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TELLUS

Annual CO_2 balance of a temperate bog

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ABSTRACT

Peatlands are generally small sinks for atmospheric CO_2. However, the sustainability of this sink functioning is threatened in a changing climate. We measured the CO_2 exchange in a temperate bog between August 2005 and July 2006 using the eddy covariance technique. During this period, the CO_2 balance was –78.6 ± 20.0 g CO_2 m^{-2} yr^{-1}, which is a lower uptake than others have reported for comparable ecosystems, but in accordance with average Holocene uptake rates. Average winter emissions were small (11 μg CO_2 m^{-2} s^{-1}), but the accumulated non-growing season fluxes (121 g CO_2 m^{-2}) represent a larger flux than the annual balance. Taking into consideration that wintertime temperatures in the northern hemisphere are expected to increase in the future, wintertime fluxes may become increasingly important. The highest instantaneous monthly average uptake occurred in June (–38 μg CO_2 m^{-2} s^{-1}), while the drier month of July showed a distinctly smaller sink (–22 μg CO_2 m^{-2} s^{-1}). It is suggested that soil drying caused gross primary production to decline, while nighttime respiration showed a steadily increase. Our findings indicate that the effect of future warmer temperatures on the growing season CO_2 exchange in peatlands is dependent on soil wetness.

1. Introduction

During the last millennia, northern peatlands have acted as a small carbon (C) sink. Estimates of the average annual C uptake are generally in the range of 20–35 g C m^{-2} yr^{-1}, where higher uptake rates are reported for bogs than for fens (Gorham, 1991; Tolonen and Turunen, 1996; Turunen et al., 2002). This small C sink has during the course of thousands of years resulted in an enormous C pool in peatland soils, amounting to almost one-third of the world total soil C pool (Post et al., 1982; Gorham, 1991), or one-half of the atmospheric C pool.

The peatland C balance is the result of the delicate balance between plant uptake of the atmospheric greenhouse gas carbon dioxide (CO_2) through gross primary production (GPP), and release through plant respiration and decomposition. Under anaerobic conditions this leads to production of the potent greenhouse gas methane. In some peatlands, C leaching in the form of dissolved organic C can be important in the annual budget (Fraser et al., 2001). The reason for the sustained peatland sink strength is not high GPP rates, but rather limited decomposition rates due to the prevailing cool, anaerobic and often nutrient-poor conditions that are typical for northern peatlands (Clymo, 1984).

Warmer temperatures, changed hydrological patterns, increased atmospheric CO_2 levels and increased nitrogen (N) deposition are all potential challenges for the future C sink functioning in undrained peatlands. Northern areas will experience increased temperatures, while changes in precipitation patterns are not as straightforward (Cubasch et al., 2001). In general, decomposition rates have higher temperature sensitivity than photosynthetic uptake rates (Gorham, 1991), thus implying a future decreased sink strength. Drying can have severe impacts on a peatland carbon balance; Alm et al. (1999) found that a boreal bog acted as a net C source for a year with an exceptionally dry summer. Decreased C sequestration in peatlands as a result of reduced soil wetness has also been observed using models (Belyea and Malmer, 2004; Tarnocai, 2006). An increased availability of nutrients, mainly N, may alter the carbon balance of peatlands. In nutrient-poor peatlands (bogs) the important peat-forming *Sphagnum* mosses suffer from competitive disadvantages if the N deposition gets too high (Aerts et al., 1992; Lamers et al., 2000; Berendse et al., 2001; Malmer and Wallén, 2005). An increased vascular plant cover may result in reduced net C sequestration due to the higher decomposability of vascular plant litter (Berendse et al., 2001).

During the last decades, the eddy covariance (EC) technique (Aubinet et al., 2000) has become the predominant means of measuring CO_2 exchange at the ecosystem level. Currently, hundreds of EC measurement sites over the world have been established (Baldocchi, 2003). However, some ecosystem types are still underrepresented. Most peatland EC sites are in the boreal, subarctic and arctic climate zones (Valentini et al., 2000; Nordstroem et al., 2001; Arneth et al., 2002; Aurela et al., 2002,

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2004; Friborg et al., 2003). Full year EC CO_2 measurements in undrained, temperate peatlands are, to our current knowledge, only represented by a raised bog in Canada (Lafleur et al., 2001, 2003) and an Atlantic blanket bog in Ireland (Sottocornola and Kiely, 2005).

The aim of this study is to quantify the CO_2 exchange of a temperate bog and to analyse its sensitivity to changes in environmental conditions.

2. Methods and material

2.1. Site description

This study was conducted in *Fäjemyr*, located in southern Sweden (lat 56°15′N, long 13°33′E, see Fig. 1) in the temperate climate zone (Kottek et al., 2006). The peatland can be classified as an eccentric bog (Lonnstad and Löfroth, 1994) with a low density tree cover. Long-term mean annual temperature and rainfall (1961–1990) are 6.2 °C (min January: –2.4 °C, max July: 15.1 °C) and 700 mm, respectively (data from a nearby weather station; Swedish Meteorological and Hydrological Institute, SMHI). Long-term and study period meteorology are shown in Fig. 2.

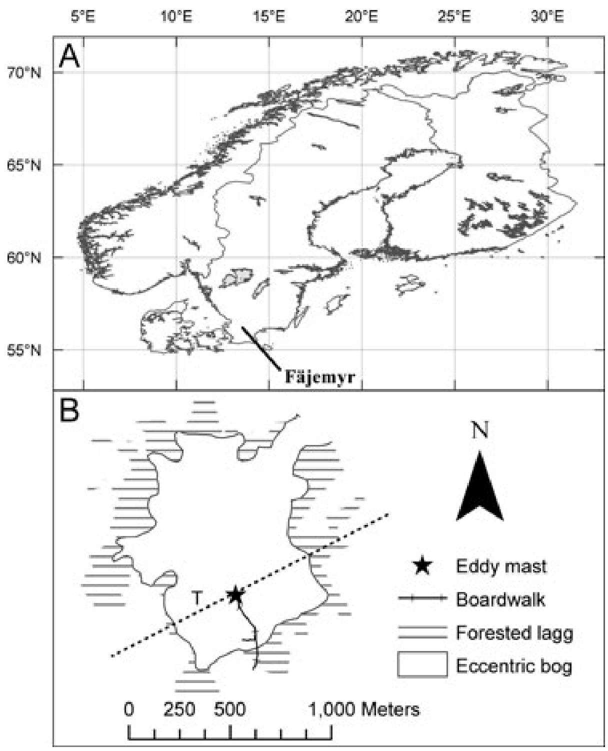

Fig. 1. Map of Scandinavia (A) indicating the geographical position of Fäjemyr in southern Sweden (lat 56°15′N, long 13°33′E). The lower map (B) depicts the southern part of Fäjemyr where this study is conducted. The transect (T) used in the SCADIS model footprint analysis is indicated by the dotted line (see Section 2.4).

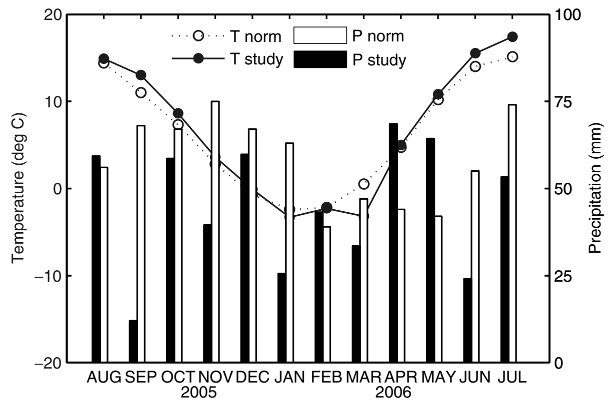

Fig. 2. Long-term (1961–1990) air temperature (T norm) and precipitation (P norm), study period air temperature (T study) and precipitation (P study). Meteorology data is from a nearby weather station (SMHI, Swedish Meteorological and Hydrological Institute). Study period precipitation in July (2006) is the total for the whole month.

Fäjemyr is considered to be in a natural state, in the sense that no large-scale anthropogenic activities such as drainage or peat harvesting, have had any significant effect upon the ecosystem functioning (Lonnstad and Löfroth, 1994). However, one exception can be made: the nitrogen (N) deposition (wet and dry deposition of $NH_x + NO_x$) in southwestern Sweden is estimated to 15–20 kg N ha^{-1} yr^{-1} (Persson et al., 2004), originating from upwind industrial activities. The N deposition on Fäjemyr was estimated to be 17.3 kg N ha^{-1} yr^{-1} from rainwater collected on the mire during the autumn 2005. The depth of accumulated peat is 4–5 m, and the age of the deepest peat layers is 6500 ± 50 yr. Surface water pH is generally below 4 throughout the season.

Fäjemyr consists mainly of a mosaic of hummocks, lawns and carpets; with a lower occurrence of hollows. Dominating plant species on the hummocks are dwarf shrubs (*Calluna vulgaris* L. Hull and *Erica tetralix* L.), and on the lawns and carpets *Sphagnum*-mosses (mainly *S. magellanicum* Brid. and *S. rubellum* Wils.). Sedges, mainly *Eriophorum vaginatum* L., are also common. Drier patches of the bog are forested by dwarf pines (*Pinus sylvestris* L.).

2.2. Instruments

The net ecosystem exchange (NEE) of CO_2 between surface and atmosphere on Fäjemyr was measured between 27 July 2005 and 26 July 2006 using the EC technique (Aubinet et al., 2000). The EC system consisted of a closed-path infrared gas analyser (IRGA, Li-Cor 6262, Li-Cor Inc, USA), and a three-dimensional sonic anemometer (Gill R3, Gill Instruments, UK) mounted 3.4 m above ground on a mast. Heating wires on the anemometer prevented frost, ice and snow to form on the sonic transducers. Air was sucked at a rate of ca. 10 l min^{-1} from approximately 20 cm below the anemometer volume through a 4.9 m high density polyethylene tube ($ø_{inner}$ = 4 mm), equipped with a 1 μm pore size filter (ACRO 50 PTFE), through the IRGA. The tube inlet had a metal cap above it to minimize water entering the tube. The pump was placed after the IRGA, which decreases the problem of condensation within the tube or sample cell due to the underpressurization. The IRGA was operated in absolute mode using pure N_2 as reference gas. Approximately bimonthly, the IRGA was flushed with a zero gas (pure N_2) and a span gas (352 ppm CO_2) in order to determine offset and sensitivity of the IRGA. The measured concentrations and fluxes were then adjusted accordingly assuming that all changes were linear between calibration points in time. The EC mast is situated in the southern part of Fäjemyr (Fig. 1). In all directions surrounding the mast, there are at least 290 m with homogenous surface properties, until the mire margin is reached.

Additional meteorological and soil physical measurements included a ventilated air temperature and humidity sensor (MP101a, Rotronic, USA); soil temperature Cu–Co thermocouples at different depths and sites (5, 20 and 50 cm in a lawn/carpet, 5 cm in a hollow and 5 cm in a hummock); photosynthetic photon flux density (PPFD) sensor (JYP 1000, SDEC, France); two soil heat flux sensors (HFP01, Hukseflux Thermal Sensors, The Netherlands); net radiation sensor (Q*6, REBS Inc, USA); rain gauge (ARG100, Skye Instruments, UK) and water table sensor (SKPS 1830, Skye Instruments, UK). All instruments were connected to MiniCube VC and ModuLog 2027 data loggers (EMS, Czech Republic); and data was recorded every 10 min and averaged every 30 min.

2.3. Data handling

Raw data from the EC system was collected at a frequency of 20 Hz, and processed in the computer software Ecoflux (In-Situ Flux Systems, 2005). Time lag between anemometer and IRGA signals was calculated using covariance optimization. Frequency response errors were accounted for using a correction factor based on transfer functions for tube attenuation and slow sensor response (Grelle, 1997). Air density fluctuations due to humidity variations were accounted for using a dilution correction (Grelle and Lindroth, 1996). No temperature correction was applied since the tube length was more than 1000 times the inner diameter (Rannik et al., 1997). Data was averaged every 30 min using a digital recursive filter with a time constant of 2000 s, which is suggested for measurements at higher European latitudes (InSitu Flux Systems, 2005). Anemometer tilt angles (below 1° in x and y directions throughout measurement year) were measured using inclinometers and corrected for. Mean pitch of the wind field was successively determined for each wind direction (in 1° wind sectors), and the coordinate system was aligned with that mean inclination. In this way, a long-term average of the slope in all wind directions was built up, which reflects local topography (InSitu Flux Systems, 2005). The storage term was calculated from the single-point IRGA CO_2 concentration measurements and added to the flux. The latent heat flux was calibrated using water vapour concentration derived from air temperature and relative humidity.

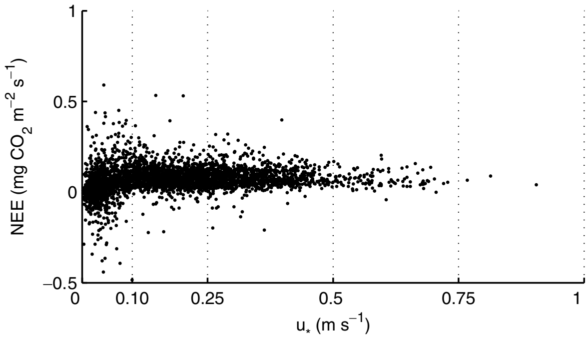

Fig. 3. Scatter plot of growing season nighttime CO_2 flux versus friction velocity (u_*).

In order to overcome the nighttime stability problem associated with EC measurements (Aubinet et al., 2003; Baldocchi, 2003), the effect of low friction velocity (u_*) on nighttime NEE was examined. We found a positive relationship (and increased scatter) below $u_* = 0.1$ m s^{-1} during the growing season (Fig. 3). Therefore, CO_2 fluxes during the whole year when $u_* < 0.1$ m s^{-1} was discarded (14% of the data set).

Gaps in data (in total 29%), originating from u_*-screening, power failure, computer crash, pressure problems, etc., were filled using different gap filling approaches. Gaps smaller than or equal to two hours were filled with linear interpolation. For the growing season (average daily temperature >5 °C for more than 3 d), daytime (PPFD ≥ 10 μmol m^{-2} s^{-1}) gaps were filled using a non-linear exponential regression [commonly referred to as the *Misterlich* function, described in Falge et al. (2001)] parametrized for biweekly periods with PPFD as independent variable;

$$\mathrm{NEE} = -(F_{\mathrm{csat}} + R_{\mathrm{d}})\left(1 - e^{\frac{-\alpha(\mathrm{PPFD})}{F_{\mathrm{sat}}+R_{\mathrm{d}}}}\right) + R_{\mathrm{d}}, \quad (1)$$

where F_{csat} is the CO_2 uptake at light saturation; α is the initial slope of the light response curve and R_d is the dark respiration rate. The remaining gaps were filled using mean diurnal variation (MDV) with a 10 d gliding window (Falge et al., 2001).

2.4. Quality and error assessment

Energy balance closure as a means of evaluating the EC data quality (Aubinet et al., 2000, 2003) was calculated as the sum of sensible and latent heat flux ($H + \lambda E$) compared to available energy; net radiation (R_n) minus soil heat flux (G). Furthermore, the error analysis procedure for EC measurements and data handling suggested by Aurela et al. (2002) was used.

Flux footprints were estimated using the atmospheric boundary layer model SCADIS (Sogachev et al., 2002, 2005). In this model, transects with different surface and vegetation properties can be analysed. We used the transect (T) shown in Fig. 1 to investigate if the flux footprint was affected by the surrounding forest. Since SCADIS currently is limited to neutral atmospheric conditions, the simple parametrization by Kljun et al. (2004) was used to extrapolate SCADIS results to other stability conditions. Intermediate mixing (defined as the standard deviation of vertical wind velocity $\sigma_w = 0.15$ m s^{-1}) and well-developed mixing ($\sigma_w = 0.60$ m s^{-1}) periods were analysed separately. The flux footprint during strongly stable conditions was not investigated since those situations were discarded in the u_*-screening.

3. Results and discussion

3.1. Quality and error assessment

The daily average energy balance at Fäjemyr during the growing season 2006 (net radiation and ground heat flux sensors were installed in spring 2006) for days without any gaps is shown in Fig. 4. The sum of turbulent fluxes is 102% of the available energy, near a complete energy balance closure. The closure reported here are within the upper range of closures reported for FLUXNET sites (Wilson et al., 2002), where the mean closure was around 80%.

The error analysis following the procedure suggested by Aurela et al. (2002) resulted in an uncertainty of the measurements and gap filling of ±20.0 g CO_2 m^{-2} on annual basis. The separate components in the error analysis, with corresponding error relative to annual balance in parentheses, were random error (8.3%), long data gap filling (1.5%), high-frequency loss (4.5%) and u_* threshold (23.4%). The highest uncertainty is associated with u_* threshold, below which CO_2 fluxes are discarded, and are modelled instead. This is shown in Fig. 5 where different u_* thresholds with corresponding annual CO_2 balances are plotted. If no u_* threshold is used, the CO_2 sink in Fäjemyr would be more than twice as strong. This is a clear indication of the under

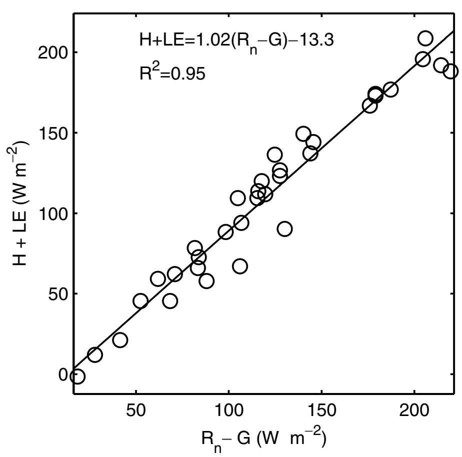

Fig. 4. Energy balance closure at Fäjemyr, using daily average growing season (2006) turbulent fluxes ($H + \lambda E$) and available energy ($R_n - G$).

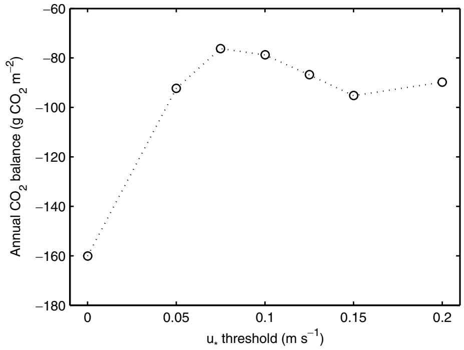

Fig. 5. The effect of different u_* thresholds on the annual CO_2 budget.

representation of night-time fluxes during stable conditions that has been identified as a main error source in EC measurements by many authors (e.g. Aubinet et al., 2003; Baldocchi, 2003; Gu et al., 2005). The threshold used in this study ($u_* = 0.1$) results in a CO_2 sink that is somewhat weaker compared to other thresholds in the range between 0.05 and 0.15.

According to the SCADIS model (Sogachev et al., 2002, 2005), more than 95% of the fluxes arise from the bog surface during neutral atmospheric conditions. Using a $u_* = 0.1$ m s^{-1} threshold eliminated 98.5% of the strongly stable atmospheric conditions (defined as Monin–Obukhov stability parameter $z/L > 0.1$), while 17.9% of the data set still had weakly stable conditions ($0.01 < z/L < 0.1$). The footprint during weakly stable situations was investigated in the simple parametrization by Kljun et al. (2004) using the lower input value of σ_w. The results confirm that the fetch for the EC measurements was adequate in different atmospheric conditions in terms of fluxes emanating from the bog (90% of fluxes within 216 m and 124 m for σ_w = 0.15 and 0.60 m s^{-1}, respectively). Since the minimum homogeneous fetch in Fäjemyr is 290 m, the whole data set is considered reliable in terms of flux footprint.

In peatlands, simple empirical relationships between half hourly nighttime NEE and environmental variables are generally noisy (Lloyd, 2006). Nighttime NEE fluxes integrate a lot of complex biological activity, for example, plant, root and microbial respiration (Trumbore, 2006). Heterotrophic respiration rates partly depend on substrate quality, which in peatlands range from easily decomposable substrates derived from fresh litter in the uppermost soil layer to old, recalcitrant material deeper down (Christensen et al., 1999). Lloyd (2006) argues that much of the scatter seen in the regressions is because of low tortuosity factors (low air-filled porosity) in wetland soils, which cause CO_2 diffusion rates to be slow. Therefore, the CO_2 exchange detected by the EC system may not correspond to the soil temperature measured at the same time. Consequently, the regressions should be less noisy during windy periods when atmospheric turbulence is well developed, which would facilitate CO_2 diffusion to the atmosphere. We divided the growing season half hourly nighttime data set into two separate turbulence classes, and compared the correlations between nighttime NEE and soil temperature. For well developed mixing ($u_* > 0.3$), the explained variance is clearly higher than for intermediate mixing ($0.1 < u_* < 0.3$); the coefficient of determination (R^2) is 45% compared to 25% (F-test: $p < 0.01$ for both regressions). Soil temperature based Q_{10} is also higher for well-mixed conditions (3.62) than intermediate conditions (2.77). We believe these relationships to be caused by CO_2 build-up in the porous top soil layers and in cavities in the *Sphagnum* moss layer during stable conditions. Increased wind speed then initially acts to release the accumulated CO_2 by pressure pumping; and when the accumulated CO_2 pool is exhausted the coupling between soil temperature and CO_2 flux measurements are tightened due to the increased atmospheric mixing. This is can be compared to CO_2 being stored in snow and released under turbulent conditions, which has been observed in other studies (Black et al., 2000; Aurela et al., 2002). However, uncertainties associated with the storage term in the flux calculations may add some bias to these results. The storage term is derived from the single-point IRGA CO_2 concentration measurement, and is more significant during intermediate conditions (21% of the flux) as compared to well-mixed conditions (3%). A more detailed CO_2 concentration profile below the EC measurement height is needed to fully address these issues.

3.2. Annual CO_2 balance

The annual CO_2 balance of the temperate, eccentric bog Fäjemyr is –78.6 ± 20.0 g CO_2 m^{-2} yr^{-1} (equals –21.5 ± 5.4 g C m^{-2} yr^{-1}); meaning that the mire acted as a small net sink during the study period. The obtained fluxes from the EC system between 27 July 2005 and 26 July 2006 are shown in Fig. 6. The sink strength is in accordance with average Holocene uptake rates of 20–35 g C m^{-2} yr^{-1} (Gorham, 1991; Tolonen and Turunen, 1996; Turunen et al., 2002), but generally weaker than others have reported for comparable ecosystems. The annual CO_2 flux in an Irish blanket bog was –180 and –224 g CO_2 m^{-2} s^{-1} in 2003 and 2004, respectively (Sottocornola and Kiely, 2005), while the annual flux in a Canadian raised bog was –278, –253, –249 and –37 g CO_2 m^{-2} s^{-1} between 1 June 1998 and 31 May 2002 (Lafleur et al., 2003). In this study, fluxes of methane and dissolved organic C are not included in the C budget, which would further act to decrease the C sink strength.

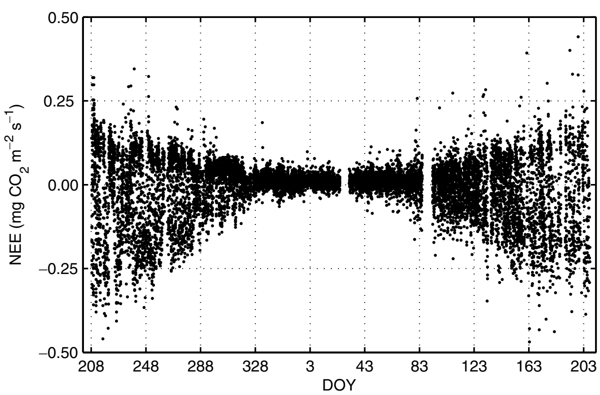

Fig. 6. Half hourly net ecosystem exchange (NEE) measurements from the EC system on Fäjemyr. Negative values imply an uptake of CO_2 by the ecosystem.

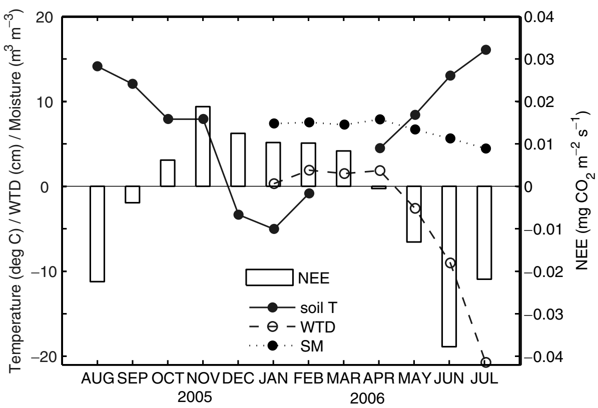

Fig. 7. Average monthly NEE, soil temperature at 5 cm (soil T), WTD and average soil moisture (SM). WTD and soil moisture only measured during 2006. Data for July is the average from July 2006.

A recent report (SMHI, 2006) show that the annual average temperature in Sweden has increased over the last decade and the 1991–2005 temperature average was 0.9 °C warmer than the 1961–1990 average. Accordingly, the study period meteorological conditions were slightly warmer (+0.5 °C) and in addition drier (–155 mm) than the 1961 to 1990 average (Fig. 2). This heat surplus was not equally distributed over the study period. March 2006 was 3.7 °C colder, which can have acted to delay the growing season onset. June and July 2006 was 1.5 and 2.3 °C warmer, respectively. The summer of 2006 was also very dry. In June, less than half of the expected precipitation fell, and in July only 14 mm of rain came before 26 July 2006.

Figure 7 shows the average monthly NEE along with soil temperature at 5 cm, water table depth (WTD) and average soil moisture. In August and September 2005, and April through to July 2006 Fäjemyr acts consistently as a net sink for atmospheric CO_2 on a monthly basis. The highest average uptake occur in June (–38 μg CO_2 m^{-2} s^{-1}), while the drier month of July shows a distinctly smaller sink (–22 μg CO_2 m^{-2} s^{-1}). The highest emission occur in November (19 μg CO_2 m^{-2} s^{-1}) when daily photosynthetic CO_2 assimilation rates have decreased, while soil temperatures and plant biomass still remain at a high level.

3.3. Growing season fluxes

The data year growing season lasted for 214 d, between 16 April 2006 and 16 November 2005. Daily average nighttime NEE (autotrophic and heterotrophic respiration) regressions with

Table 1. Coefficients of determination (R^2) and Q_{10} for daily averaged growing season (2006) nighttime NEE as a function of independent variables: AirT = air temperature; SoilTx = soil temperature in representative area at x (5, 20, 50) cm depth; SoilTHumm = soil temperature in a hummock 5 cm depth; SoilTHoll = soil temperature in a hollow 5 cm depth; WTD = water table depth and SM˙mean = average soil moisture

Independent variable[a]	R^2	Q_{10}[b]
AirT	0.49	1.81 (1.65, 1.98)
SoilT5	0.61	2.83 (2.47, 3.24)
SoilT20	0.55	2.91 (2.49, 3.39)
SoilT50	0.68	2.71 (2.29, 3.22)
SoilTHumm	0.70	2.32 (2.02, 2.67)
SoilTHoll	0.61	2.54 (2.10, 3.09)
WTD	0.68	
SM˙mean	0.25	

[a]For temperature, an exponential equation (*Van't Hoff*) was used (NEE $= ae^{bT}$), and for WTD and SM_mean a second-order polynomial equation was used.
[b]Q_{10} is calculated from $Q_{10} = e^{10b}$. In parentheses the 95% confidence bounds derived from regression uncertainty.

environmental drivers as independent variables are shown in Table 1. Air and soil temperatures are generally highly correlated with nighttime NEE ($0.49 > R^2 > 0.70$; F-test: $p < 0.01$ for all regressions). Soil temperature Q_{10}:s are in the range between 2.32 and 2.91, somewhat lower than the temperature sensitivity in a Canadian bog (Lafleur et al., 2005), and do not differ significantly from each other (at the 95% confidence level).

Lafleur et al. (2005) reported that temperature was the main driver for ecosystem respiration in a temperate bog, and not WTD. In our data, both average WTD and soil moisture explain much of the variance in nighttime NEE, R^2 is 0.68 and 0.25 (F-test: $p < 0.01$ for both regressions), respectively. However, if nighttime NEE is normalized against soil temperature, the explanatory power of both WTD and soil moisture decreases (R^2 decreases to 0.02 and 0.10 (F-test: $p < 0.01$ for both regressions) for WTD and soil moisture, respectively). The seasonal trend in NEE shows a strong correspondence to the trends in temperature, soil moisture and WTD in our present data set. The separate effects of the environmental drivers on NEE are thus difficult to distinguish. Lloyd (2006) discusses the fact that recent research regarding the soil respiration response to changes in WTD often is contradictory. One conclusion that can be drawn is that these ecosystem processes act in a highly site-specific and often non-linear way, which cannot always be explained using simple linear models.

As mentioned above, the average CO_2 uptake in July is significantly lower than in June (Fig. 7). During this period, air and soil temperatures rose steadily, while the soil became drier. We modelled GPP_{max} (maximum gross primary production at light saturation) for biweekly periods in June and July, by summing

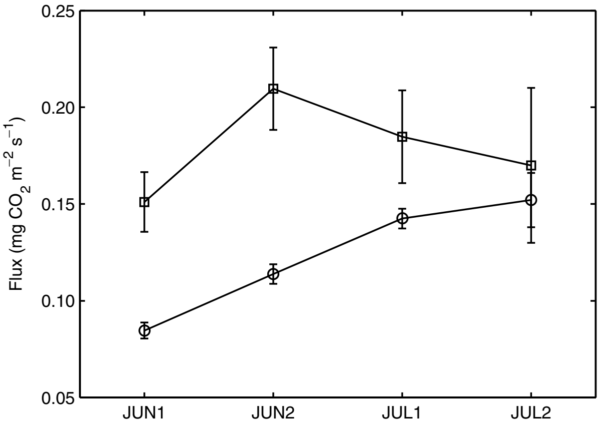

Fig. 8. GPP_{max} (error bars depict sum of 95% confidence intervals for F_{csat} and R_d derived from regression uncertainty) and mean R_{eco} (error bars are standard error of the mean) for biweekly periods during June and July 2006.

the parameters R_d and F_{csat} in eq. (1). Biweekly GPP_{max} for June and July 2006 is plotted in Fig. 8, along with average nighttime NEE during well-developed mixing ($u_* > 0.3$), which serves as a proxy for the ecosystem respiration, R_{eco} (heterotrophic and autotrophic respiration, excluding photorespiration).

R_{eco} follows the increasing trend that also can be seen for air and soil temperature. In contrast, there is a tendency of a peak in GPP_{max} in late June followed by a slight decline in July. During this period, it was observed in field that a large fraction of the *Sphagnum* mosses suffered from desiccation. Consequently, we hypothesize that decreasing WTD and soil moisture caused plant water stress and decreased photosynthetic CO_2 uptake by the ecosystem. We believe that this was mainly due to *Sphagnum* desiccation, while water stress induced vascular plant stomatal closure during full daylight was of less importance.

Several authors have stressed the importance of soil wetness for the future C sequestration in peatlands (Alm et al., 1999; Moore, 2002; Belyea and Malmer, 2004; Tarnocai, 2006). Even if average precipitation increases, droughts might become more abundant due to higher evapotranspiration rates as a result of increased temperatures (Cubasch et al., 2001); this being the case aerobic decomposition may increase. A further complication of soil drying is more frequent fires and burning of peat (Tarnocai, 2006). In this study, there was a clear decrease in NEE during the warm and dry month of July 2006. If summers get drier, the sink strength of Fäjemyr will likely be reduced.

During reconstructions of the C sequestration in a south-Swedish bog Belyea and Malmer (2004) found abrupt changes, which were associated with major transitions in vegetation and dominant *Sphagnum* species. Species distribution in peatlands is known to show a close relationship with temperature, moisture and chemical gradients (Glaser et al., 1990, Weltzin et al., 2003; Malmer and Wallén, 2005). Any disturbance of these parameters will influence vegetation distribution, cause vegetation shift and potentially affect ecosystem functioning. In addition to changes in temperature and wetness; the historical increase of N deposition might already have caused the important peat-forming *Sphagnum*-species in Fäjemyr to suffer from competitive disadvantages, and may thus have reduced the net C sequestration.

3.4. Non-growing season fluxes

The dynamics behind wintertime NEE fluxes in peatlands are poorly understood. A tendency towards higher CO_2 emissions at warmer winter temperatures is often found (Aurela et al., 2004), which is also the case in this study (data not shown). Mean CO_2 flux during December, January and February is 11 μg CO_2 m^{-2} s^{-1}, which is in close correspondence to the mean winter flux of 12 μg CO_2 m^{-2} s^{-1} reported for a Canadian bog (Lafleur et al., 2001).

In the boreal and subarctic climate zones, several authors have stressed the importance of wintertime CO_2 fluxes in order to obtain reliable annual sums (e.g. Friborg et al., 2003; Aurela et al., 2004). Here, we report that the accumulated non-growing season (151 d) CO_2 emissions in the temperate bog Fäjemyr was 121 g CO_2 m^{-2}, which is 154% of the average annual NEE. This may partly be explained by the weak sink strength. However, wintertime fluxes would still amount to approximately 50% of the annual average uptake if we assume that interannual variation could lead to an up to threefold higher sink function of Fäjemyr in a different year. Such an assumption would place Fäjemyr more at the high end of the annual CO_2 fluxes found in other comparable studies (Lafleur et al., 2003; Sottocornola and Kiely, 2005). Since the highest temperature increase in the northern hemisphere is predicted to occur during winter (Cubasch et al., 2001), these fluxes may become even more important.

4. Conclusions

The CO_2 sink for the temperate bog Fäjemyr was found to be very small. Further studies are needed to verify if the obtained CO_2 balance of –78.6 ± 20.0 g CO_2 m^{-2} yr^{-1} is representative for the current annual CO_2 balance in Fäjemyr, since the measurements only span over 1 yr. However, the ecosystem may easily change from being a net C sink to a source in the future, due to raised temperatures and CO_2 levels, and changed hydrological patterns and nutrient availability. The impact of these changes will presumably affect both GPP and respiration rates, the question is how the effects will be balanced. As indicated by our results, the outcome is likely dependent on future soil wetness. In July 2006, average CO_2 uptake was significantly lower than in June, which was caused by a combination of warmer temperatures (increased respiration) and soil drying induced plant water stress (decreased GPP). If summer droughts become more abundant, the C sink strength of Fäjemyr will likely decline. The wintertime fluxes were of major importance in the annual C balance. Taking into account the expectations of strong winter warming in the northern hemisphere, winter fluxes may become increasingly important. To be able to foresee how future changes will affect the peatland C sink functioning, it is necessary to obtain multiyear NEE measurements, and establish a mechanistic, process-based knowledge of the C fluxes in different peatland types. This is identified as a high-priority area on which future research ought to focus.

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