Biogeosciences Discuss., 8, 5787–5825, 2011
www.biogeosciences-discuss.net/8/5787/2011/
doi:10.5194/bgd-8-5787-2011

Biogeosciences Discussions

Greenhouse gas flux measurements in a forestry-drained peatland indicate a large carbon sink

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Received: 16 May 2011 – Accepted: 7 June 2011 – Published: 21 June 2011

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

Abstract

Drainage for forestry purposes changes the conditions in the peat and leads to increased growth of shrubs and trees. Concurrently, the production and uptake of the greenhouse gases carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are likely to change: due to the accelerated decomposition of oxic peat, drained peatlands are generally considered to loose peat carbon (C). We measured CO_2 exchange with the eddy covariance (EC) method above a drained nutrient-poor peatland forest in Southern Finland for 16 months in 2004–2005. The site, classified as a dwarf-shrub pine bog, had been ditched about 35 years earlier. CH_4 and N_2O fluxes were measured at 2–5 week intervals with the chamber technique. Drainage had resulted in a relatively little change in the water table level, being on average 40 cm below the ground in 2005. The annual net ecosystem exchange was $-870\,g\,CO_2\,m^{-2}\,yr^{-1}$ in the calendar year 2005, varying from -810 to $-900\,g\,CO_2\,m^{-2}\,yr^{-1}$ during the 16 month period under investigation. The site was a small sink of CH_4 ($-0.12\,g\,CH_4\,m^{-2}\,yr^{-1}$) and a small source of N_2O ($0.10\,g\,N_2O\,m^{-2}\,yr^{-1}$). Photosynthesis was detected throughout the year when the air temperature exceeded $-3\,^{\circ}C$. As the annual accumulation of C in the above and below ground tree biomass ($550\,g\,CO_2\,m^{-2}$) was significantly less than the net exchange of CO_2, about $300\,g\,CO_2\,m^{-2}\,yr^{-1}$ ($\sim 80\,g\,C\,m^{-2}$) was likely to have accumulated as organic matter into the peat soil. This is a higher average accumulation rate than previously reported for natural northern peatlands, and the first time C accumulation has been shown, by EC measurements, to occur in a drained peatland. Our results suggest that forestry-drainage may significantly increase the CO_2 uptake rate of nutrient-poor peatland ecosystems.

1 Introduction

One-third of the European peat soil area is located in Finland (Montanarella et al., 2006), where more than half of the original wetland area of $100\,000\,km^2$ has been

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drained, mostly for forestry (Lappalainen, 1996). This constitutes 34 % of the global area of forestry-drained peatlands; the rest of the peatlands ditched to improve forest growth are located in Russia (26 %), Sweden (11 %), other Northern European countries (23 %), North-America (3 %), and China (0.5 %) (Minkkinen et al., 2008). The drainage of peatlands has been suggested to lead to rapid aerobic decomposition of organic matter and, consequently, to high carbon dioxide (CO_2) emissions and to a gradual depletion of peat carbon (C) pool (e.g., Turetsky and Louis, 2006). At the same time, methane (CH_4) emissions typically cease, in some cases even leading to CH_4 uptake by the forest soil (Minkkinen et al., 2007b). Nitrous oxide (N_2O) emissions may increase in minerotrophic peatlands, but not in the ombrotrophic ones (Martikainen et al., 1993; Regina et al., 1996).

Direct measurements of net ecosystem exchange (NEE) on peatlands converted to agricultural use have shown high decomposition rates of peat and large C losses due to drainage (Lohila et al., 2004; Veenendaal et al., 2007). Peat C loss was also observed in an afforested agricultural site 30 years after the forest had been established (Lohila et al., 2007), whereas C uptake on an afforested peatland in Scotland was reported by Hargreaves et al. (2003). In contrast, a moderately rich fen in Canada with naturally generated tree cover and relatively deep water table (30–70 cm) was found to act as a large annual CO_2 sink, although this site had not been managed (Syed et al., 2006; Flanagan and Syed, 2011). To our knowledge no NEE measurements including tree canopy have been made previously in forestry-drained peatlands without agricultural history.

Studies on peat subsidence and bulk density have indicated a trend that nutrient-rich peatlands tend to lose peat C following drainage while nutrient-poor ones may still sequester C (Minkkinen and Laine, 1998; Minkkinen et al., 1999). In forestry-drained peatlands, the nutrient status has been shown to regulate post-drainage tree stand growth (Keltikangas et al., 1986). Stand volume, in turn, regulates water table depth through transpiration (Sarkkola et al., 2009), and water table depth is the main control over the organic matter decomposition in peatlands (e.g. Silvola et al., 1996).

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Measurements of CO_2 efflux by the chamber method have supported the idea of higher soil respiration rates in well-drained nutrient-rich sites in contrast to less-well-drained nutrient-poor sites (Silvola et al., 1996; Minkkinen et al., 2007a; Ojanen et al., 2010).

We measured NEE above a drained peatland forest in Southern Finland with the micrometeorological eddy-covariance (EC) technique, which is the only viable method to monitor biosphere-atmosphere CO_2 exchange of a whole forest ecosystem. Earlier, Pihlatie et al. (2010) have reported greenhouse gas (GHG) fluxes measured at this site during April–June 2007, in particular the short-term dynamics of N_2O and CH_4 and the effect of soil thawing on them. Here we report, for the first time, a full year of data on CO_2 exchange of a forestry-drained peatland drained 35 years before the start of our EC measurements. These data cover a 16 month period from September 2004 to December 2005. In addition, annual dynamics and balances of CH_4 and N_2O fluxes are presented based on soil chamber measurements.

2 Material and methods

2.1 Site presentation

Measurements were conducted at Kalevansuo-peatland, located in the municipality of Loppi, in southern Finland (60°38′49′′ N, 24°21′23′′ E; elevation 129 m). The site, originally classified as a dwarf shrub pine bog, was drained in 1969 with open ditches at around 40 m intervals (Fig. 1). Drainage has resulted in a lowered water table (on average 40 cm below the ground) and has increased the growth of the natural tree stand. The topography of the site was flat. Within 160 m of the EC measurement mast the peat depth, measured from the 33 sample plots, varied from 1.3 to 3.0 m, being deepest in the middle (Fig. 2). The average peat depth (± SD) was 2.2 ± 0.5 m. The physical and chemical properties of the peat soil (surface humus and the layers 0–10 cm and 10–20 cm below the humus) were determined from eight samples taken evenly around the measurement mast. The ash content was determined as loss on

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ignition (550 °C) and the C and N concentrations using LECO CHN-2000. Element concentrations (Al, Ca, Fe, K, Mg, Mn, P, B, Cu, Mn, Zn) were measured by an ICP Iris emission spectrometer in dry-ashed material. The bulk density of the peat varied from 0.08 to 0.11 g cm^{-3} at the depths of 0–10 cm and 10–20 cm, respectively (Table 1). The CN-ratio was high, varying from 34 to 41, the lowest values being measured at a depth of 0–10 cm. The concentrations of most of the measured elements were highest in the humus layer and lowest deeper in the peat (Table 1). The pH of the peat was 5.0 (Pihlatie et al., 2010). The concentration of soil NO_3^- was negligible, whereas the NH_4^+ concentration in the peat varied between 5 and 15 mg N kg^{-1} and that of dissolved N between 75 and 225 mg N kg^{-1} soil (Pihlatie et al., 2010).

Basic tree stand variables for the biomass calculations (diameter, height) were measured from 33 plots (500 m^2) in eight radial transects extending 160 m from the EC mast (Fig. 2). Biomasses were estimated with the functions of Marklund (1988). The tree stand consisted of a dominant Scots pine (*Pinus sylvestris*) stand of 835 stems ha^{-1}, and an understorey of pubescent birch (*Betula pubescens*) trees (<500 stems ha^{-1}) that were mainly found on the ditch banks. Scots pine constituted 63 % of the number of trees taller than 1.3 m and 98 % of the stand volume. The pine stand had a dominant height of 15 m, a basal area of 17 m^2 ha^{-1}, and the annual stem volume growth was 5.5 m^3 ha^{-1} yr^{-1}. The annual increment of live tree stand biomass was 3.13 tonnes of dry mass ha^{-1}, corresponding to about 160 g C m^{-2} yr^{-1}. During the summertime maximum biomass, the all-sided leaf area index (LAI) of the needles estimated from the needle mass, was 5 m^2 m^{-2}. The field layer was dominated by *Ledum palustre, Vaccinium uliginosum, V. vitis-idaea, V. myrtillus, Empetrum nigrum, Calluna vulgaris, Eriophorum vaginatum and Rubus chamaemorus*. The bottom layer was dominated by forest-mosses *Pleurozium schreberi, Dicranum polysetum, Aulacomnium palustre* and *Polytrichum strictum* with some peat-mosses like *Sphagnum angustifolium, S. magellanicum* and *S. russowii* on the wetter spots. Mosses cover about 90 % of the land surface in Kalevansuo. The one-sided LAI of the field layer varied from 0.1 to 0.6 m^2 m^{-2} during the course of the growing season (Badorek et al., 2011).

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2.2 Measurements of the CO_2 exchange and meteorological variables

The turbulent fluxes of CO_2, H_2O, sensible heat and momentum were measured with the eddy covariance technique on top of a 21.5 m telescopic mast (at 17.5 m from April 2005). Fluctuations of wind velocity components were measured with a sonic anemometer/thermometer (SATI-3SX, Applied Technologies, Inc.) and those of CO_2 concentration with a closed-path infrared CO_2/H_2O analyzer (LI-7000, LI-COR, Inc.). The heated inlet tube for the LI-7000 was 17 m in length, and a flow rate of 6 L min^{-1} was used. CO_2-free synthetic dry air was used as a reference gas. From February 2005 onwards, the mean CO_2 concentration ([CO_2]) was also observed at a height of 4 m with a LI-820 CO_2 analyzer. Both analyzers were calibrated monthly with two known [CO_2] (0 and 421 ppm). The fluxes were calculated on-line as 30 min averages as described by Pihlatie et al. (2010). The results were post-processed by correcting for systematic flux losses due to running mean filtering and the imperfect frequency response of the measurement system (with a half power frequency 1.6 Hz estimated for the CO_2 flux), and for the density fluctuations related to the water vapour flux (Webb et al., 1980).

The storage flux of CO_2 was calculated from the [CO_2] data measured at the top of the mast and at the height of 4 m and was added to the measured turbulent flux (hereafter NEE refers to the sum of turbulent and storage fluxes). However, before 21 February 2005, the storage flux was calculated from the [CO_2] measured at the top of the mast only, with the assumption that it represented the whole air column below that height. In this paper, we use the convention that a positive value of NEE indicates a flux from the ecosystem to the atmosphere.

Supporting meteorological measurements were conducted at the study site as follows: air temperature (T_{air}) and relative humidity (RH) (Vaisala HMP230) at 2 m and at the top of the mast, soil temperature (PT100) at depths of 0.05, 0.15 and 0.30 m in a moist hollow, and at 0.05 cm in a hummock, soil moisture (ThetaProbe ML2x, Delta-T Devices Ltd.) at depths of 0.07 and 0.30 m, soil heat flux (HFP01) at a depth of 0.15 m, net radiation (Kipp & Zonen NR Lite), global and reflected global radiation (LI-200SZ), photosynthetic photon flux density (PPFD) and reflected PPFD (Licor LI-190SZ) at the top of the mast, and the water table level (WTL) (PDCR 830). The data were acquired using a Vaisala QLI 50 and Campbell CR10X1 sensor collectors and stored as 30 min averages. The snow depth and the precipitation data, as well as the T_{air} data in cases of data collection failure at the Kalevansuo site were collected from four nearby weather stations operated by the Finnish Meteorological Institute (Vojakkala, Maasoja, Nurmijärvi and Jokioinen, at distances of 19–53 km, on average 29.5 km, from the site). To cover the spatial variation, manual measurements of WTL were carried out at bimonthly intervals from eight perforated plastic pipes, which were located in four directions within a distance of ca. 50 m from the EC mast. The half-hourly water table data were then calibrated against the average WTL from these manual measurements.

2.3 CO_2 flux data screening

Longer gaps in the CO_2 flux data were mainly caused by power failure, sensor malfunction and freezing of the anemometer. The longest gaps took place between 2–13 April 2005, 7–11 August 2005, 21 August–5 September 2005 and 9–24 November 2005. The remaining 30 min data records were screened according to the following criteria: (1) $[CO_2] > 350$ ppm, (2) number of spikes in the vertical wind speed (w) and $[CO_2]$ raw data < 180, (3) variances of the raw data $\sigma^2_{T_{air}} < 3\,K^2$, $\sigma^2_{CO_2} < 50\,ppm^2$ and $\sigma^2_w < 3\,m^2\,s^{-2}$ and (4) $-40\,^\circ C < T_{air} < 40\,^\circ C$.

In order to estimate how well the measured fluxes represent the Scots pine stand around the measurement mast, a source area analysis was carried out with a micrometeorological footprint model. The relative source weight functions (flux footprints) were calculated for each 30 min averaging period using the footprint model of Kormann and Meixner (2001). The horizontal dimension of the stand was defined as six circular sectors (Fig. 1), and the modelled (cross-wind-integrated) footprint was accumulated over the radius of the sector corresponding to the observed wind direction. If this cumulative footprint was larger than 70 %, the flux data of that period were considered sufficiently representative of the peatland forest and accepted for further analysis. Owing to the high surface roughness, the source areas were concentrated relatively close to the measurement mast with the typical distance of the footprint maximum being less than 30 m.

During suppressed turbulence (typically summer nights), part of the CO_2 produced by ecosystem respiration may accumulate near the surface and be advected below the measurement height, in which case the measured vertical flux is likely to underestimate NEE. Therefore we replaced the NEE data measured during low turbulence conditions with modelled values. At Kalevansuo, the friction velocity (u_*) limit below which the nocturnal respiration was likely to be underestimated was 0.10 m s^{-1} (Fig. 3). By applying the footprint and u_* criteria, an additional 17 % of the data were discarded.

After filtering the data according to the quality criteria shown above, altogether a total of 10 959 flux values (47.3 %) of the 30 min periods during the whole measurement period (11 September 2004–31 December, 2005) were accepted and used in the further analysis. Of these, night-time data accounted for 49 % ($n = 5361$). Most of the data were related to the south-western and southern wind directions, whereas the contribution of other directions was more evenly distributed (Fig. 4). During the growing season, most of the data originated from the south-west, and the least data from the north-east and east.

2.4 Chamber measurements of CH_4 and N_2O fluxes

Chamber measurements were carried out in 2–5 week intervals between 7 July, 2004–17 September, 2005. The CH_4 and N_2O fluxes were measured with static chambers at 16 sampling points located in four directions (plots 1–4) each at a distance of about 50 m from the EC mast (Fig. 1). Round, metallic chambers (diameter = 0.315 m, height = 0.30 m) equipped with a fan for mixing the air in the chamber headspace were used. During the measurement, the chamber was placed in a 0.02 m deep collar that had been carefully installed on the soil to ensure sealing but not to cut any

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root connections. In winter, when the snowpack was deeper than 0.10 m, fluxes were measured with the help of an 0.1 m deep collar inserted on the snowpack prior to measurement. Four air samples (20 ml) were drawn into syringes at 10 min intervals (5, 15, 25, 35 min). The samples were analysed within 24 h using a gas chromatograph with flame ionisation and electron capture detectors in the laboratory of the Finnish Forest Research Institute, Vantaa Unit.

Gas fluxes were calculated from the linearised change of the gas concentration over time (slope estimated by linear regression). All data were used, regardless of the goodness of fit of the regression, as in most cases the fluxes were very small and close to the detection limit (below 0.4 mg m^{-2} day^{-1}). Fluxes exceeding 0.4 mg m^{-2} day^{-1} had minimum/mean r^2 values of 0.63/0.91 (CH_4) and 0.67/0.90 (N_2O). Four measurements were deleted as a result of chamber sealing problems in the winter 2005. As the site was well drained no ebullition events were observed, so the data represents diffusive or/and plant-mediated gas fluxes. During each chamber measurement, the soil temperatures at 0.05 and 0.30 m were recorded and the WTL relative to each sampling point was measured from perforated water wells.

Annual CH_4 and N_2O balances were calculated as the mean of the 16 plots for each measurement day. Mean fluxes between these days were linearly interpolated and seasonal fluxes were then integrated from these interpolated daily fluxes.

3 Results

3.1 Meteorology and water table level

The measurement period from September 2004 to December 2005 was slightly warmer and wetter than average: at the four closest weather stations the mean annual temperature during the period varied from 4.9 to 5.5 °C, whereas the mean annual long-term (1971–2000) temperature of this district was 4.4 °C (Drebs et al., 2002). Annual precipitation during the measurement period ranged from 638 to 718 mm, which is

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slightly higher than the long-term average of 627 mm. Daily mean temperatures varied from −16 to 22 °C. The first snow appeared on the ground on 18 November, but by 20 January, the snow-pack had melted twice during warm spells. Thereafter, snow was present until mid-April with the maximum depth of 37 cm being measured on 14 February. The largest deviations from the long-term monthly mean temperatures were observed in January (+4.4 °C above average) and in March (−5.6 °C below average). Furthermore in November 2005 the monthly temperature clearly exceeded the long-term mean (by 3.5 °C). The monthly precipitation exceeded the 30 year mean between May and August but also in January and November 2005. In contrast, September and October 2005 were especially dry. During the study period, the WTL ranged from −31 to −50 cm. The lowest average WTL was observed in mid-October 2005.

3.2 Seasonal dynamics and factors affecting the CO_2 exchange

The seasons were defined according to meteorological conditions. The start of the autumn season took place when the daily mean air temperature dropped permanently below 10 °C, and after that did not exceed 10 °C for more than two consecutive days. In 2004, when autumn started on 29 September, the amplitude of the diurnal NEE cycle was still rather high, but began to decline soon after this (Fig. 5). In 2005, the autumn period began on 12 October. The start of winter was defined as the first day when the daily mean temperature was less than 0 °C, and that the temperature stayed below 0 °C for at least five consecutive days. The winter seasons, which began on 17 November and 16 November in 2004 and 2005, respectively, were characterized by a low amplitude in NEE, which varied from −0.005 to 0.1 mg m^{-2} s^{-1} and averaged 0.025 mg m^{-2} s^{-1}. We defined the start of the spring season as the first day when the daily mean temperature exceeded 0 °C, and remained above that value for at least 10 consecutive days. The start of the spring, 31 March, likely coincided with the rapid increase in the CO_2 uptake, although the exact date is unknown due to a gap in the measurement data. Summer was specified to begin when the daily mean temperature exceeded 10 °C for five consecutive days, and afterwards did not drop below that value

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for more than five consecutive days. This took place on 10 May 2005. The highest uptake rates of about $-0.85\,\mathrm{mg\,m^{-2}\,s^{-1}}$ were observed at the end of July, at about the same time as the maximum night-time respiration of about $0.45\,\mathrm{mg\,m^{-2}\,s^{-1}}$.

Although NEE was mainly positive in winter, periods of small uptake of CO_2 were detected occasionally, particularly between November 2004 and mid-February 2005. We found that when temperatures fell below $-3\,^{\circ}$C, CO_2 fluxes measured during the daytime and night-time were similar, increasing with higher temperature (Fig. 6a). When the air temperature exceeded $-3\,^{\circ}$C, the difference between the day and night fluxes increased rapidly due to CO_2 uptake by the trees and ground vegetation during the daytime. When T_{air} was lower than $-3\,^{\circ}$C, the diurnal variation in NEE disappeared, whereas with higher temperatures, a clear pattern with CO_2 uptake peaking at noon was observed (Fig. 6b).

Irradiance is generally recognized as the most important variable causing diurnal variation in growing season NEE. This was also observed at the Kalevansuo peatland forest. However, a significant correlation between the atmospheric vapour pressure deficit (VPD) and the 30 min NEE was observed in May–August (Fig. 7). The correlation was strongest in July with the deepest regression slope and the highest coefficient of determination being observed then. However, since temperature and VPD are likely to show a positive correlation, it is possible that the correlation between NEE and VPD can be attributed to increased respiration rather than decreased photosynthesis. To determine the impact of air temperature and VPD on ecosystem processes, we grouped the July NEE observations at full radiation (PPFD$>1200\,\mathrm{\mu mol\,m^{-2}\,s^{-1}}$) into temperature classes of $1\,^{\circ}$C. In each class, a linear correlation between NEE and VPD was observed (Fig. 8). However, the correlation was not explained by the temperature (Fig. 8).

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3.3 CO_2 balances

3.3.1 Gap-filling of NEE

In order to gap-fill the CO_2 flux time-series, which is required to calculate the CO_2 balances, and for the analysis of seasonal patterns of the flux components, the measured CO_2 flux was partitioned by means of empirical equations into gross primary production (GPP) and total ecosystem respiration (R_{tot}). R_{tot} was modelled as a function of temperature using the Arrhenius-type model of Lloyd and Taylor (1994):

$$R_{tot} = R_{ref} \times \exp\left[E_0 \times \left(\frac{1}{T_{ref}} - \frac{1}{T_{air} - 227.13}\right)\right] \quad (1)$$

Air temperature measured at 2 m height was used for T_{air} (in K). T_{air} was selected since a full time-series was easily available and a slightly higher correlation was obtained for T_{air} than for soil temperature. In Eq. (1), R_{ref} is equal to R_{tot} at T_{air} = 283.15 K, $T_{ref} = 56.02$ K, and E_0 is the temperature sensitivity of the respiration (in K).

NEE was modelled using PPFD and the modelled R_{tot} as input values to the following equation:

$$\mathrm{NEE} = \mathrm{GPP} + R_{tot} \quad (2)$$

$$\mathrm{NEE} = f_{VPD} \times \left(\frac{\alpha \times \mathrm{PPFD} \times \mathrm{GP}_{max}}{\alpha \times \mathrm{PPFD} + \mathrm{GP}_{max}}\right) + R_{tot} \quad (3)$$

where α is the apparent quantum yield and GP_{max} is the full daylight asymptotic value of NEE after subtracting the modelled R_{tot}. f_{VPD} is a unitless function that was estimated based on the relationship between the measured NEE (with PPFD $> 1000\ \mu\mathrm{mol\,m^{-2}\,s^{-1}}$) and VPD in July. f_{VPD} was given a value of 1 when VPD < 10 hPa, and a value of 0.2 when VPD > 25 hPa (Fig. 7c), and are within the typical limits of observed VPD effects in Scots pine forests (Mills et al., 2010).

The fitting procedure has been presented in more detail in Appendix A. The daily, seasonal and annual CO_2 balances were calculated from the full time-series consisting of measured and gap-filled half-hourly CO_2 flux data.

3.3.2 Seasonal dynamics in CO_2 balance

In 2005, annual R_{tot} was 2750 g CO_2 m^{-2}, GPP was −3620 g CO_2 m^{-2} and annual NEE was −871 g CO_2 m^{-2} (−238 g C m^{-2} yr^{-1}). From 2 September 2004 to 31 December 2005, the annual balance ranged from −806 to −898 g CO_2 m^{-2} yr^{-1}, when calculated for different 365-day periods.

In autumn 2004, the daily CO_2 balance varied from −5 to 10 g m^{-2} day^{-1}, the ecosystem being a sink during warm and sunny days and a source during overcast days (Fig. 9). After mid-November (start of the winter), photosynthesis ceased, and the daily balance turned positive. Wintertime NEE was on average 2.0 g CO_2 m^{-2} day^{-1}. During the winter months, the lowest average NEE was measured in March (1.6 g CO_2 m^{-2} day^{-1}). This was attributed to the low respiration rate following the lowest monthly mean temperature, rather than to the occurrence of CO_2 uptake, which was only observed during a few days. At the beginning of April and during the spring season, the forest turned to a CO_2 sink. With a few exceptions, the ecosystem acted as a CO_2 sink until mid-September. During this period, positive daily CO_2 balances were only observed during cloudy days, e.g. between 8–11 August 2005, when the total precipitation exceeded 50 mm. In 2005, the length of the sink period was approximately 210 days, ending at the beginning of November, two weeks after the end of summer and two weeks before the start of winter. Again, a strong reduction in photosynthesis coincided exactly with the beginning of the winter season.

The contribution of the wintertime photosynthesis on the seasonal and annual balances was estimated by calculating the balance by different methods. First, the CO_2 balance for the winter period (17 November 2004–30 March 2005) was calculated as a sum of the modelled respiration (Eq. 1). The result, 286 g CO_2 m^{-2}, represents a

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situation where no photosynthesis occurred during winter. If calculated as a sum of the measured and modelled values, then gap-filling, which is carried out with the modelled respiration data and ignores photosynthesis, results in a balance of 279 g CO_2 m^{-2}. In this estimate, winter photosynthesis is accounted for in that part of the data, where accepted records exist. However, since the gap-filling was done with Eq. (1), which ignores photosynthesis, NEE is potentially overestimated when $T_{air} > -3\,°C$. If the gaps were filled using a radiation-response model, the wintertime CO_2 balance was 264 g m^{-2}. This method represented the best estimate and was used in the calculation of the wintertime and annual balances presented in this paper.

3.4 CH_4 and N_2O fluxes between the soil and the atmosphere

The site was a small sink of CH_4 (-0.35 ± 0.58 mg CH_4 m^{-2} day^{-1}; mean ± SD) and a small source of N_2O (0.30 ± 0.25 mg N_2O m^{-2} day^{-1}). N_2O fluxes were very similar at all 16 sampling points (Fig. 10): no statistical differences were detected (ANOVA; $p = 0.358$). In contrast, CH_4 fluxes varied between the sampling points ($p = 0.000$), and ranged from sample points with a small consumption to points with small emissions (Fig. 10). Surprisingly, the highest consumption (-1.0 ± 0.5 mg m^{-2} day^{-1}) of CH_4 was measured at plot 2, which also had the highest WTL, whereas the highest emissions (0.02 ± 0.40 mg m^{-2} day^{-1}) were measured at plot 1 with the deepest water levels. Emissions showed no correlation with the plant community (forest mosses/*Sphagnum*), nor with the microtopography (hummock/non-hummock) (Fig. 10). CH_4 consumption and N_2O emissions peaked at midsummer, although some high N_2O emissions were also detected in winter (Fig. 11). The highest CH_4 emissions were detected in autumn 2005 at plots 3 and 4.

The seasonal and annual fluxes were integrated from the interpolated fluxes (Fig. 11). The growing season (May–September) fluxes were on average -58 mg m^{-2} CH_4 and 47 mg N_2O m^{-2} and the annual fluxes (August 2004–July 2005) were -120 mg CH_4 m^{-2} and 100 mg N_2O m^{-2}. When converted to global warming

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potential (GWP) values using a time horizon of 100 years (Forster et al., 2007), the annual emissions were −3 and 30 g CO_2eq. m^{-2}.

4 Discussion

4.1 Annual uptake of CO_2 exceeds peat decomposition

In this paper we have reported a significant CO_2 sink in a drained peatland forest in southern Finland. Ombrotrophic treed peatlands, such as the Kalevansuo site presented in this study, constitute over 10 % of the total area (5.4–5.7 million ha) of peatlands ever drained for forestry in Finland (Minkkinen et al., 2002), and the site type (dwarf-shrub type) is the single most commonly drained one in southern Finland. Such sites therefore have general importance in regard to their impacts on global-scale GHG balances and climate, for example.

The annual net CO_2 uptake at our site (240 g C m^{-2}) was much higher than the amount of C accumulated in the tree biomass (160 g C m^{-2}), which indicates that the forest floor, i.e. the ground layer vegetation and the underlying peat must also have constituted a C sink. This observation, based on direct EC flux measurements, is new. In general, the mineralisation rate of peat should increase after drainage, since lowering of the water level increases the aeration of the surface peat (Laine et al., 2006; Nykänen et al., 1995; Silvola et al., 1996; Maljanen et al., 2001; Veenendaal et al., 2007).

On the other hand, the annual NEE reported here supports the findings from peat subsidence/C stock studies by Minkkinen and Laine (1998) and Minkkinen et al. (1999), who showed that nutrient-poor peatland types may continue to sequester C after drainage for forestry. As speculated by Minkkinen (1999), the lower peat decomposition rate, the higher allocation of C into the roots with low nutrient availability, and lush, actively photosynthesising ground vegetation (Badorek et al., 2011) could explain the C accumulation into the nutrient-poor peatland ecosystem. After drainage, the quantity and quality of the litterfall change. There is an increase in the input of slow decomposing woody and moss litter and a decrease in the input of faster-decomposing grasses and herbs (Laiho et al., 2003). In addition, part of the C released from the decayed litter is translocated as a solute to deeper peat layers and contributes to the C accumulation in the peat (Domisch et al., 2000).

Nutrient-poor sites are typically situated in the thick-peated, relatively flat centre area of mires. In those conditions drainage by ditching is not as successful as in the mire margins, as peat subsides after drainage, and ditches on a flat terrain tend to get blocked with vegetation. Tree stand growth remains rather slow because of a lack of nutrients, and drainage through tree stand transpiration also remains low. Therefore, water tables in nutrient-poor sites remain relatively high, keeping peat decomposition rates at moderate levels (e.g. Silvola et al., 1996; Ojanen et al., 2010).

We did not measure C leaching from the ecosystem. The site was rather flat and water movement was very slow outside the snowmelt events. Most of the ditches were blocked by vegetation and therefore functioned poorly. This means that the drainage at the site was maintained mainly by the transpiration of the tree stand, which is a typical situation in drained peatland forests in Finland (Hökkä et al., 2008). Leaching of dissolved carbon (DC) from Finnish drained peatlands typically results in a loss of about 10 to 15 $g\,C\,m^{-2}\,yr^{-1}$ (Sallantaus and Kaipainen, 1996; Kortelainen et al., 1997; Sarkkola et al., 2009; Rantakari et al., 2010). On the other hand, C is also imported into the peatland from surrounding landscapes. Typically leaching is higher from organic, C-rich soils, so it can be assumed that the DC balance at Kalevansuo was negative, i.e., more C was lost than was received from surface waters, but this amount is likely to be so small that it has little significance for the C balance at this site.

We are not aware of other year-round NEE measurements conducted on forestry-drained peatlands. If we also consider other peatland types, the annual CO_2 uptake at our site is the highest among the published values. Flanagan and Syed (2011) reported an average annual sink of 690 $g\,CO_2\,m^{-2}$ over a six year period in a natural treed fen in Canada. At their site, the average GPP (–3100 $g\,CO_2\,m^{-2}$) and R_{tot} (2400 $g\,CO_2\,m^{-2}$)

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were lower than at our site (−3600 and 2800 g CO_2 m^{-2}). Even though their site was natural (undrained), it had as deep or deeper average water table (30–70 cm) than our ditched site, indicating similar aeration in the peat soil. Lowered water table in dry years did not increase C loss from the system, since the increased respiration was compensated by increased photosynthesis.

Higher annual CO_2 balances (i.e. lower C accumulation) have been measured on bogs with sparse or absent tree cover. In Scotland, the annual NEE of an ombrotrophic peatland used for sheep grazing varied from −350 to −500 g CO_2 m^{-2} yr^{-1} (Dinsmore et al., 2010), while in southern Sweden, in an undrained bog with a low tree cover, it was about −80 g CO_2 m^{-2} (Lund et al., 2007). In an ombrotrophic bog with only very small trees in Canada, the annual NEE varied from −40 to −280 g CO_2 m^{-2} (Lafleur et al., 2003), and in an Irish maritime blanket bog with no tree cover NEE ranged between −45 and −310 g CO_2 m^{-2} during six years (Koehler et al., 2011). At this site, a significant proportion of C was lost through leaching and CH_4 emission, resulting in an average C balance of −50 g C m^{-2}.

In contrast, the annual net CO_2 balance was close to zero in a well-drained afforested peatland with an agricultural history in Finland, indicating that the peat decomposition rate outweighed the C accumulation in trees (Lohila et al., 2007). Since the tree growth rate was substantial, this showed that the peat was still vigorously decomposing 30 years after the afforestation. Using combined snap-shot measurements and modelling, Hargreaves et al. (2003) suggested that conifer plantations in Scotland may become net sinks of CO_2 around 4–8 years after afforestation. However, in contrast to our results, after subtracting the tree C accumulation component of NEE, the peat at their ecosystem showed a net loss of CO_2 at a rate of 370 g m^{-2} yr^{-1}.

It is interesting to note that the NEE at Kalevansuo was similar to that observed in the Hyytiälä Scots pine forest, located 150 km to the north of Kalevansuo (Ilvesniemi et al., 2009). The development stage of these Scots pine forests is approximately the same and the most significant difference between the sites is the underlying soil type, which is haplic podzol at Hyytiälä. At this site, the annual balance has varied between

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-510 and $-920\,g\,CO_2\,m^{-2}$ over a ten year period (Ilvesniemi et al., 2009). The annual GPP and R_{tot} were slightly higher at Hyytiälä, -3800 and $3000\,g\,CO_2\,m^{-2}$, respectively, against -3600 and $2800\,g\,CO_2\,m^{-2}$ at Kalevansuo. The higher GPP values are expected, since the trees in Hyytiälä are younger and are thus growing faster, accumulating $240\,g\,C\,m^{-2}\,yr^{-1}$ (Ilvesniemi et al., 2009), i.e. 50 % faster than the tree stand at Kalevansuo ($160\,g\,C\,m^{-2}$). On the other hand, the ground vegetation at Kalevansuo is denser and contributes more to the observed NEE than that at Hyytiälä. The contribution of the ground vegetation is likely to explain why the observed difference in NEE between Hyytiälä and Kalevansuo is smaller than expected on the basis of the tree C accumulation at the sites.

Direct measurements of the sub-canopy CO_2 fluxes have indicated that the ground layer of Kalevansuo was a C source in April-June (Pihlatie et al., 2010). However, this sub-canopy flux consists of not only the NEE of the peat and ground layer vegetation, but also the tree root respiration. Since the contribution of the root-derived respiration to GPP may vary from about 10 to 50 % (Moyano et al., 2009), it is likely that the sum of the tree root and peat respiration overrides the CO_2 sink of the ground vegetation.

4.2 On the factors controlling NEE

Irradiation was not the only significant meteorological variable controlling diurnal dynamics of CO_2 exchange during the growing season. In addition, there was a significant correlation between NEE and VPD, indicating suppression of the photosynthesis of the peatland vegetation under drier conditions. Since NEE is a sum of R_{tot} and GPP, the relationship between NEE and VPD could be partially explained by the increased R_{tot} with higher air temperatures, in addition to the suppressed assimilation. Using standardized environmental conditions we still found a significant correlation between the NEE and VPD (Fig. 8), suggesting that the relationship could be attributed to stomatal closure rather than an increase in ecosystem respiration due to higher temperatures. The strong control of VPD is somewhat surprising, as the maximum

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distance of the ground water level was only about 50 cm from the peat surface in summer (Fig. 9). Hence, water should be rather easily available for the tree roots. The relationship reflects the immediate response of needle stomata to VPD and suggests that the ecosystem C uptake may be weakened during a dry spell due to stomatal restrictions, although water is available for roots. A similar phenomenon of lowered CO_2 uptake during drought has been observed in natural open peatlands (Lafleur et al., 2003; Aurela et al. 2007, 2009) and in non-peatland forests (e.g., Luyssaert et al., 2007; Lasslop et al., 2010).

Introducing the VPD into the NEE-model (Eq. (3)) improved the fit between the measured and modelled values only slightly ($r^2 = 0.88$ against $r^2 = 0.86$). However, it corrected the deviation from the linearity observed at the lowest end of the data (i.e., high CO_2 uptake values) (results not shown), indicating the importance of VPD for the gap-filling modelling during dry periods.

We observed CO_2 uptake at our forest site throughout the winter. In January, for example, when the monthly mean temperature was $-1.2\,^{\circ}$C, photosynthesis was observed when T_{air} exceeded $-3\,^{\circ}$C. In February and March (mean temperatures of $-6.6\,^{\circ}$C and $-8.0\,^{\circ}$C, respectively), photosynthesis was detected only occasionally. Wintertime assimilation by trees has been also reported to take place in the Hyytiälä forest (Sevanto et al., 2006), but photosynthesis was not observed in January there, possibly due to low radiation levels. Sevanto et al. (2006) also observed CO_2 uptake by tree shoots in air temperatures as low as $-7\,^{\circ}$C. At Kalevansuo, a higher T_{air} ($> -3\,^{\circ}$C) was needed for photosynthesis to take place. Our results show that CO_2 uptake may occur in boreal forests throughout the year, depending on meteorological conditions.

By ignoring the wintertime CO_2 uptake in the gap-filling the estimated CO_2 emission during the winter would increase by 8 %, but the effect on the annual balance would be less than 3 %. It can be concluded therefore that the contribution of the winter-time CO_2 uptake to the annual balance was not significant, at least in a winter like 2004–2005 at Kalevansuo. In warmer winters, however, a larger significance of wintertime photosynthesis can be anticipated. It is recommended that at such boreal sites where temperatures close to zero occur regularly, the winter photosynthesis should be taken into account by including an appropriate light response model in gap-filling methods.

4.3 GHG balance and global warming potentials

The annual balance of CH_4 uptake ($-0.12\,g\,m^{-2}\,yr^{-1}$) and N_2O emission ($0.10\,g\,m^{-2}\,yr^{-1}$) for Kalevansuo are in line with those measured from the same (dwarf-shrub) site type in an extensive study covering the whole Finland (Ojanen et al., 2010) and with those measured during a 3-month period at the same site (Pihlatie et al., 2010). CH_4 emissions in natural, undrained bogs, such as Kalevansuo before drainage, are on average $6\,g\,m^{-2}\,yr^{-1}$ (Saarnio et al., 2007). In general, CH_4 emissions are strongly reduced after drainage, and in many cases, CH_4 oxidation in the peat surface overrides the production deeper in the soil. The resulting CH_4 uptake is more typical of fens than bogs with the poorest sites with weakest tree growth often acting as a post-drainage source of CH_4 (Martikainen et al., 1995; Minkkinen et al., 2007b). Considering the climatic impact of an annual pulse emission/uptake of the three greenhouse gases at Kalevansuo, CO_2 was by far the most significant one. Therefore it can be concluded that the drainage of this peatland has not resulted in the site having a net warming impact on climate.

5 Conclusions

This study presents the first year-round NEE data measured on forestry-drained peatland and supports earlier results, obtained by measuring changes in the peat C store, that demonstrated that nutrient-poor peatland forests may accumulate C at the same or even increased rates after drainage. During a 16 month period in 2004–2005, the annual NEE at Kalevansuo varied between -810 and $-900\,g\,CO_2\,m^{-2}$, depending on the start of the period. The increase in tree biomass only explained about 60 % of the C sink. No increase was observed in the ground vegetation biomass either. Therefore, it is likely that C is accumulated into the soil as dead organic matter, i.e., the soil is

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accumulating C as is typical for natural, undrained peatlands. This may be attributed to the increased below-ground productivity and the continuous growth of peat and forest mosses at the site. Simultaneously, the decomposition of soil organic matter has remained at a moderate level because of only a moderate drop in the water table. N_2O emissions had not increased dramatically after the drainage, contributing less than 5 % to the climatic impact of this ecosystem in its current state. CH_4 uptake by the forest soil was practically negligible in comparison with the high cooling impact caused by the net CO_2 uptake. Following on from this study, the fate of CO_2 in the ecosystem should be examined in detail, to understand the mechanisms in the soil and ground vegetation which contribute to the excess C accumulation and the high CO_2 sink at this site. With such understanding, the results could be more easily generalized by incorporating them into biogeochemical process models.

5.1 Appendix A: Gap-filling of the CO_2 exchange data

To estimate E_0 outside the winter, Eq. (1) was fitted to the night-time (PPFD <1 µmol m^{-2} s^{-1}) NEE data in time windows of 15 days, shifting the window five days at a time. E_0, (constrained to > 100 K), was averaged over all periods where (1) the number of data points exceeded 40, (2) the temperature range exceeded 5 K and (3) $E_0 <$ 450 K, resulting in E_0 = 225 K and E_0 = 173 K for the periods of 2 September–18 November 2004 and 11 April–17 November 2005, respectively. The number of accepted/discarded E_0 values was 23/0 and 30/8 in 2004 and 2005, respectively. Thereafter, R_{ref} was estimated for the same periods as described above using Eq. (1) and the constant E_0 values. The obtained parameter values represent the mid-point of each 15-day period, and were interpolated for the missing periods in daily steps.

The parameters of the NEE model (Eq. 3) were also estimated for 15-day subsets shifting the window five days at a time. The values obtained from this were only accepted if the number of the measured flux values was larger than 100 and the parameter values were not considered unrealistic ($GP_{max} > -4$ mg m^{-2} s^{-1}, $\alpha < -0.002$ mg µmol^{-1}).

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In winter, R_{tot} was modelled by fitting Eq. (1) to the night-time (PPFD < 1 µmol m^{-2} s^{-1}) CO_2 flux data, to avoid data with photosynthetic CO_2 uptake. This time, E_0 and T_{ref} were derived commonly from all winter data (17 November 2004–30 March 2005 and 16 November–31 December 2005). Using the resulting parameter values (R_{ref} = 0.0603 mg CO_2 m^{-2} s^{-1} and E_0 = 136 K) and T_{air}, the half-hourly R_{tot} was calculated. Thereafter, Eq. (3) (without f_{VPD}) was fitted to the NEE data measured when $T_{air} > -3\,^{\circ}$C from 18 November 2004–31 January 2005 (the period when photosynthesis was observed) using the modelled R_{tot} as an input value. The α and GP_{max} obtained from this were used to reconstruct NEE for both winter periods, for half-hour periods with $T_{air} > -3^{\circ}$C. With $T_{air} < -3^{\circ}$C the modelled respiration rate was used for gap-filling.

For the 10-day gap in spring 2005, the daily modelled R_{tot} and GPP and their correlation with air temperature and irradiation, respectively, were used. In addition, since the emergence of photosynthesis after the winter occurred during this gap, we used a linearly increasing photosynthesis factor in the gap-filling of GPP data. This factor was given a value from 0 to 1, which was derived from the difference between the average GPP of the five days preceding and following the gap.

Acknowledgements. The Kalevansuo site was set up during the Research Program "Greenhouse Impacts of the Use of Peat and Peatlands in Finland" (2002–2005), with funding from Ministry of Agriculture and Forestry and Ministry of Trade and Industry. The financial support by the European Commission through the projects NitroEurope (017841) and GHG Europe (244122), and by the Academy of Finland Centre of Excellence program (project 1118615) are gratefully acknowledged. Thanks are due to Arska Halm for technical help and Juha Hatakka for constructing the data acquisition system. Tiina Badorek, Raimo Jaatinen, Soili Kojola, Timo Haikarainen, Ismo Kyngäs, Inkeri Suopanki and Tea Thum are thanked for the field work, data processing and maintenance of the measurements. We are grateful to Sotainvalidien veljesliitto (Disabled War Veterans Association of Finland) for allowing us to draw a power cable from their premises. Metsähallitus (Finnish Forest and Park Service) is acknowledged for permitting the establishment of the study site on their land.

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Table 1. Soil characteristics and element concentrations at the surface peat at Kalevansuo.

Soil layer	Bulk density ($kg\,m^{-3}$)	Ash content	C (%)	N (%)	C/N	Al^1	Ca^1	Fe^1	K^1	Mg^1	Mn^1	P^1	B^1	Cu^1	Mn^1	Zn^1
Humus	–	2.4	49	1.2	41	210	4000	260	3100	880	260	1000	4.6	5.5	260	63
0–10 cm	81 ± 9	2.9	50	1.5	34	800	2400	1000	470	460	56	680	1.9	4.7	56	56
10–20 cm	106 ± 8	2.0	51	1.4	38	740	1300	950	140	260	5.2	450	0.73	1.4	5.2	16

1 = total amount of the element in $mg\,kg^{-1}$

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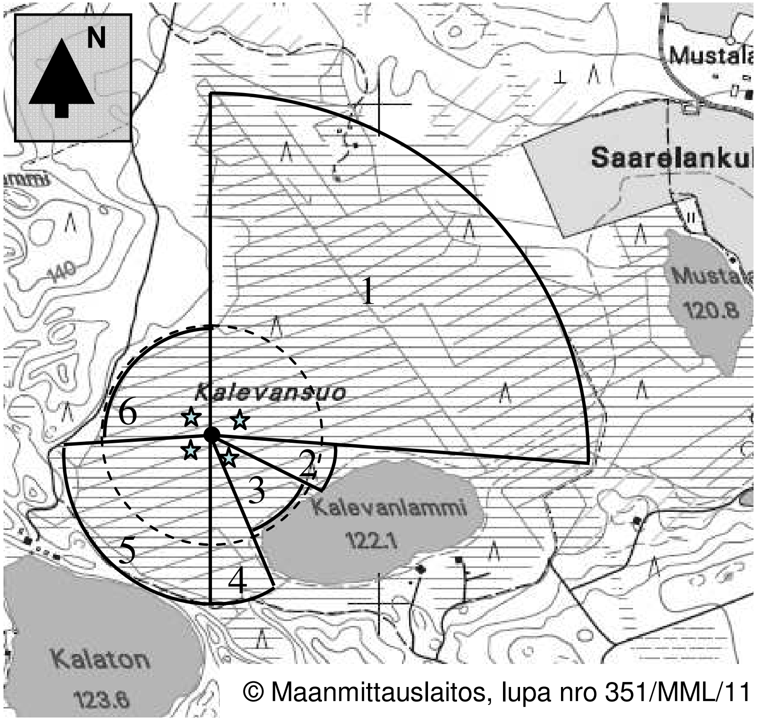

Fig. 1. Map of the Kalevansuo drained peatland showing the location of the EC measurement mast (black circle) and the chamber measurement plots (stars). The black solid lines indicate the borders of the sectors (1–6) used in the footprint analysis. The dashed circle shows the distance of 200 m from the mast. The main drainage ditch that empties towards the south-east and the smaller ditches that empty into the main ditch have been indicated by the gray solid lines. The two lakes, Kalaton and Kalevanlammi, located on the borders of the site are indicated in the map together with their elevation from the sea level.

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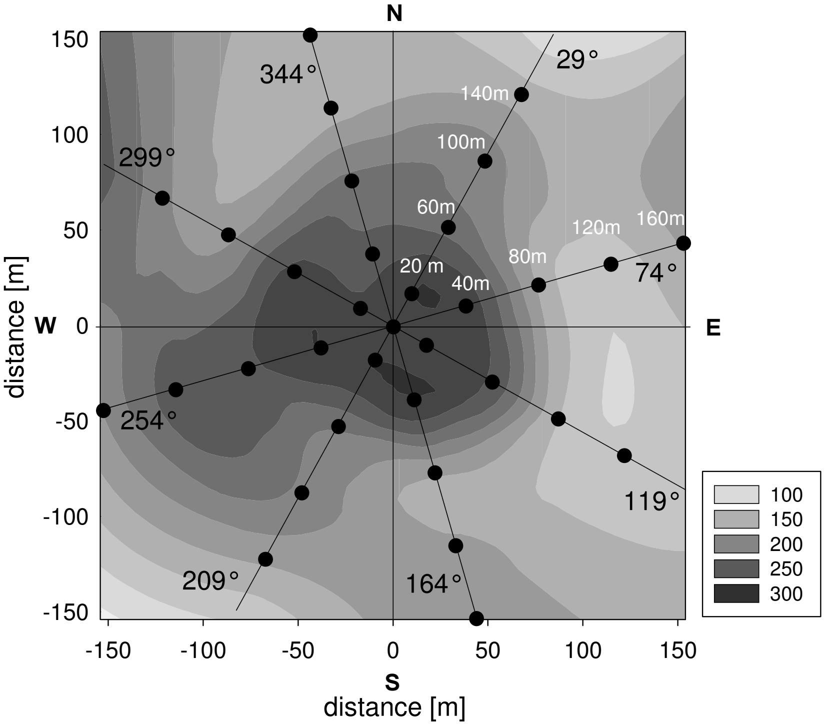

Fig. 2. Peat depth (cm), interpolated as a contour plot, around the EC flux measurement mast (at (0,0)) at Kalevansuo. The black dots show the locations of the tree stand and peat depth measurement points ($n = 33$), with the directions of lines and the distances of points from the EC mast indicated. The lines 344° and 164° were perpendicular to the drainage ditches while the lines 74° and 254° were parallel to the ditches. The distances from the centre of the plot on lines 119°, 209° and 299° follow those depicted for line 29°, and the distances of the points on lines 164°, 254° and 344° follow those depicted for line 74°.

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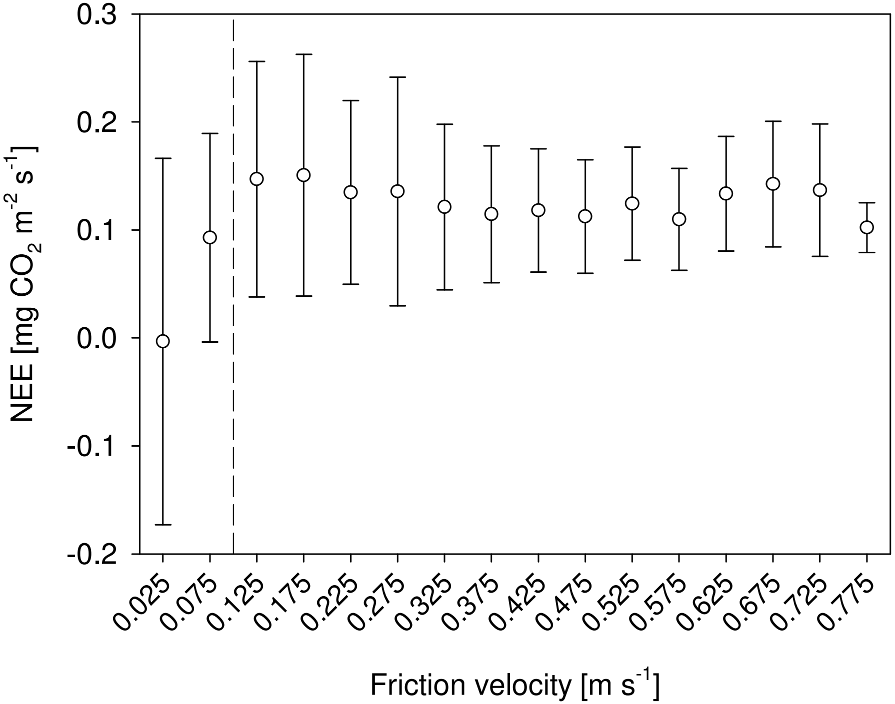

Fig. 3. Average night-time CO_2 flux (± SD) in the growing season 2005 plotted against the friction velocity. Data were grouped into u_* classes of 0.05 m s^{-1}. The u_* limit below which the data was rejected from the further analysis, 0.1 m s^{-1}, is indicated with the dashed line.

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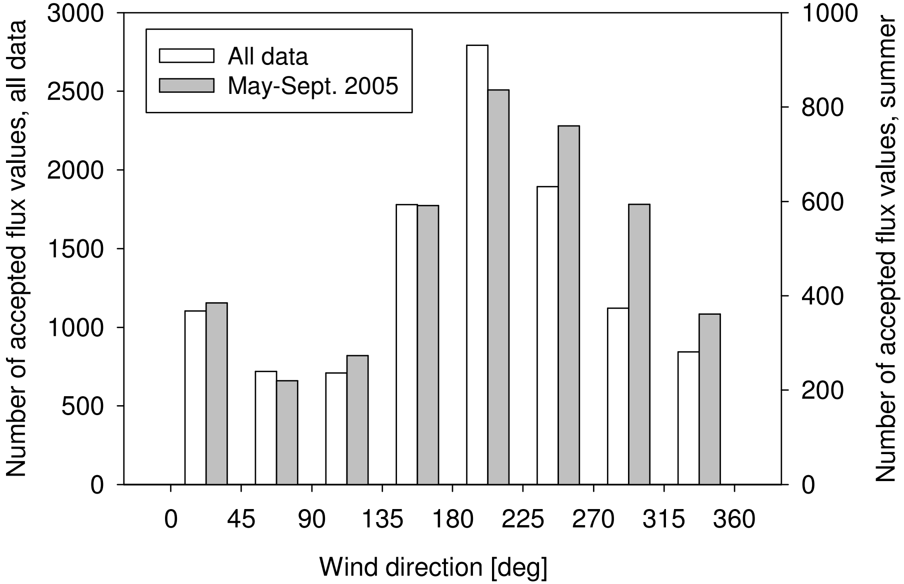

Fig. 4. Number of the accepted CO_2 flux data separated into different wind direction sectors at 45° intervals. Data are shown for the periods of September 2004–December 2005 (white bars) and May–September 2005 (gray bars) (note different y-axes).

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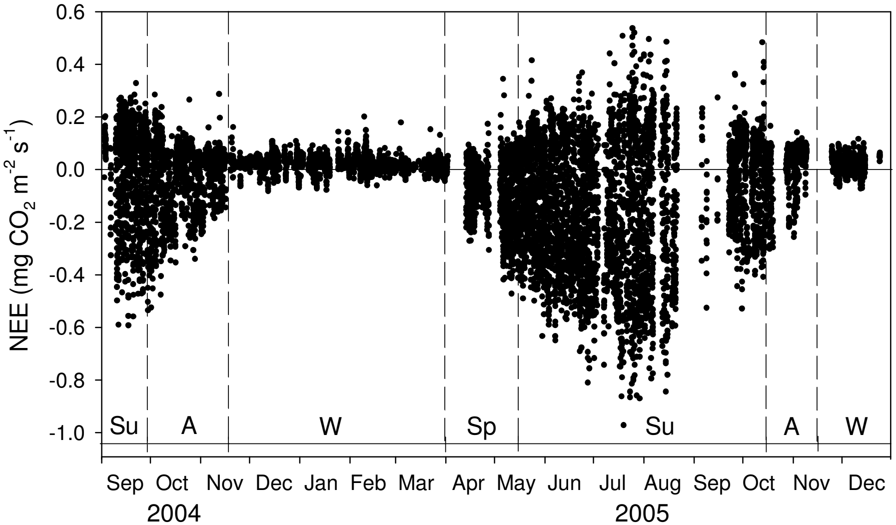

Fig. 5. Time series of the accepted half-hourly measurements of the CO_2 exchange at Kalevansuo in September 2004–December 2005. Positive values indicate emission of CO_2 from the ecosystem to the atmosphere. Letters indicate meteorologically defined seasons (Su = summer, A = autumn, W = winter, Sp = spring).

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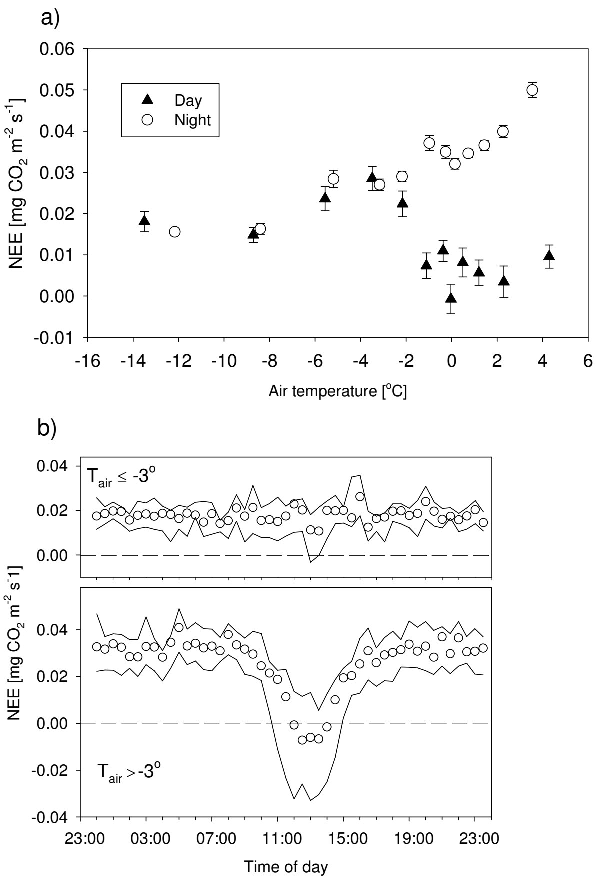

Fig. 6. **(a)** Average (± SE) nocturnal and day-time (PPFD<1 and PPFD>1 µmol m^{-2} s^{-1}, respectively) NEE plotted against air temperature in winter. The data are grouped into 12 classes with equal amount of observations ($n = 170$ and $n = 93$ in night and day, respectively). **(b)** Half-hourly medians (± 25th and 75th percentiles) of measured NEE in winter when air temperature is below −3 °C (upper graph) and above −3 °C (lower graph).

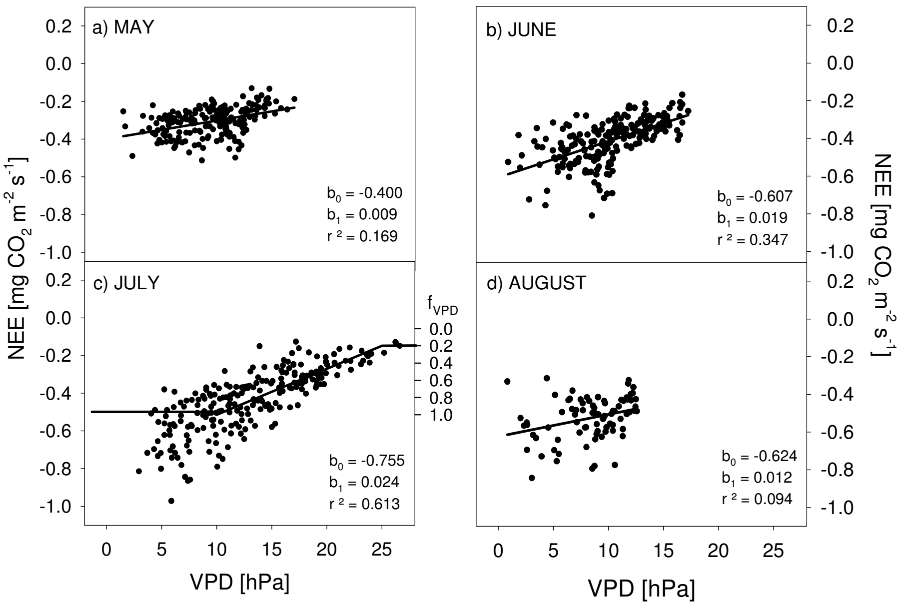

Fig. 7. Half-hourly NEE measured during high irradiance (PPFD>1000 µmol m^{-2} s^{-1}) plotted against vapour pressure deficit (VPD) in May–August 2005. The parameter values of the linear regression (NEE = b_0 + b_1 × VPD) are shown. In c) the line shows the f_{VPD} function used in Eq. (3), defined according to the regression for the July data.

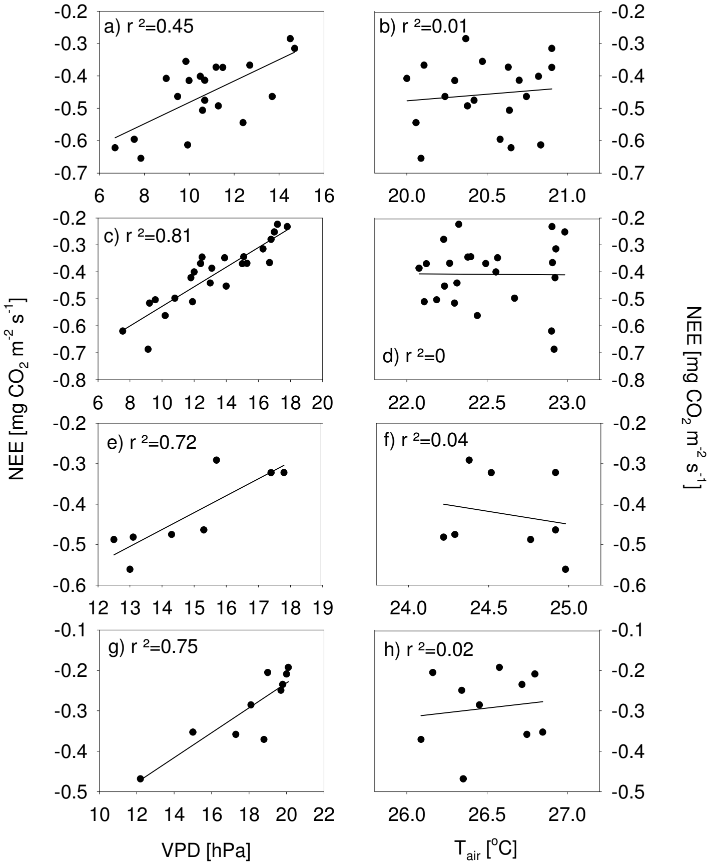

Fig. 8. Measured half-hourly NEE (PPFD>1200 µmol m^{-2} s^{-1}) plotted against VPD (left panel) and air temperature (right panel) in temperature ranges 20–21 °C **(a, b)**, 22–23 °C **(c, d)**, 24–25 °C **(e, f)** and 26–27 °C **(g, h)**. Parallel plots represent the same NEE data.

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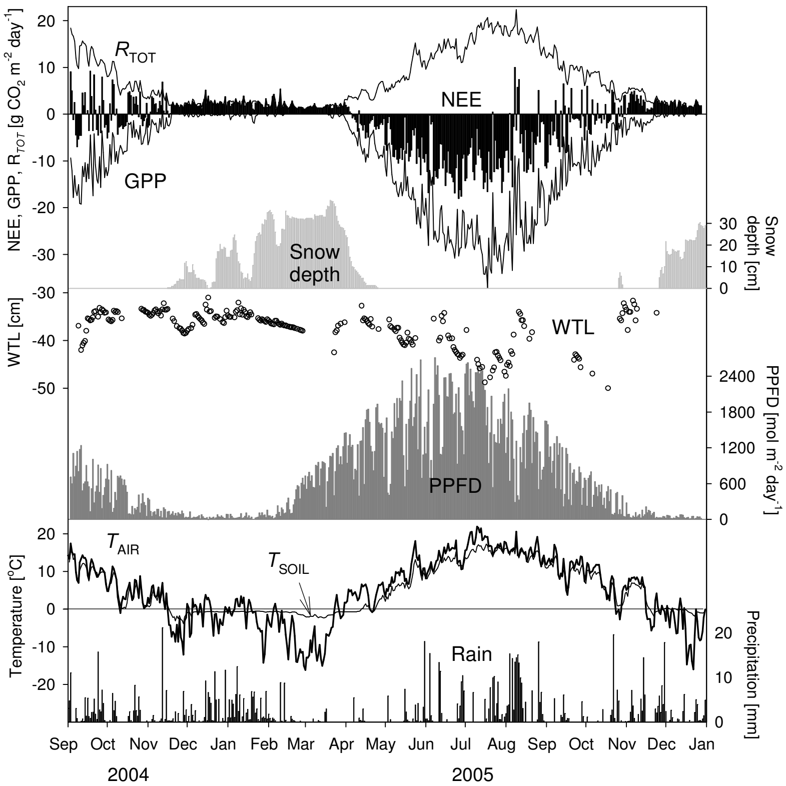

Fig. 9. Daily NEE (top black bars), modelled R_{tot} and GPP (lines in the upper panel), snow depth (light gray bars), water table depth (WTL; open circles), daily cumulative photosynthetic radiation (PPFD, dark gray bars), daily air temperature (thick line in the bottom), daily soil temperature at 5 cm depth (thin line in the bottom), and precipitation (black bars in the bottom) at Kalevansuo peatland forest from September 2004 to December 2005. The snow depth and precipitation data represent the average of the four nearest weather stations.

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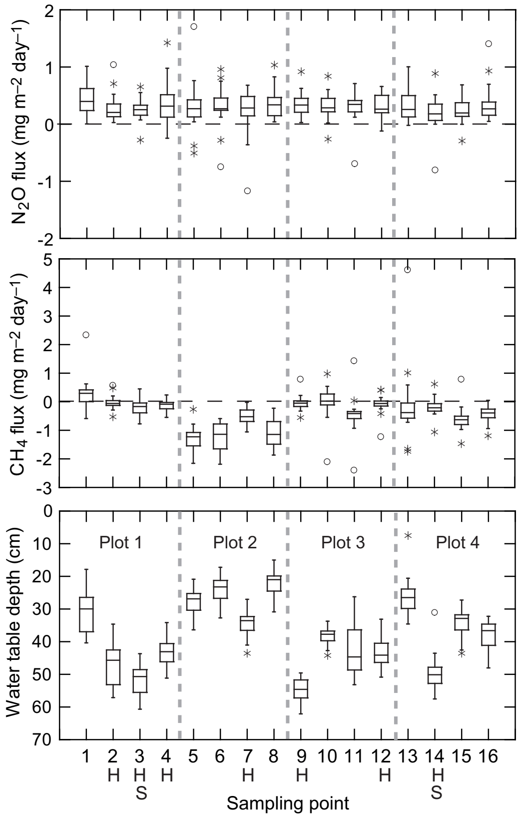

Fig. 10. Box plot of N_2O and CH_4 fluxes and water table levels in 16 sampling points at four plots around the EC mast in the Kalevansuo drained peatland forest. H = hummock, S = Sphagnum-dominated community (others forest-moss-dominated). The box plot shows the distribution of the data: The box shows the quartiles (lower edge 25 %, upper edge 75 %) and median (band inside box) of the data. The whishers show data that falls within 1.5 × box height (interquartile range, IRQ) and asterixes 3 × IRQ. Circles show data that fall outside these limits and are considered outliers (Systat 12, Systat software).

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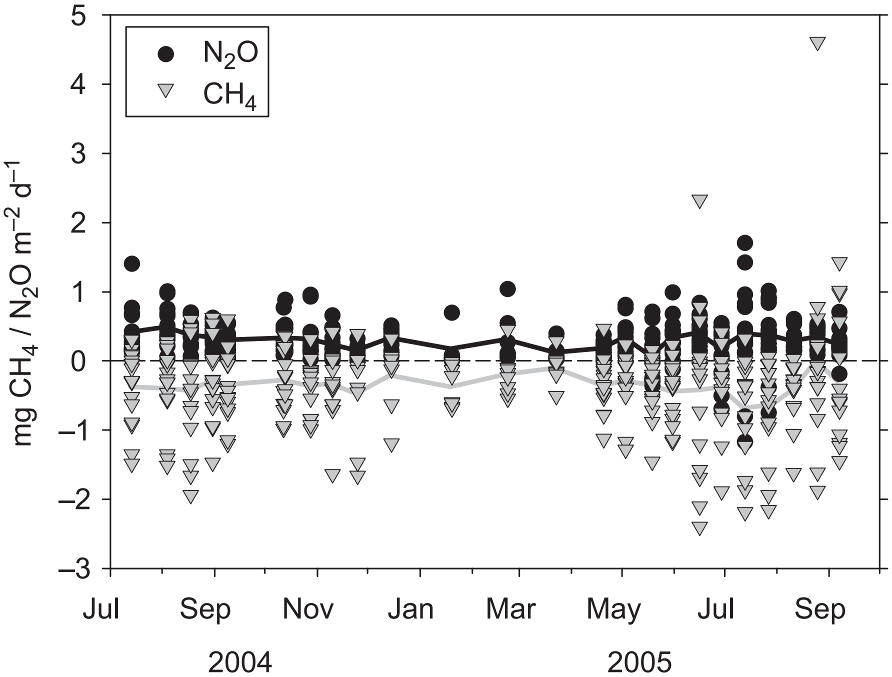

Fig. 11. Observed (circle and triangle), mean, and interpolated (black and grey lines) daily N_2O and CH_4 fluxes, measured by closed chambers in 24 days in Kalevansuo during 2004–2005.

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