Carbon dioxide exchange on a northern boreal fen

Mika Aurela[1], Annalea Lohila[1], Juha-Pekka Tuovinen[1], Juha Hatakka[1],
Terhi Riutta[2] and Tuomas Laurila[1]

[1] *Finnish Meteorological Institute, Climate Change Research, P.O. Box 503, FI-00101 Helsinki, Finland*
[2] *Oxford University Centre for the Environment,* School of Geography and the Environment, *South Parks Road, Oxford OX1 3QY, United Kingdom*

Aurela, M., Lohila, A., Tuovinen, J.-P., Hatakka, J., Riutta, T. & Laurila, T. 2009: Carbon dioxide exchange on a northern boreal fen. *Boreal Env. Res.* 14: 699–710.

Long-term net ecosystem CO_2 exchange measurements were conducted on a nutrient-rich fen in northern Finland using the eddy covariance method. During the three measurement years (2006–2008), the mean daytime CO_2 flux in July was -0.40 mg CO_2 m^{-2} s^{-1}, while in mid-winter (January–March) the mean efflux was 0.008 mg CO_2 m^{-2} s^{-1}. Annual balances of -12, -123 and -216 g CO_2 m^{-2} a^{-1} were observed in 2006, 2007 and 2008, respectively. It is suggested that the low uptake in 2006 was related to the warm and dry conditions during the growing season and the consequent reduction in vegetation activity. When compared with two other fens in Finland, there was a clear correspondence between the nutrient status, mean pH value, maximum LAI and the mid-summer CO_2 uptake. A similar pattern was not seen in the annual CO_2 balance, which correlates more with the growing season length.

Introduction

The northern peatlands cover about 4% of the global land surface area, but they store up to 30% of the total soil organic carbon (Lappalainen 1996, Gorham 1991, Turunen 2002). By fixing all this carbon from the atmosphere during the last Holocene, these peatlands have had a significant influence on both the past and the present climate. In the future, their role in climate considerations is equally central, due to the climate feedbacks related to the predicted warming and the associated changes in the fluxes of the most important greenhouse gases, carbon dioxide and methane (Denman *et al.* 2007).

The CO_2 exchange between the atmosphere and northern peatlands has been studied extensively during the last 30 years with the tradi-

tional chamber method (e.g. Silvola *et al.* 1996, Alm *et al.* 1999, Bubier *et al.* 2003), and during the last decade also with the micrometeorological eddy covariance method (e.g. Shurpali *et al.* 1995, Lafleur *et al.* 1997, Aurela *et al.* 2002). These studies show that the annual CO_2 balance of pristine wetlands varies depending on meteorological and hydrological conditions. It is generally considered that hot and dry conditions may cause a depression in the net uptake of these ecosystems, either by increasing respiration or by suppressing photosynthesis, or both (Moore 2002, Bubier *et al.* 2003). On the other hand, the warmer conditions may also increase uptake by improving the photosynthetic capacity of the vegetation (Shaver *et al.* 1998, Griffis and Rouse 2001) or by prolonging the growing season (Myneni *et al.* 1997, Griffis *et al.* 2000, Aurela

Fig. 1. Aerial photograph of the measurement site. The measurement mast is indicated by a white dot. The white lines show the limit between the open fen and forest areas (hatching = peatland; no hatching = mineral soil).

et al. 2004). Springtime warming, or a general, moderate increase in mean temperatures, probably has a different influence on the annual CO_2 balance than individual heat waves in summer, which are often accompanied by drought.

In order to understand the influence of climate change on different spatial and temporal scales, we need continuous long-term measurements of the carbon exchange between the atmosphere and northern peatlands of different types. An increasing number of such studies have been initiated during the recent years (e.g. Lafleur *et al*. 2003, Aurela *et al*. 2004, Lindroth *et al*. 2007), but these must still be considered too few for large-scale projections, given the high diversity of northern wetlands and the observed interannual variation of fluxes.
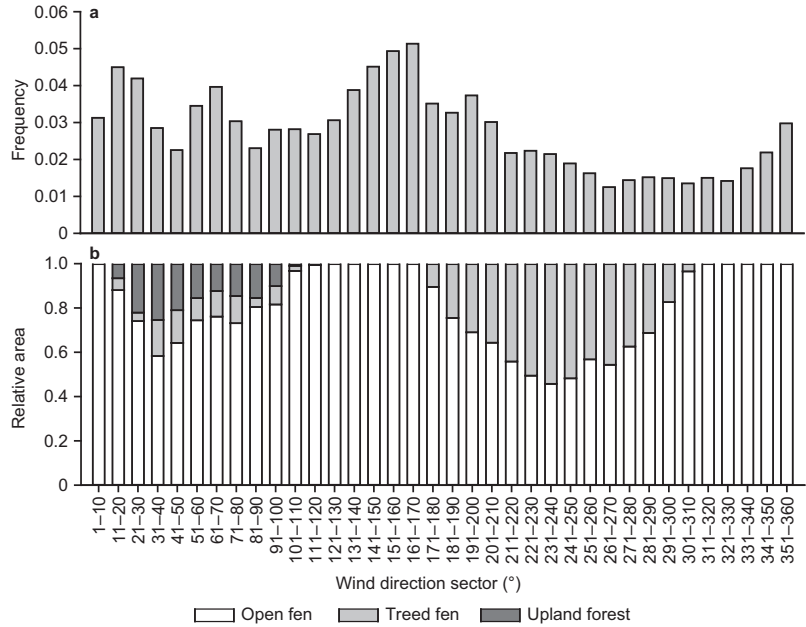
This study presents an analysis of the CO_2 exchange of a northern boreal fen based on atmospheric flux measurements by the eddy covariance method. The Lompolojänkkä measurement site is currently a Level-3 NitroEuropeIP site (Sutton *et al*. 2007), situated near the Pallas Global Atmosphere Watch station (Hatakka *et al*. 2003). Measurements were initiated at Lompolojänkkä in March 2005; the present analysis covers the years 2006–2008. The aims of the study were to (1) determine the annual CO_2 balances of the fen, (2) investigate the interannual variation of fluxes and the related environmental controls, and (3) compare the results with those from similar studies, with the emphasis on two other fens in Finland.

Material and methods

Measurement site

The Lompolojänkkä measurement site is an open, nutrient-rich sedge fen located in the aapa mire region of north-western Finland (67°59.832´N, 24°12.551´E, 269 m a.s.l.) (Fig. 1). The relatively dense vegetation layer is dominated by *Betula nana*, *Menyanthes trifoliata*, *Salix lapponum* and *Carex* spp. The mean vegetation height on the fen is 40 cm. A one-sided leaf area index (LAI) of 1.3 was estimated during at the height of summer using a SunScan canopy analysis system (SS1, Delta-T Devices Ltd.). The moss cover on the ground is patchy (57% coverage), consisting mainly of peat mosses (*Sphagnum angustifolium*, *S. riparium* and *S. fallax*) and some brown mosses (*Warnstorfia exannulata*). A small stream flows through the site; the stream zone is dominated by willow bushes (*S. lapponum*) approximately 60 cm in height. The stream and its margins cover about 10% of the target area of the eddy covariance flux measurements. The peat depth is up to 3 m at the centre of the fen; an average pH value of 5.5 was measured for the top peat layer. The site is surrounded by forest, and a homogeneous fetch suitable for the eddy covariance measurements varies from 100 to 400 m in different directions (Fig. 1). The mean annual temperature

Fig. 2. (**a**) Wind direction frequency and (**b**) the contribution of the open fen, treed fen and upland forest areas to the measured source area in 10° wind-direction sectors in summer conditions in 2006–2008 at Lompolojänkkä.

of –1.4 °C and precipitation of 484 mm have been measured at the nearest long-term weather station of Alamuonio (67°58´N, 23°41´E) during the period 1971–2000 (Drebs *et al*. 2002). The prevailing wind direction in 2006–2008 was south-east (Fig. 2a)

Measurement system

The eddy covariance system used for measuring the vertical CO_2 fluxes included a USA-1 (METEK) three-axis sonic anemometer/thermometer and a closed-path LI-7000 (Li-Cor, Inc.) CO_2/H_2O gas analyzer. The measurement height was 3 m. The length of the heated inlet tube for the gas analyzer was 8 m. The mouth of the inlet tube was placed 15 cm below the sonic anemometer and a flow rate of 5–6 l min^{-1} was used for the sample air. Synthetic air with a zero CO_2 concentration was used as the reference gas. For more details of the eddy covariance measurement system consult Aurela *et al*. (2002).

Supporting meteorological measurements, including air temperature and humidity (Vaisala, HMP), soil temperatures (PT100) at various levels, water table level (WTL) (PDCR1830), net radiation (Kipp & Zonen, NR LITE) and photosynthetic photon flux density (PPFD) (Li-Cor, LI-190SZ), were collected by a Vaisala QLI-50 datalogger as 30-min averages.

Footprint analysis

In order to estimate how well the measured fluxes represent the Lompolojänkkä fen area, a source area analysis was carried out using a micrometeorological footprint model. The relative source weight functions (flux footprints) were calculated for neutral stability using the footprint model of Kormann and Meixner (2001). The aerodynamic roughness length required for this was determined separately for the open fen (120°–170° and 300°–350°) and other wind direction sectors, and for snow-covered and snow-free periods. The corresponding wind speed was averaged over these periods.

The boundary between the open fen and the surrounding forested areas was defined using an aerial photograph (Fig. 1). The forested area was further divided into treed fen (peatland) and upland forest (mineral soil) areas, based on a field survey. The average contribution of different surface types was estimated by weighting the area of each type by the footprint functions up to

a distance corresponding to 80% of the cumulative footprint. The results of this procedure are shown in 10° sectors in Fig. 2.

Data processing

Half-hour flux values were calculated using standard eddy covariance methods. The original 10-Hz data were block-averaged, and a double rotation of the coordinate system was performed (McMillen 1988). The time lag between the anemometer and gas analyzer signals, resulting from the transport through the inlet tube, was taken into account in the on-line calculations. An air density correction related to the sensible heat flux is not necessary for the present system (Rannik *et al.* 1997), but the corresponding correction related to the latent heat flux was made (Webb *et al.* 1980). Corrections for the systematic high-frequency flux loss owing to the imperfect properties and setup of the sensors (insufficient response time, sensor separation, damping of the signal in the tubing and averaging over the measurement paths) were carried out off-line using transfer functions with empirically-determined time constants (Aubinet *et al.* 2000).

All data with wind directions from sectors 20°–70° and 190°–290° were discarded during the snow-free period due to insufficient fetch. In winter, slightly more stringent conditions (20°–110° and 180°–290°) were used, due to the typically longer footprints in stable winter conditions. Some data were also discarded due to instrument failures. After additional screening for weak turbulence (friction velocity < 0.1 m s^{-1}) and outliers, the final dataset covered 15422 observations, about one-third (31.3%) of the whole measurement period. The micrometeorological sign convention, in which negative values indicate downward flux, i.e., uptake by the ecosystem, is used throughout the paper.

Parameterisation of the NEE

In order to calculate the long-term CO_2 balances, a full time series of CO_2 fluxes is needed. Here we fill the missing CO_2 flux data using the following parameterization:

$$NEE = GP + R \qquad (1)$$

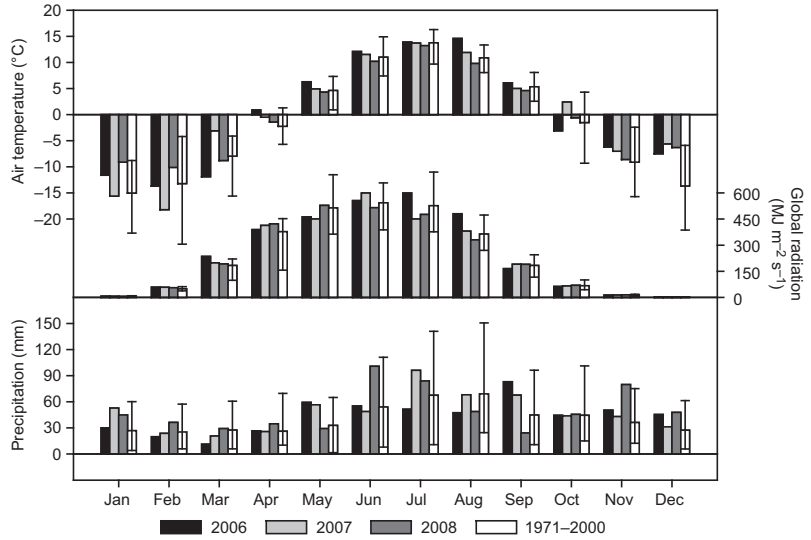$$GP = PI \frac{\alpha \times PPFD \times GP_{max}}{\alpha \times PPFD + GP_{max}} \qquad (2)$$

$$R = R_0 \exp\left[E\left(\frac{1}{T_0} - \frac{1}{T_{air} + T_1} \right) \right] \qquad (3)$$

where NEE is the net ecosystem CO_2 exchange, GP is gross photosynthesis, R is respiration, PI is the effective phytomass index (Aurela *et al.* 2001, 2002), GP_{max} is the gross photosynthesis rate in optimal light conditions, α is the initial slope of NEE *versus* photosynthetic photon flux density (PPFD), R_0 is the rate of ecosystem respiration at 10 °C, E is an activation-energy-related physiological parameter, T_{air} is the air temperature, T_0 = 56.02 K and T_1 = 227.13 K (Lloyd and Taylor 1994). PI was calculated by subtracting the nighttime (PPFD < 20 μmol m^{-2} s^{-1}) respiration flux from the daytime (PPFD > 800 μmol m^{-2} s^{-1}) flux.

The fluxes during the snow-free period were modelled for gap-filling purposes in three steps. First, E was determined for three seasonal subperiods (spring, summer, autumn) by fitting the respiration (Eq. 3) to the nighttime data separately for the three years. As the seasonally-averaged values varied relatively little (ranging from 298 to 324 K), a mean value of E = 313 K was used during subsequent steps for all data. Second, the nighttime data were re-divided into 192 weekly periods, and an R_0 value was determined for each of these. Finally, using the same weekly division, the values of α and GP_{max} were obtained by fitting the NEE equations (Eqs. 1–3) to the data set including also the daytime data. During winter with no uptake of CO_2, the gaps were filled by a moving average with a 30-d window. At the beginning and end of the winter periods, the window was shortened to 7 days.

In addition to gap-filling, Eqs. 1–3 were used for analyzing the monthly CO_2 balances, which were partitioned into gross photosynthesis (Eq. 2) and respiration (Eq. 3) components. In order to further analyze the controls behind the GP and R sums, a sensitivity analysis of the model was performed. There are two sources of variation in the monthly CO_2 exchange: differences in environmental responses (changes in parameter values) and differences in meteorological condi-

Fig. 3. Monthly mean air temperature, global radiation and precipitation at Lompolojänkkä in 2006–2008, together with their long-term averages (1971–2000). The error bars denote the minimum and maximum values. The air temperature and precipitation data were measured at the Alamuonio weather station (67°58´N, 23°41´E). The global radiation data are from the Sodankylä weather station (67°22´N, 26°38´E).

tions (changes in input data). The inter- and intra-annual variations in the former were characterised by calculating the monthly means of two essential parameters, GP_{1200} and R_0. The GP_{1200} value, which represents GP in typical clear-sky light conditions, was derived from Eq. 2 by using the optimal GP_{max}, α and PI values obtained and a PPFD value of 1200 μmol m^{-2} s^{-1}. Similarly, the monthly average of R_0 represents the temperature-normalized respiration potential of the ecosystem. In order to disentangle the influence of the meteorological factors, all the data were pooled to monthly bins, and three-year averages of the parameters were calculated for each month. The model was then run for all years using these average parameters.
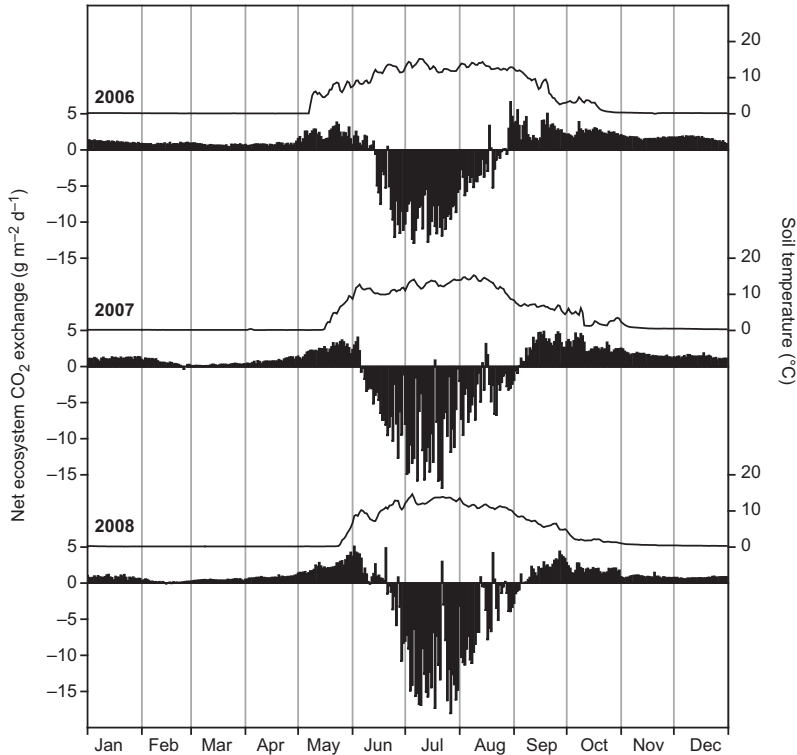
Results and discussion

Meteorology

Data from the nearby long-established weather stations Alamuonio (67°58´N, 23°41´E) and Sodankylä (67°22´N, 26°38´E) were used for analyzing the meteorological conditions during the measurement period 2006–2008 and compared with the long-term means (1971–2000) (Fig. 3). The annual average temperatures in 2006, 2007 and 2008 (Table 1) were somewhat higher than the long-term (1971–2000) average of –1.4 °C. The annual precipitation sums during the measurement years (Table 1) were also somewhat higher than the long-term average of 484 mm at Alamuonio.

The summer months (June–August) of 2008 were slightly cooler than normal, while in 2006 and 2007 they were warmer than the long-term average (Fig. 3). The August of 2006 was actually warmer than any August during the 1971–2000 reference period. The low temperatures in summer 2008 occurred concurrently with relatively low radiation levels and, on average, high precipitation. The July of 2007 was somewhat wetter, and July 2006 slightly drier, than normal,

Table 1. Seasonal averages of different meteorological and hydrological parameters at Lompolojänkkä in 2006–2008.

	2006	2007	2008
Annual mean temperature (°C)	0.1	0.1	–0.2
Annual precipitation (mm)	525	578	605
Snow melt date	3 May	17 May	24 May
Snow appearance date	16 Oct.	30 Oct.	26 Oct.
Maximum snow depth (cm)	77 (8 Apr.)	93 (20 Mar.)	102 (16 Apr.)
Summer mean water table level (cm)	–1.5	2.3	5.0

Fig. 4. Daily averages of soil temperature (at –5 cm, line) and the net ecosystem CO_2 exchange (bars) at Lompolojänkkä in 2006–2008.

but these monthly averages did not differ significantly from the long-term values (Fig. 3).

The precipitation in the late winter of 2008 was higher than during the preceding measurement years (Fig. 3), which resulted in the greatest snow depth of the three years (Table 1). Together with the lowest April–May temperatures, this led to a late snow melt in 2008. In 2006, contrasting conditions caused an early snow melt, while the relatively warm October 2007 delayed the autumnal snow appearance in that year (Table 1).
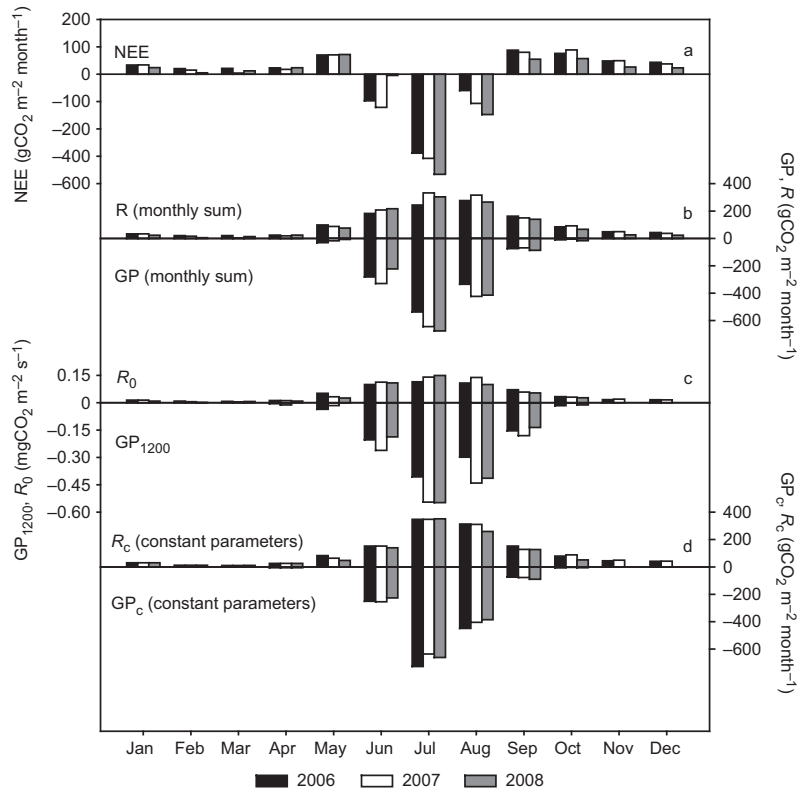
Net ecosystem CO_2 exchange

Seasonal cycle

During the winter, the CO_2 efflux shows a weak decreasing trend from November to March. An average flux of 0.008 mg CO_2 m^{-2} s^{-1} (0.7 g CO_2 m^{-2} d^{-1}) was observed for the mid-winter period (January–March) during the three measurement years (Fig. 4). The soil temperature (at –5 cm) was stable during the wintertime, but

increased rapidly after the snow melt in May (Fig. 4). A consequent rise in the respiration rates was observed as an increase in the daily net CO_2 efflux until photosynthesis took over, when the fen turned into a sink of CO_2, roughly a month after the snow melt. The highest daily net uptake was observed in July with the maximum values of –12, –14 and –18 g CO_2 m^{-2} d^{-1} in 2006, 2007 and 2008, respectively (Fig. 4). The corresponding mean daytime (PPFD > 500 μmol m^{-2} s^{-1}) net uptake rates in July were –0.32, –0.43 and –0.45 mg CO_2 m^{-2} s^{-1}. In August, the net uptake started to decrease, and at the beginning of September the fen became a net source of CO_2.

Monthly and annual balances

In 2006–2008, the Lompolojänkkä fen acted as a net sink of CO_2 for less than three months (76–90 days) of the year (Fig. 4) and correspondingly as a source for over nine months. During the snow-cover period from November to April, the monthly fluxes were rather similar between the years, decreasing from an average balance
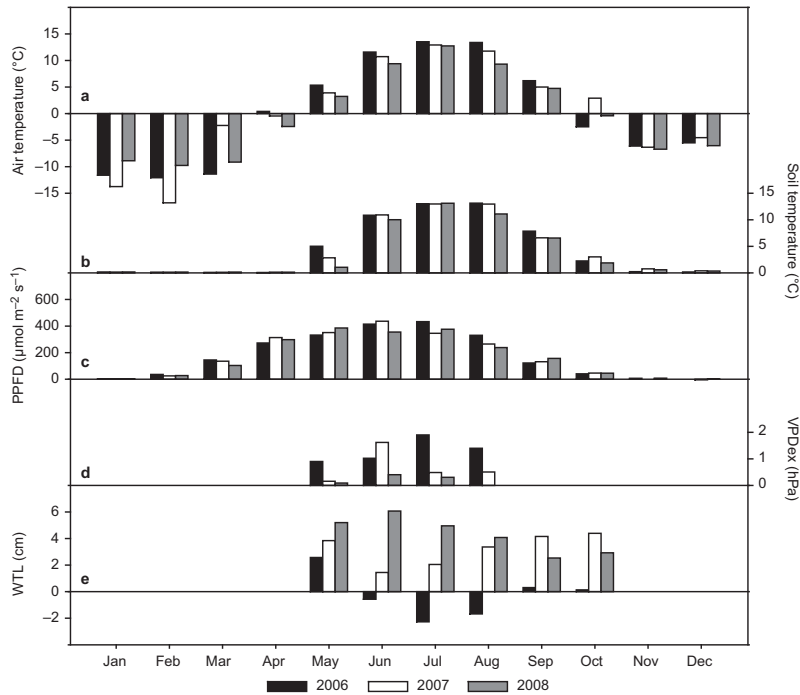
Fig. 5. Average monthly balances at Lompolo-jänkkä of (**a**) net ecosystem CO_2 exchange (NEE), (**b**) modelled respiration (*R*) and gross photosynthesis (GP), (**c**) mean parameter values R_0 and GP_{1200} and (**d**) respiration (R_c) and gross photosynthesis (GP_c) obtained from the sensitivity test with constant parameters.

of 41 g CO_2 m^{-2} month^{-1} in November to 12 g CO_2 m^{-2} month^{-1} in March (Fig. 5). Air temperatures varied markedly between the winters, but as the soil temperature remained at 0 °C (Figs. 4 and 6), the fluxes remained relatively constant.

During the snow-free period, the interannual variation in the CO_2 exchange was significant. It was greatest during the uptake period, when the absolute values of the opposite flux components, i.e., respiration and photosynthesis, are at their peak (Figs. 5a and 5b). The interannual differences in phenology and the mean photosynthetic capacity of the vegetation is illustrated by the GP_{1200} values (Fig. 5c), which represent the mean gross photosynthesis rate in typical clear-sky conditions (*see* above). In addition to the amount and state of the vegetation, the GP_{1200} value is influenced by temporal variation in the environmental variables that are not included in the model (e.g., WTL and water vapour pressure deficit, VPD). The influence of the differences in the meteorological conditions can be assessed from the outcome of the sensitivity analysis described above (Fig. 5d).

In general, the net CO_2 uptake during the summer of 2006 was lower than during the following years (Fig. 5a). According to the modelled partitioning of the net CO_2 exchange, both respiration and gross photosynthesis were limited during that year (Fig. 5b). However, the meteorological conditions considered in the model were actually more favourable for both GP (high PPFD) and *R* (high T_{air}) (Fig. 5d). The GP_{1200} values, on the other hand, indicate that the vegetation activity was relatively low during the whole summer 2006 (Fig. 5c). Such a reduction in mean activity and the consequent low net CO_2 uptake rates are often explained by dry and warm conditions, which may reduce the net uptake in various ways, especially on wetlands. Dry conditions increase the soil respiration by deepening the aerobic layer, but they may also decrease the uptake by suppressing photosynthesis (e.g. Moore 2002, Bubier *et al*. 2003). High temperatures increase respiration rates (e.g. Silvola *et al*. 1996), and the associated rise in VPD may further decrease photosynthesis by stomatal control. As plant respiration is strongly con-

Fig. 6. The monthly averages of (**a**) air temperature, (**b**) soil temperature, (**c**) photosynthetic photon flux density (PPFD), (**d**) water vapour pressure deficit (VPD) and (**e**) water table level (WTL) at the Lompolojänkkä fen in 2006–2008. VPD_{ex} denotes the mean excess of VPD above 10 hPa.

nected to photosynthesis, this will also probably suppress plant respiration.

In the present study, the partitioning of NEE does not indicate increased respiration in 2006 (Fig. 5b), which suggests that the reduction in net uptake was related to photosynthesis. The reduced photosynthetic capacity in 2006 was probably a combined effect of various factors. The WTL was lower in 2006 than in 2007 and 2008, but the difference is only a few centimetres (Fig. 6e). However, for this kind of fen with the WTL close to the peat surface, even a minor decrease in WTL could influence the fen vegetation, especially the mosses. The lowering of WTL also decreases the nutrient input to fens, which, in addition to the WTL as such, may be an important factor. At the same time, VPD was on average higher in 2006 than in the following years (Fig. 6d). There were also more frosty nights in 2006 than during the other years ($T_{air} < 0$ °C on five nights between 25 June and 5 August, in 2006, but not once in 2007, and only once in 2008). All these stress factors may have caused temporary or permanent depression of the photosynthetic apparatus of certain species.

During late summer (June–July) in 2007 and 2008, the photosynthetic capacities were of the same order, indicating that the state of vegetation was similar (Fig. 5c). The lower GP_{1200} in June 2008 is mainly due to the later onset of the growing season, which was not subsequently reflected in the vegetation status. As a response to the lower GP_{1200} and radiation levels (Figs. 5d and 6c), the net uptake in June 2008 was markedly lower than that in 2007 (Fig. 5a). In July, by contrast, NEE was greater in 2008 than in 2007, even though GP_{1200} was slightly lower in 2008. The small difference in the mean PPFD level explains the greater GP sum in July (Fig. 5b), and also partly the greater NEE. Part of the greater net uptake was caused by the lower respiration sum associated with a slightly lower respiration potential (R_0) (Fig. 5c). The net uptake during August was higher in 2008 than in 2007. Here the greatest difference was in the respiration sum, which corresponded to the higher soil and air temperatures in 2007. This effect seems to have overshadowed the effect of the higher radiation and the slightly higher GP_{1200} in 2007.

The highest monthly net CO_2 release rates were observed just before and after the growing season in May, September and October. Despite the clear difference in the snow melt dates (Table 1), the NEE of May was rather similar in differ-

ent years. The higher respiration in 2006 was compensated by the equally higher GP. September was also warmest in 2006 and coolest in 2008, but in this case the higher respiration of 2006 was not counterbalanced by photosynthesis. On the contrary, favourable radiation conditions increased the uptake in 2008 and hence the difference between the years. In October, the net respiration was similar to that in September, as the decreased temperature was balanced by the simultaneously decreased photosynthetic uptake. The high temperatures and the late snow cover resulted in especially high respiration rates in October 2007.

In 2006, 2007 and 2008, annual CO_2 balances of –12, –123 and –216 g CO_2 m^{-2} a^{-1}, respectively, were obtained for the Lompolojänkkä fen. The interannual variation in the balances is significant; in 2006, in particular, the net sink was markedly low. The modelled monthly balances suggest that this depression was caused by the reduced photosynthetic capacity of the vegetation.

Comparison with other wetlands

In addition to Lompolojänkkä, there are two other fens in Finland with continuous multi-year CO_2 measurements: the sub-arctic fen at Kaamanen in northern Finland (69°08´N, 27°17´E) (Aurela *et al*. 2002, 2004, Aurela 2005) and the boreal Siikaneva fen in southern Finland (61°50´N, 24°12´E) (Aurela *et al*. 2007, Riutta *et al*. 2007). These three fens represent a latitudinal gradient from southern to northern Finland (Table 2). They also show differences in their nutrient status from the poor Siikaneva fen to the rich Lompolojänkkä, with Kaamanen occupying an intermediate position. The characterisation of the fens in terms of their nutrient status is based on vegetation analyses, but the pH values measured at the sites are consistent with this (Table 2). A similar gradient was also observed in LAI, which correlates well with the pH value. The peak summer CO_2 exchange follows the nutrient gradient, but is probably more directly related to LAI (Aurela 2005). The mean daytime (PPFD > 500 μmol m^{-2} s^{-1}) NEE in July follows the same pattern, and an even closer relationship is found between LAI and the July NEE sum. On the other hand, the annual NEE does not show any similar correspondence to pH or LAI. The annual balances were more dependent on the lengths of the growing season and the sink period (Table 2).

The long-term carbon accumulation of bogs is typically somewhat greater than that of fens (Turunen 2002), but the measured annual balances show a lot of variation. In Scandinavia, CO_2 balances have been measured at a poor sedge fen at Degerö in Sweden (64°11´N, 19°33´E), where Sagerfors *et al*. (2007) observed annual balances similar to the Siikaneva fen, averaging

Table 2. Net ecosystem CO_2 exchange (NEE) together with different variables describing the vegetation and the nutrient status of three Finnish fens: Lompolojänkkä in 2006–2008 (this study), Kaamanen in 1997–2002 (Aurela *et al*. 2002) and Siikaneva in 2005 (Riutta *et al*. 2007, Aurela *et al*. 2007).

	Lompolojänkkä: Rich fen	Kaamanen: Rich fen with ombrotrophic hummocks	Siikaneva: Poor fen
Coordinates	68°00´N, 24°13´E	69°08´N, 27°17´E	61°50´N, 24°12´E
pH	5.5	4.6[a]	4.2
Leaf area index (single-sided) (m^2 m^{-2})	1.3	0.7	0.4
Mean daytime[b] NEE in July (mg CO_2 m^{-2} s^{-1})[c]	–0.32	–0.16	–0.14
Total NEE in July (g CO_2 m^{-2} $month^{-1}$)[c]	–321	–165	–116
Total annual NEE (g CO_2 m^{-2} a^{-1})[c]	–117	–81	–188
Length of the sink period (days)[c]	81	81	154
Length of thermal growing season (days)[c]	119	120	166

[a] Area-weighted average of hummocks and hollows. [b] Data with PPFD > 500 μmol m^{-2} s^{-1}. [c] Averages for the measurement years.

–201 g CO_2 m^{-2} a^{-1} in 2001–2003. A low annual uptake of –80 g CO_2 m^{-2} a^{-1} was measured at the Fäjemyr bog in southern Sweden (56°15´N, 13°33´E) (Lund *et al.* 2007). During four years of measurements at the Mer Bleue bog in central Canada (45°40´N, 75°50´W), Lafleur *et al.* (2003) obtained a mean annual balance of –205 g CO_2 m^{-2} a^{-1}. Sottocornola and Kiely (2005) reported an average net flux of –202 g CO_2 m^{-2} a^{-1} based on two years of measurements on a blanket bog in Ireland (51°55´N, 9°55´W), while Arneth *et al.* (2002) estimated a mean annual balance of –105 g CO_2 m^{-2} a^{-1} for a boreal bog in central Siberia (60°45´N, 89°23´E). In permafrost areas, the net uptake is typically lower, as was the case on a high arctic fen in north-east Greenland (75°N, 8°E) with a small sink of –20 g CO_2 m^{-2} a^{-1} (Nordstroem *et al.* 2001). On the other hand, Corradi *et al.* (2005) observed a markedly higher uptake of –139 g CO_2 m^{-2} a^{-1} on tussock tundra permafrost in Siberia (68°37´N, 161°20´E).

The interannual variation observed at Lompolojänkkä, ranging from –12 to –216 g CO_2 m^{-2} a^{-1}, is relatively large but very close to that observed at Kaamanen in 1997–2002 (–15 to –192 g CO_2 m^{-2} a^{-1}); a somewhat greater variation (–37 to –278 g CO_2 m^{-2} a^{-1}) was observed at the Mer Bleue bog (Lafleur *et al.* 2003). The two long time series, Kaamanen and Mer Bleue, suggest that such a large variation in the annual balances is typical for these northern wetlands. At both sites, the year having the lowest uptake was characterized by warm and dry conditions. The lowest annual uptake at Lompolojänkkä was also observed in a year that had the lowest water table and the highest growing-season temperatures, although no serious drought was observed.

Conclusions

Continuous eddy covariance measurements of the net ecosystem CO_2 exchange at Lompolojänkkä in northern Finland suggest that, on an annual scale, this rich fen is currently a net sink for CO_2. The average annual uptake of –117 g CO_2 m^{-2} a^{-1} is similar to the CO_2 exchange observed for comparable northern wetlands. During the three measurement years, the Lompolojänkkä fen was a sink for CO_2 for less than

three months of the year. The weak but stable wintertime efflux (0.008 mg CO_2 m^{-2} s^{-1} in January–March) contributes significantly to the annual balance, but is more than compensated by the stronger growing season uptake (with a mean daytime uptake of –0.40 mg CO_2 m^{-2} s^{-1} in July).

While the interannual variation of CO_2 exchange was small during winter, it was marked during the sink period. On a monthly scale, the most important determinant of the CO_2 balances was the photosynthetic capacity of the fen vegetation. The direct effect of solar radiation and temperature was also seen in the monthly balances, but their influence was greater through their impact on the physiological state of the vegetation.

The annual balances of –12, –123 and –216 g CO_2 m^{-2} a^{-1}, were observed in 2006, 2007 and 2008, respectively. Similar interannual variation has been reported in many wetland studies, showing that a low annual net uptake is often related to dry and warm conditions during the growing season. This was also observed in the present study. The year with the lowest net uptake at Lompolojänkkä was the warmest, and had the lowest water table level and the highest mean VPD.

The CO_2 exchange fluxes of the rich Lompolojänkkä fen were compared with two other Finnish fens: a rich fen with ombrotrophic hummocks in northern Finland and a poor fen located in the southern part of the country. There was a clear correspondence between the nutrient status, mean pH value, maximum LAI and the midsummer CO_2 uptake. A similar pattern was not seen in the annual CO_2 balance, which corresponds more to the growing season length.

References

Alm J., Schulman L., Walden J., Nykänen H., Martikainen P.J. & Silvola J. 1999. Carbon balance of a boreal bog during a year with an exceptionally dry summer. *Ecol-*

ogy 80: 161–174.

Arneth A., Kurbatova J., Kolle O., Shibistova O., Lloyd J., Vygodskaya N.N. & Schulze E.D. 2002. 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* 54B: 514–530.

Aubinet M., Grelle A., Ibrom A., Rannik Ü., Moncrieff J., Foken T., Kowalski A.S., Martin P. H., Berbigier P., Bernhofer Ch., Clement R., Elbers J.A., Granier A., Grünwald T., Morgenstern K., Pilegaard K., Rebmann C., Snijders W., Valentini R. & Vesala T. 2000. Estimates of the annual net carbon and water exchange of forests: the EUROFLUX methodology. *Adv. Ecol. Res.* 30: 113–175.

Aurela M., Tuovinen J.-P. & Laurila T. 2001. Net CO_2 exchange of a subarctic mountain birch ecosystem. *Theor. Appl. Climatol.* 70: 135–148.

Aurela M., Laurila T. & Tuovinen J.-P. 2002. Annual CO_2 balance of a subarctic fen in northern Europe: Importance of the wintertime efflux, *J. Geophys. Res.* 107: 4607, doi:10.1029/2002JD002055.

Aurela M., Laurila T. & Tuovinen J.-P. 2004. The timing of snow melt controls the annual CO_2 balance in a subarctic fen. *Geophys. Res. Lett.* 31: L16119, doi:10.1029/2004GL020315.

Aurela M. 2005. *Carbon dioxide exchange in subarctic ecosystems measured by a micrometeorological technique.* Ph.D. thesis, Finnish Meteorological Institute Contributions 51, Finnish Meteorological Institute, Helsinki.

Aurela M., Riutta T., Laurila T., Tuovinen J.-P., Vesala T., Tuittila E.-S., Rinne J., Haapanala S. & Laine J. 2007. CO_2 balance of a sedge fen in southern Finland — the influence of a drought period. *Tellus* 59B: 826–837.

Baldocchi D. 2003. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. *Global Change Biol.* 9: 479–492.

Bubier J.L., Bhatia G., Moore T.R., Roulet N.T. & Lafleur P.M. 2003. Spatial and temporal variability in growing-season net ecosystem carbon dioxide exchange at a large peatland in Ontario, Canada. *Ecosystems* 6: 353–367.

Corradi C., Kolle O., Walter K., Zimov S.A. & Schulze E.D. 2005. Carbon dioxide and methane exchange of a northeast Siberian tussock tundra. *Global Change Biol.* 11: 1910–1925.

Denman K.L., Brasseur G., Chidthaisong A., Ciais P., Cox P.M., Dickinson R.E., Hauglustaine D., Heinze C., Holland E., Jacob D., Lohmann U., Ramachandran S., da Silva Dias P.L., Wofsy S.C. & Zhang X. 2007. Couplings between changes in the climate system and biogeochemistry. In: Solomon S., Qin D., Manning M., Chen Z., Marquis M., Averyt K.B., Tignor M., Miller H.L. (eds.), *Climate change 2007: The physical science basis*, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, pp. 499–587.

Drebs A., Nordlund A., Karlsson P., Helminen J. & Rissanen P. 2002. *Climatological statistics of Finland 1971–2000*. Climatic statistics of Finland 2002:1, Finnish Meteoro-

logical Institute.

Gorham E. 1991. Northern peatlands: role in the carbon balance and probable responses to climatic warming. *Ecol. Appl.* 1: 182–195.

Griffis T.J., Rouse W.R. & Waddington J.M. 2000. Interannual variability in net ecosystem CO_2 exchange at a subarctic fen. *Global Biogeochem. Cyc.* 14: 1109–1121.

Griffis T.J. & Rouse W.R. 2001. Modelling the interannual variability of net ecosystem CO_2 exchange at a subarctic sedge fen. *Global Change Biol.* 7: 511–530.

Kormann R. & Meixner F.X. 2001. An analytical footprint model for non-neutral stratification. *Boundary Layer Meteorology* 99: 207–224.

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

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

Lappalainen E. 1996. *Global peat resources*. International Peat Society and Geological Survey of Finland.

Lindroth A., Lund M., Nilsson M., Aurela M., Christensen T.R., Laurila T., Rinne J., Sagerfors J., Ström L. & Vesala T. 2007. Environmental controls on CO_2 exchange of boreal mires in northern Europe. *Tellus* 59B: 1–14.

Lloyd J. & Taylor J.A. 1994. On the temperature dependence of soil respiration. *Func. Ecol.* 8: 315–323.

Lund M., Lindroth A., Christensen T. R. & Ström L. 2007. A temperate bog balance on the edge. *Tellus* 59B: 804–811.

McMillen R.T. 1988. An eddy correlation technique with extended applicability to non-simple terrain. *Boundary Layer Meteorology* 43: 231–245.

Moore P.D. 2002. The future of cool temperate bogs. *Environ. Cons.* 29: 3–20.

Moore T., Bubier J.L., Frolking S.E., Lafleur P. & Roulet N.T. 2002. Plant biomass and production and CO_2 exchange in an ombrotrophic bog. *J. Ecol.* 90: 25–36.

Myneni R.B., Keeling C.D., Tucker C.J., Asrar G. & Nemani R.R. 1997. Increased plant growth in the northern high latitudes from 1981 to 1991. *Science* 386: 698–702.

Nordstroem C., Soegaard H., Christensen T.R., Friborg T. & Hansen B.U. 2001. Seasonal carbon dioxide balance and respiration of a high-arctic fen ecosystem in NE-Greenland. *Theor. Appl. Climatol.* 70: 149–166.

Rannik Ü., Vesala T. & Keskinen R. 1997. On the damping of temperature fluctuations in a circular tube relevant to the eddy covariance measurement technique. *J. Geophys. Res.* 102: 12789–12794.

Riutta T., Laine J., Aurela M., Rinne J., Vesala T., Laurila T., Haapanala S., Pihlatie M. & Tuittila E.-S. 2007. Spatial variation in plant community functions regulates carbon gas dynamics in a boreal fen ecosystem. *Tellus* 59B: 838–852.

Sagerfors J., Lindroth A., Grelle A., Klemedtsson L., Weslien P. & Nilsson M. 2008. Annual CO_2 exchange between a nutrient-poor, minerotrophic, boreal mire and the atmosphere. *J. Geophys. Res.* 113: G01001,

doi:10.1029/2006JG000306.

Shaver G.R., Johnson L.C., Cades D.H., Murray G., Laundre J.A., Rastetter E.B., Nadelhoffer K.J. & Giblin A.E. 1998. Biomass and CO_2 flux in wet sedge tundras: Responses to nutrients, temperature, and light. *Ecol. Monogr.* 68: 75–97.

Shurpali N.J., Verma S.B. & Kim J. 1995. Carbon dioxide exchange in a peatland ecosystem. *J. Geophys. Res.* 100: 14319–14326.

Silvola J., Alm J., Ahlholm U., Nykänen H. & Martikainen P. 1996. CO_2 fluxes from peat in boreal mires under varying temperature and moisture conditions. *J. Ecol.* 84: 219–228.

Sottocornola M. & Kiely G. 2005. An Atlantic blanket bog is a modest CO_2 sink. *Geophys. Res. Lett.* 32: L23804, doi: 10.1029/2005GLO24731.

Sutton M.A., Nemitz E., Erisman J.W., Beier C., Butterbach Bahl K., Cellier P., de Vries W., Cotrufo F., Skiba U., Di Marco C., Jones S., Laville P., Soussana J.F., Loubet B., Twigg M., Famulari D., Whitehead J., Gallagher M.W., Neftel A., Flechard C.R., Herrmann B., Calanca P.L., Schjoerring J.K., Daemmgen U., Horvath L., Tang Y.S., Emmett B.A., Tietema A., Penuelas J., Kesik M., Brueggemann N., Pilegaard K., Vesala T., Campbell C.L., Olesen J.E., Dragosits U., Theobald M.R., Levy P., Mobbs D.C., Milne R., Viovy N., Vuichard N., Smith J.U., Smith P., Bergamaschi P., Fowler D. & Reis S. 2007. Challenges in quantifying biosphere — atmosphere exchange of nitrogen species. *Environ. Pollut.* 150: 125–139.

Turunen J., Tomppo E., Tolonen K. & Reinikainen A. 2002. Estimating carbon accumulation rates of undrained mires in Finland — application to boreal and subarctic regions. *Holocene* 12: 79–90.

Webb E.K., Pearman G.I. & Leuning R. 1980. Correction of flux measurements for density effects due to heat and water vapour transfer. *Q. J. R. Meteorol. Soc.* 106: 85–100.