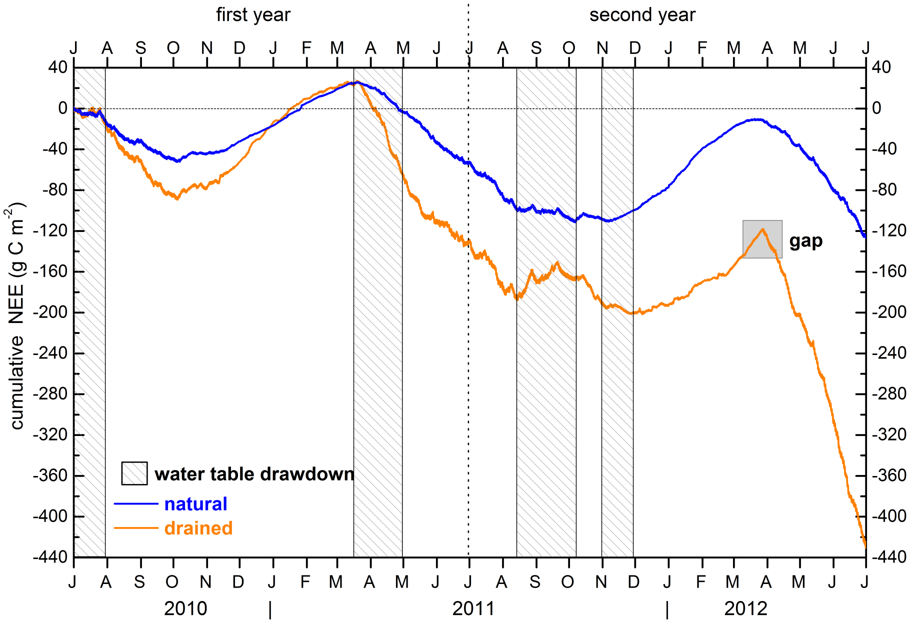

Fig. 8. Cumulative NEE at both sites over the whole measurement period (01 July 2010 to 30 June 2012). The grey shaded box marks a long data gap at Mooseurach due to power failure. The dotted vertical line shows the end of the first annual cycle. The horizontal dashed line highlights the zero line; negative slope of NEE represent carbon uptake and positive values carbon release. Uncertainty intervals are not shown for clarity.