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Contemporary carbon accumulation in a boreal oligotrophic minerogenic mire – a significant sink after accounting for all C-fluxes

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Abstract

Based on theories of mire development and responses to a changing climate, the current role of mires as a net carbon sink has been questioned. A rigorous evaluation of the current net C-exchange in mires requires measurements of all relevant fluxes. Estimates of annual total carbon budgets in mires are still very limited. Here, we present a full carbon budget over 2 years for a boreal minerogenic oligotrophic mire in northern Sweden (64°11′N, 19°33′E). Data on the following fluxes were collected: land–atmosphere CO_2 exchange (continuous Eddy covariance measurements) and CH_4 exchange (static chambers during the snow free period); TOC (total organic carbon) in precipitation; loss of TOC, dissolved inorganic carbon (DIC) and CH_4 through stream water runoff (continuous discharge measurements and regular C-concentration measurements). The mire constituted a net sink of 27 ± 3.4 ($\pm$ SD) $g\,C\,m^{-2}\,yr^{-1}$ during 2004 and $20 \pm 3.4\,g\,C\,m^{-2}\,yr^{-1}$ during 2005. This could be partitioned into an annual surface–atmosphere CO_2 net uptake of $55 \pm 1.9\,g\,C\,m^{-2}\,yr^{-1}$ during 2004 and $48 \pm 1.6\,g\,C\,m^{-2}\,yr^{-1}$ during 2005. The annual NEE was further separated into a net uptake season, with an uptake of $92\,g\,C\,m^{-2}\,yr^{-1}$ during 2004 and $86\,g\,C\,m^{-2}\,yr^{-1}$ during 2005, and a net loss season with a loss of $37\,g\,C\,m^{-2}\,yr^{-1}$ during 2004 and $38\,g\,C\,m^{-2}\,yr^{-1}$ during 2005. Of the annual net CO_2-C uptake, 37% and 31% was lost through runoff (with runoff $TOC > DIC \gg CH_4$) and 16% and 29% through methane emission during 2004 and 2005, respectively. This mire is still a significant C-sink, with carbon accumulation rates comparable to the long-term Holocene C-accumulation, and higher than the C-accumulation during the late Holocene in the region.

Keywords: boreal mire, carbon balance, DOC, Eddy covariance, methane, NECB, NEE, peat, runoff, *Sphagnum*, TOC

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Introduction

Boreal mires cover 3% of the earth's land area, but contain a quarter to a third of the global pool of soil organic carbon (Gorham, 1991; Turunen *et al.*, 2002). The global estimate for long-term apparent carbon accumulation (LARCA) rates in mires approximates 15–$30\,g\,C\,m^{-2}\,yr^{-1}$ (Gorham, 1991; Turunen *et al.*, 2002). Based on an extensive data set, using 1300 peat cores from Finnish mires, the area-weighted, average, long-term (Holocene) apparent C-accumulation has been estimated at $18\,g\,C\,m^{-2}\,yr^{-1}$, with an average for minerogenic mires of $17\,g\,C\,m^{-2}\,yr^{-1}$ (Turunen *et al.*, 2002).

Peatlands are known to interact in important, and often neglected, ways with the climate system through

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the long-term accumulation of atmospheric carbon dioxide and release of methane (Klinger *et al*., 1996; Frolking & Roulet, 2007). Furthermore, the current carbon sink potential of mire ecosystems has been questioned, on the basis of both empirical measurements (Oechel *et al*., 1993, 1995; Oechel & Vourlitis, 1994; Christensen *et al*., 1999) and theories of mire development (e.g. Clymo, 1984; Belyea & Baird, 2006). The growth of mires is believed to eventually lead to the cessation of carbon accumulation through two processes. Firstly, as peat accumulates, decomposition (at even very low rates) in the lower levels will eventually lead to the production of gaseous carbon (CO_2 and CH_4) equaling the rate of photosynthetic C-fixation at the surface. Secondly, the gradual rising of the mire surface relative to the local groundwater table level increases the depth of the aerated zone below the mire surface, promoting degradation of the mire plant litter and reductions in the incorporation of peat in the catotelm. In addition to the uncertainty about their current role in carbon sequestration, the effects of climate change on carbon exchange in peatlands are also of concern (Moore *et al*., 1998; Belyea & Baird, 2006).

The carbon balance of mires comprises an intricate balance of additions and losses of carbon, many of which are sensitive to changes in temperature and/or precipitation. Additions of carbon occur via photosynthetic carbon fixation and inputs of organic carbon through water recharge from surrounding areas and precipitation. C-losses occur through the release of both carbon dioxide and methane from the mire surface to the atmosphere and via C-exports in water runoff from the mire. Runoff-C losses comprise C lost in the forms of total organic carbon (TOC), methane and dissolved inorganic carbon (DIC). The net land–atmosphere (vertical) exchange of CO_2-C is referred to as net ecosystem exchange (NEE). This measure does not distinguish between gross fluxes of CO_2-uptake and CO_2-loss, nor does it include land–atmosphere exchange of CH_4 or horizontal C-fluxes in and out of the system. As suggested by Chapin *et al*. (2006), we use the term 'net ecosystem carbon balance (NECB)' when referring to total fluxes, considering all contributory fluxes of carbon in and out of the mire ecosystem.

To acquire data concerning current rates of mire C-exchange for comparison with estimates of long-term carbon accumulation rates based on peat cores, complete annual C-exchange budgets are required. A few estimates of total annual budgets of carbon exchange in mires have been published. Notably, a 6-year study of the ombrotrophic mire Mer Bleu, in southern Canada, included all significant fluxes and estimated the annual net C-exchange ($\pm$ SD) to be $21 \pm 39\,g\,m^{-2}\,yr^{-1}$ (Roulet *et al*., 2007). Estimates of NECB based on combinations of data from different mire sites and/or years (e.g. Rivers *et al*., 1998; Worrall *et al*., 2003; Billett *et al*., 2004), or combinations of both measured and modeled data (Clair *et al*., 2002; Worrall *et al*., 2003), have also been published. Although few in number, these estimates indicate that the current total C-exchange in mires varies between them being in balance and being net sinks. However, there are large variations in annual fluxes of NEE (Lafleur *et al*., 2003; Aurela *et al*., 2004; Roulet *et al*., 2007), methane emissions (Granberg *et al*., 2001a; Nilsson *et al*., 2001) and stream-C fluxes (Kortelainen *et al*., 1997; Elder *et al*., 2000; Roulet *et al*., 2007) both between sites and between years, reflecting the strong influences of mire type and annual weather conditions. These variations make merging data from different sites or years difficult, and prone to error. In addition, any responses of peat-C accumulation rates to climate change are likely to differ between mire types, due to differences in the relative importance of the component C-fluxes and differences in the climatic effects on each of the fluxes. Thus, measurements of complete C balances from individual sites are highly important for attempts to elucidate and predict responses of the 'net ecosystem carbon balance' (NECB) of mires to climate change.

The overall aim of this study was to produce a complete annual net carbon budget for a typical representative of one of the most common boreal mire types (e.g. Eurola *et al*., 1984; Zoltai *et al*., 1988), based on measurements of all C-exchanges. To achieve this, we used established measurement systems to collect data from a minerogenic oligotrophic mire in northern Sweden over 2 consecutive years (2004 and 2005).

Methods

Site description

The study was conducted within the Degerö Stormyr mire complex (64°11′N, 19°33′E), a mixed acid mire system covering 6.5 km^2 situated in the Kulbäcksliden Experimental Forest near Vindeln in the county of Västerbotten, Northern Sweden. The mire, which consists of a complex system of interconnected smaller mires divided by islets and ridges of glacial till, is situated on high land (270 m a.s.l.) between two major rivers, the Umeälven and Vindelälven, approximately 70 km from the Gulf of Bothnia. The peat depth is mainly between 3 and 4 m, but depths of 8 m have been measured. The deepest peat layers correspond to an age of $\sim$8000 years.

The part of the mire complex used for the measurements of CO_2 and methane exchange presented here is a minerogenic oligotrophic mire, [i.e. poor fen (Eurola

et al., 1984)], dominated by lawn and carpet plant communities (Fig. 1). The vascular plant community on this part of the mire is dominated by *Eriophorum vaginatum* L., *Trichophorum cespitosum* (L.) Hartm., *Vaccinium oxycoccos* L., *Andromeda polifolia* L. and *Rubus chamaemorus* L., with both *Carex limosa* L. and *Schezeria palustris* L. occurring more sparsely. *Carex rostrata* L. is characteristic in areas with direct minerogenic water inflow. The bottom layer of the carpets (approximate average water table level during the growing season 0–10 cm below the mire surface) is dominated by *Sphagnum majus* Russ. C. Jens, and the lawns (approximate average water table level during the growing season 10–25 cm below the mire surface) by *S. balticum* Russ. C. Jens., and *S. lindbergii* Schimp., while *S. fuscum* Schimp. Klinggr. and *S. rubellum* Wils. dominate on the more sparse hummocks.

The area of the mire used for the flux measurements is part of the Vargstugbäcken subcatchment. Subcatchment boundaries of the catchment (including ~33% of the total mire area of 6.5 km^2) were delimited on the basis of field observations and a 50 m grid, 10 cm vertical resolution digital elevation model (DEM) using the 'watershed' function in IDRISI 14 software (Clark Labs, Worcester, MA, USA). The catchment area was determined to be 3.1 km^2, with 69% of the area consisting of mire and 31% of the area underlain by till and covered by coniferous forest. The mire area within the catchment is dominated by minerogenic oligotrophic mires, [i.e. poor fen (Eurola *et al.*, 1984)], dominated by lawn and carpet plant communities, as is the area used for the EC-measurements. Peat and till distributions were determined from a 1 : 100 000 scale digital quaternary sediments coverage map (Geological Survey of Sweden, Uppsala, Sweden), and the forest area was delimited using a 1 : 50 000 scale digital land-cover map (Lantmäteriet, Gävle, Sweden). The forested areas are at the far reaches of the catchment relative to the stream, which originates as an upwelling near the NW corner of the catchment and flows NW. Thus, drainage water originating in the forested area must pass through at least 950 m (horizontal distance) of peat en route to the stream.

The climate of the site is defined as cold temperate humid. Based on data from the closest (4 km north of the measurement site) national reference climate station, Kulbäcksliden (64°12′N, 19°34′E, altitude 200 m a.s.l.), the 30-year mean (1961–1990) annual precipitation is 523 mm and mean annual, July and January temperatures based on the same period are +1.2, +14.7 and −12.4 °C, respectively (Alexandersson *et al.*, 1991). The length of the *growing season*, defined

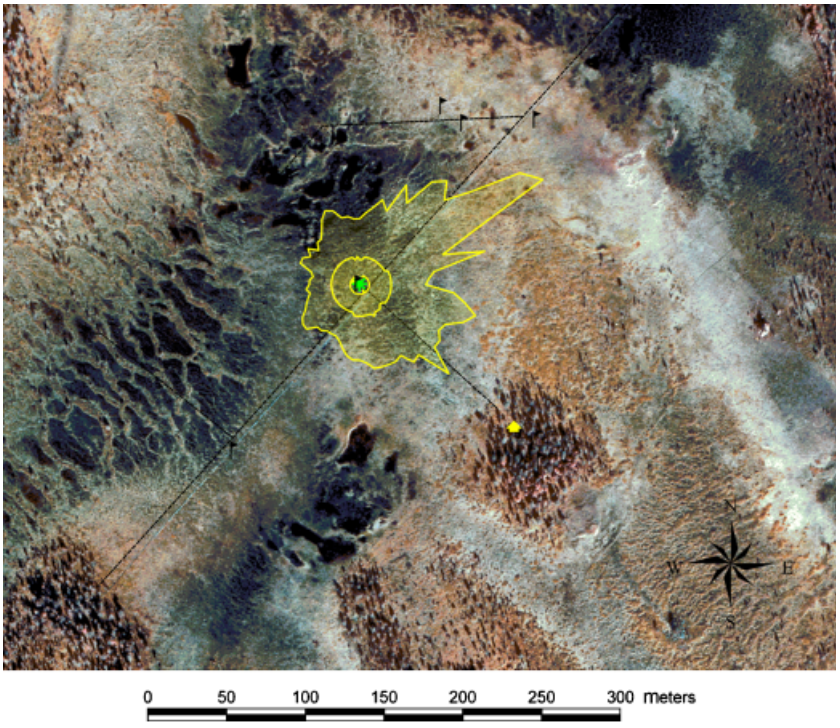

Fig. 1 Aerial photograph of Degerö Stormyr. The yellow-tinted area inside the periphery contributes 90% of the total 30 min measurements of the CO_2-exchange, example from summer 2003 (0306–0309). The outer line represents the night-time footprint and the middle line the daytime footprint. The footprint inside the innermost circle corresponds to 5% of the measurements. The green star shows the location of the tower. Black flags represent sites of other experiments at the site.

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as the period in which daily mean temperature exceeds + 5 °C (Ångström *et al*., 1974), was 157 ± 7 days during each year in the measuring period (2004–2005) (Ottosson-Löfvenius, 2005, 2006). The snow cover normally reaches depths up to 60 cm and lasts for 6 months on average.

Air and soil measurements

Instruments for measuring meteorological variables and Eddy covariance measurements of CO_2 were mounted in a 4 m tower located 200 m from the southeast border in the center of the mire, accessed by boardwalks (Fig. 1). All data were collected and stored on a computer in a hut 150 m south of the tower. Electrical power (240 V AC) was available at the site. Air and soil temperatures, air humidity, radiation (net, global and photosynthetically active) and depth of the water table were monitored continuously. During winter, the snow depth was also monitored continuously. The sensors were either mounted on the same tower as the Eddy covariance system or placed in representative plant community areas within 100 m of the tower. Air temperature and humidity were measured using a temperature and moisture sensor (Rotronic-MP100; Rotronic AG, Bassersdorf, Switzerland) mounted 1.8 m above the mire surface beside the eddy-flux system and inside a radiation protection shield. Snow cover depth was measured using an ultrasonic sensor (SR-50; Campbell Scientific, Logan, UT, USA) placed approximately 6 m from the flux-tower. Water table depth and soil temperatures were measured in a lawn plant community 100 m northeast of the flux tower. Peat surface and water table surface were measured using a float and counterweight system attached to a potentiometer (Roulet *et al*., 1991). Soil temperature was measured using thermistors mounted in a sealed, waterproof, stainless steel tube (TO3R; TOJO Skogsteknik, Djäkneboda, Sweden) at depths of 2, 5, 8, 16, 24 and 32 cm. Precipitation was measured using a tipping-bucket (ARG 100; Campbell Scientific) located 4 m from the tower. To account for the systematic underestimation in precipitation measurements, the recorded values were multiplied by a correction factor of 1.1, according to Eriksson (1983). Data from radiation sensors were collected at 10 s intervals and temperature sensors at 10 min intervals and stored as 30 min mean values on data loggers (CR10X; Campbell Scientific), then downloaded daily to the main computer in the hut.

Eddy covariance measurements

The Eddy covariance measurement system (*In Situ* Flux AB, Ockelbo, Sweden) consisted of a three-dimensional (3-D) sonic anemometer (model R3 Research; Gill Instruments, Lymington, UK) and a closed-path infrared gas analyzer (IRGA, model LI-6262; LI COR, Lincoln, NE, USA). The 3-D sonic anemometer was mounted on the tower (7.5 cm in diameter), 1.8 m above the surrounding mire and positioned on a 1.0 m long boom oriented in a northerly direction. During the winter, the measurement height was adjusted frequently to ensure that it remained 1.8 m above the snow surface. Signals from the 3-D sonic anemometer, which was heated when air temperatures dropped below 0 °C, were acquired on a computer that calculated the fluxes in real-time using ECOFLUX software (*In Situ* Flux AB, Ockelbo, Sweden). Data were stored as both 10 Hz raw data and 30 min averages. Schotanus correction (Schotanus *et al*., 1983) for sensible heat flux was applied and the water vapor concentration was adjusted using reference measurements from a MP100 hygrometer (Rotronic AG) to correct the latent heat flux after comparison with the IRGA data. The CO_2 measurements from the IRGA were adjusted against a reference gas, based on calibrations undertaken approximately every 2 weeks. The determination of fluxes followed the Euroflux methodology (Aubinet *et al*., 2000). The proportions of accepted data, based on half-hour flux values, following the protocol in Sagerfors *et al*. (2008) were 65% and 82% for 2004 and 2005, respectively. The higher proportion of data lost during 2004 was mainly due to system failures during the winter time. Gap-filling over even longer time periods during the winter time period had a minor influence on the annual budget calculations (Sagerfors *et al*., 2008).

A negative flux designates an uptake of carbon by the mire, a positive flux an efflux. The day when the mire switched between being a sink and a source with respect to the daily NEE was defined as the first day in a 7-day period when the 7-day moving average NEE changed sign. Gap-filling was performed according to the mean diurnal variation (MDV) method (Greco & Baldocchi, 1996; Jarvis *et al*., 1997; Sagerfors *et al*., 2008). Further details on the Eddy covariance measurements, ECOFLUX software and gap-filling can be found in Sagerfors *et al*. (2008).

A random error corresponding to a SD of 20% was applied to the 30 min fluxes (Morgenstern *et al*., 2004; Humphreys *et al*., 2006), both for the measured and gap-filled 30 min values and the same approach was also applied to the gap-filled data for the daily means. The total annual uncertainty (SD) was then calculated as the square root of the sum of the respective variances. The estimated error of the average annual NEE includes the following components: random measurement errors, σ_m; errors from the gap-filling, σ_{gf} and between-year variation, σ_{byv},

caused by climatic differences. It is calculated as follows:

$$\sigma_{tot} = \sqrt{\sigma_m^2 + \sigma_{gf}^2 + \sigma_{byv}^2}.$$

Methane exchange measurements

Methane emissions were measured using opaque static chambers (0.5 m × 0.5 m × 0.3 m) that were placed on permanent stainless steel frames, inserted 0.15 m into the mire surface. A total of 15 chambers were used, of which 12 were installed in carpet plant communities and three in lawn plant communities. Together, these plant communities were representative of the source area for the Eddy covariance CO_2-flux measurements. To calculate representative average methane emission rates for the Eddy covariance source area, the two plant communities were given equal area weightings (0.5). The areal estimates of the two plant communities were based on field-supervised analysis of an IR photo (Fig. 1) of the area. To include the effects of potential errors in the estimated proportions of the two different plant communities, we estimated methane emissions with 10% changes in the proportions (i.e. with either 40% lawns and 60% carpets or 60% lawns and 40% carpets), and included the effects of these potential errors in the estimated uncertainties for both annual methane release and the NECB.

Gas samples were collected with a syringe, fitted with a three-way stop valve, through a 1.5 m length of Teflon tubing, then transferred to evacuated glass vials, where they were allowed to equilibrate to atmospheric pressure before analysis. Gas samples were taken at the time that the chamber was installed, then every second minute up to 6 min. The concentration of methane in the samples was analyzed using a gas chromatograph (Auto System; Perkin Elmer, Waltham, MA, USA) equipped with a flame ionization detector (FID). During 2004, the setup was as follows: stainless steel column, outer diameter 1/8″, inner diameter 2.2 mm, length 2.4 m, packed with Haysep Q 80/100 mesh, with helium as the carrier gas supplied at 70 mL min^{-1}. The temperatures in the injector, oven and detector were 50, 35 and 100 °C, respectively. During 2005, a different column with Haysep N, 80/100 mesh was used (outer diameter 1/8″, i.d., 2.2 mm, length 2.0 m) with nitrogen as the carrier gas, supplied at 40 mL min^{-1}; the rest of the setup was the same. The rate of methane emission was estimated by linear regression of the change in concentration over time. We used the criteria described by Granberg *et al*. (2001b) to select acceptable rate estimates. Methane fluxes were measured approximately every second week during the snow free season, and daily flux rates were derived by interpolation between the measurement occasions. The amount of methane emitted outside the measurement period was assumed to constitute 20% of the annual release (Dise, 1992; Melloh & Crill, 1996; Alm *et al*., 1999), evenly distributed over the entire season.

TOC in precipitation

To estimate the amount of TOC added to the mire via wet deposition, we combined data on TOC concentrations and precipitation. The concentration of TOC was estimated from seasonally bulked samples ($N = 20$) from a climate reference site 10 km northeast of Degerö Stormyr, for the period 1994–1998. TOC was analyzed as described in 'Stream C Methods'. Data on precipitation were obtained from the rain gauge at the mire.

Catchment discharge measurements

Hourly stream discharge was calculated by taking measurements of stream height from water height loggers (wt-hr logger; Trutrack Inc., Christchurch, New Zealand) at a V-notch weir and applying them to an established height–discharge rating curve. Height measurements were not available from the stream site during 45% of the study period, mainly during the winter when stream flow was very low, and ice and freezing temperatures made height measurements unreliable. During these periods, stream flow was estimated for the site using a calibrated ratio of flow between this site and a 50 ha reference stream 10 km north of Degerö Stormyr (Ågren *et al*., 2007; Buffam *et al*., 2007) at which flow is measured at a V-notch weir in a heated dam house.

Stream C methods

Stream water samples were taken frequently during the high-flow snow melt season (every 2–3 days) and less frequently during the rest of the year (weekly to monthly). Samples for pCO_2 and CH_4 headspace gas analysis were collected in N_2-filled 60 mL glass vials, sealed with bromobutyl rubber septa. For each gas sample, a 15 mL aliquot of bubble-free stream water was injected into the glass vial and subsequently acidified to pH 2–3 with ultrapure HCl (0.5% v/v). Sampling for TOC consisted of collecting grab samples, with multiple rinses of stream water, in acid-washed 250 mL high-density polyethylene bottles. Samples were kept cool and dark for up to 1 week, but usually <2 days, until processing. During 2004, samples were filtered through a 0.45 µm syringe-driven sterile filter (Millex-HA MCE, Millipore Ireland B.V., Tullagreen, Carrigtwohill, Co. Cork, Ireland) and were then frozen until analyzed.

During 2005, TOC samples were frozen without filtration until analysis. A comparison covering the extremes of observed flows showed that filtering made no detectable difference to the TOC concentration.

Stream water samples were collected at two sites along the Vargstugbäcken stream: an upstream site at the upwelling that forms the source of the stream and drains a catchment area of 2.9 km^2, and a second site 250 m downstream (3.1 km^2 catchment) at which a permanent V-notch weir is installed for measuring discharge. Based on previous results, TOC concentrations and pH were not significantly different between the two sites, and for this study TOC and pH samples were taken from the downstream site. However, concentrations of CO_2 and CH_4 were always higher at the upstream than at the downstream site, due to degassing in the intervening stream length. Thus, because the goal of this study was to measure fluxes exiting the mire complex, gas samples were taken from the upstream site, except for 21% of the sampling occasions, when gas samples from the upstream site were not available. On these occasions, CO_2 concentrations at the upstream site were estimated from concentrations at the downstream site, using the mean ratio of upstream to downstream concentrations calculated from occasions when both were available [$CO_{2(up)}/CO_{2(down)} = 2.2 \pm 0.5$ ($\pm$ SD), $n = 11$]. In contrast to CO_2, CH_4 degassing occurred very quickly from the stream and thus CH_4 at the downstream site could not be used to estimate CH_4 inputs at the upstream site. For the missing sampling occasions, the mean value of CH_4 from the other sampling occasions [0.8 ± 1.1 mg C L^{-1} ($\pm$ SD), $n = 40$] was substituted. Because stream CH_4 concentrations were too low to contribute substantially to the C-flux, this uncertainty has no effect on the uncertainty in the overall C balance.

Total organic carbon was measured by combustion and analysis as CO_2 using a Schmidzu TOC-V_{CPH} (Shimadzu Scientific Instruments, CO, USA) analyzer after acidifying and sparging the samples to remove inorganic carbon. Instrument precision based on replicate injections averaged 2% and was always better than 5%. The pH was measured at room temperature using a Ross 8102 low-conductivity combination electrode (Thermo Fisher Scientific Inc., Waltham, MA, USA) in the laboratory immediately after collection. Partial pressures of headspace CH_4 and CO_2 were analyzed by gas chromatography using either a Varian 3800 (Varian Inc. Corporate, Palo Alto, CA, USA) equipped with a Haysep DB column and N_2 as the carrier gas (Klemedtsson *et al*., 1997), or a Perkin Elmer Auto System gas chromatograph (see 'Methane exchange measurements'). Stream water CH_4 concentrations were calculated from the headspace CH_4 concentrations using a value of 0.0013 mol L^{-1} for CH_4 solubility (Stumm & Morgan, 1996). Stream water DIC concentrations were calculated from sample headspace pCO_2 using temperature-dependant equations for carbonate equilibrium (Gelbrecht *et al*., 1998) and Henry's Law (Weiss, 1974), together with measured stream water pH and temperature. Stream pH ranged between 4.3 and 5.3, well below the carbonic acid equilibrium pK_a, making our DIC calculations relatively insensitive to uncertainty in pH.

Stream water C export

Daily stream carbon exports were calculated from daily flow measurements and linearly interpolated concentrations of TOC, DIC and CH_4. The precision of TOC, CO_2 and CH_4 stream water analyses were estimated to average 2%, 5% and 5%, respectively, based on replicate sample analyses. As conservative measures 5%, 8% and 10% (SD), respectively, were used for the uncertainty in the export analyses. The higher uncertainty for CH_4 was based on its faster degassing rate and hence larger sampling error. With respect to flow-related uncertainty, the potential error was associated with two sources: stage-discharge calibration uncertainty and errors arising from water-stage logger failures. The stage-discharge calibration uncertainty was estimated (by comparing instantaneous discharge measurements by the salt dilution technique and the stage-runoff relationship) to be <3%, and errors associated with gap-filling were estimated (by comparing specific discharges from the site and the nearby reference hydrological station) to be 6%. A total uncertainty of 10% SD for stream water discharge was used, which is similar to the regional estimate of 8% in annual discharge found by Laudon *et al*. (2004) from seven boreal catchments in northern Sweden. The total uncertainties in TOC, CO_2 and CH_4 exports were estimated using Monte Carlo simulations, with 10 000 realizations generated from the distributions discussed above. The total uncertainties (SD) for TOC, CO_2 and CH_4 from stream water export were 11%, 13% and 14%, respectively.

To consider the effect of uncertainty in both the delineation of the Vargstugbäcken sub-catchment and the partitioning between mire and upland forest within the catchment for the runoff C-export, we applied 5% errors to both the catchment delineation and the partitioning. The effects of these errors are included in the error estimates of both the annual total runoff C-export and the annual NECB calculations.

Calculation of mire-specific discharge and C export

Calculation of stream carbon export from the mire was based on the mire source area (69% of the catchment)

using both specific discharge and concentrations of the different C-species. The mire-specific discharge was estimated as the difference between precipitation and evapotranspiration (derived from the Eddy covariance measurements), both measured at the mire (Sagerfors, 2007). The forest-specific discharge was then calculated as the difference between the discharge derived from the continuous stream measurements, representing the total catchment area, and the calculated mire-specific discharge. The mire-specific export of each of the C-species was estimated as follows. Annual average values for each of the C-species from a forested sub-catchment of the reference catchment 10 km to the north (Ågren *et al*., 2007; Buffam *et al*., 2007) were used together with the estimated forest-specific discharge to estimate the export of the forest C. The C-export specific to the mire area was then derived as the difference between the measured total C-export and the fraction calculated to originate from the forested part of the catchment. The concentrations of C-species used to account for the contributions from the forested part of the catchment were 6.6 ± 3.9 (SD) mg L^{-1} for DIC (from samples, taken weekly over a year, of soil water in the uppermost saturated zone of an upland forest soil in the same area; M. G. Öquist, personal communication); 2.3 ± 1.1 (SD) mg L^{-1} for TOC (annual average over the 20–90 cm depth at the same site where DIC was measured; Bishop *et al*., 2004) and zero for CH_4.

Calculation of the net ecosystem carbon balance

The annual NECB is estimated as the sum of the annual net fluxes for each of the ecosystem flux components: $NECB = NEE + C_{precip} + CH_4\text{-}C + Discharge\text{-}C$, where NEE refers to the Eddy covariance based measurements of the CO_2 NEE; C_{precip} represents the addition of organic carbon through precipitation; CH_4-C is the annual exchange of methane between the mire and the atmosphere and discharge-C is the annual export of carbon through runoff (net flux into the mire is assigned a negative sign and net flux from the mire is assigned a positive sign). The total error for NECB is calculated as the square root of the sum of the squared errors for each of the flux components.

Results

Climate

Both years had cooler summers (May–September), warmer nongrowing seasons (October–April) and more precipitation than the long-term (1960–1990) averages (Fig. 2). The precipitations were higher in 2004 and 2005 (651 and 716 mm, respectively), compared with the long-term average of 523 mm, due to increases during the period from May to September; 393 mm falling in 2004 and 474 mm in 2005, compared with the long-term

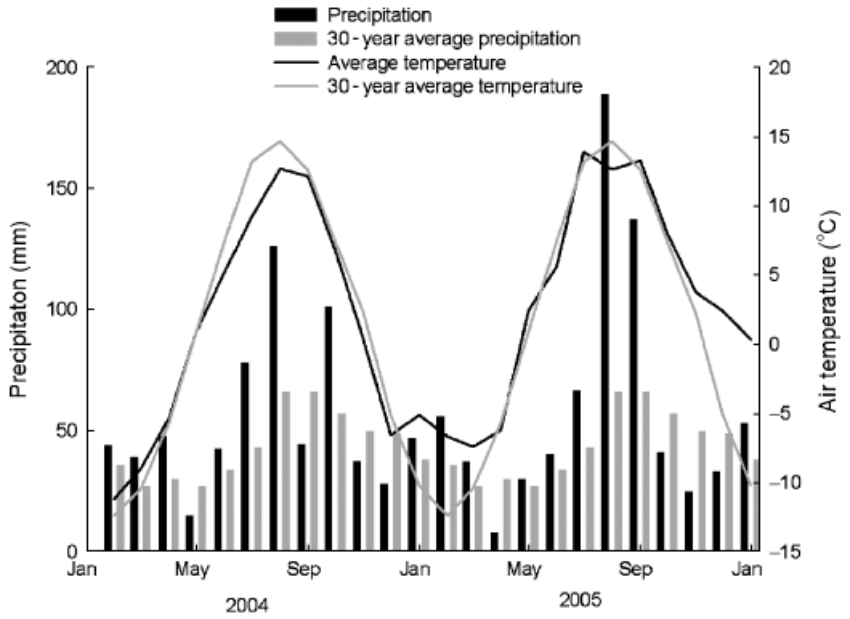

Fig. 2 Air temperature and precipitation during 2004 and 2005 and the 1960–1990 averages. Air temperature represented by a black line (30-year, 1961–1990, average represented by the gray line); monthly precipitation: black bars (30-year, 1961–1990, average represented by gray bars).

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Table 1 Description of the climate during 2004 and 2005 and deviations from the long-term average climate between 1960 and 1990

	Cumulated precipitation (mm)						Air temperature sum (degree days)					
	Annual*		May–September†		October–April†		Annual		May–September		October–April	
2004	651	128	393	127	258	1	330	−140	1411	−286	−1081	145
2005	716	193	474	208	242	−15	1301	830	1635	−62	−334	892

*The left column shows absolute annual values and the right column deviations from 1960–1990 long-term averages (all categories).
†These time periods approximate to the net ecosystem exchange net uptake and net loss periods but are not exactly the same.

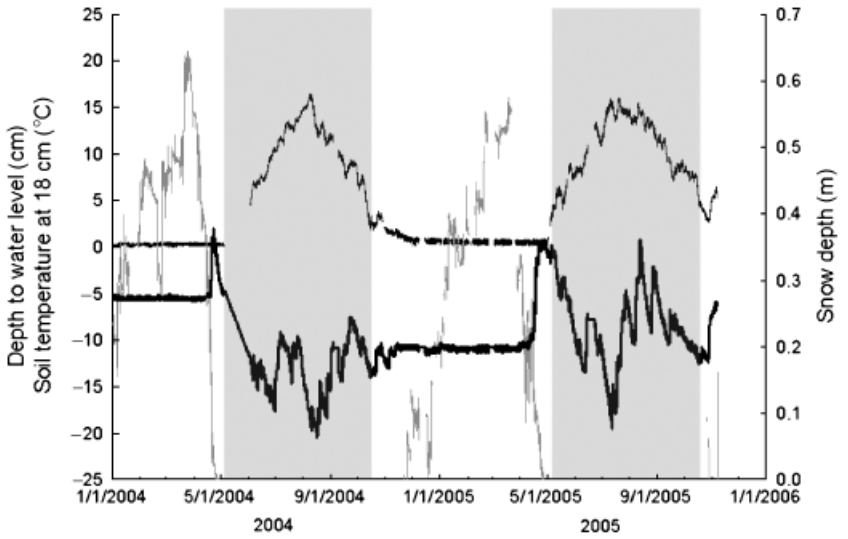

Fig. 3 Depth from the mire surface to the water table (thick black line), snow depth (fine dotted line) and soil temperature at 18 cm (thin black line). Gray shaded zones represent NEE net uptake periods.

average of 266 mm during this period (Table 1). The temperature sum during May to September was lower, 1411 °C days and 1635 °C days for 2004 and 2005, respectively, compared with the long-term average of 1697 °C days. The long-term average temperature sum during October–April was −1226 °C days, compared with −1081 °C days during 2004 and −334 °C days during 2005. The annual temperature sum for 2004 was somewhat lower (330 °C days) than the long-term average (471 °C days), but was considerably higher during 2005 (1301 °C days).

The snow cover reached approximately 0.6 m during both winters and lasted until late April in both years (Fig. 3). The water table during May and September was generally lower in 2004 than 2005. For most of the time during May to September 2004, the water table was between 10 and 15 cm below the surface. During May to September 2005, the water level dropped to below 15 cm during July, but stayed above 10 cm for the rest of the time between May and September, and reached above 5 cm in early autumn (Fig. 3).

NEE

The annual NEE in 2004 and 2005 corresponded to a net uptake of 55 ± 1.9 and 48 ± 1.6 g CO_2-C m^{-2} yr^{-1}, respectively (Fig. 4). During 2004, the daily NEE changed from emission to uptake on 7 May and from uptake to emission on 14 September. The corresponding shifts during 2005 occurred on 26 April and 21 September. The uptake of CO_2-C by the mire ecosystem during the net uptake period during 2004 (130 days) was 92 g CO_2-C m^{-2} yr^{-1} and during 2005 (148 days) it was 86 g CO_2-C m^{-2} yr^{-1}. The loss of CO_2-C via emissions to the atmosphere during the net source period (236 days) of 2004 amounted to 37 g CO_2-C m^{-2} yr^{-1}. During 2005, the emission during the net source period (217 days) was 38 g CO_2-C m^{-2} yr^{-1}.

Methane emissions

During the growing season, the water table normally ranged between 10 and 20 cm below the mire surface in the lawn plant community, and between 0 and 10 cm in

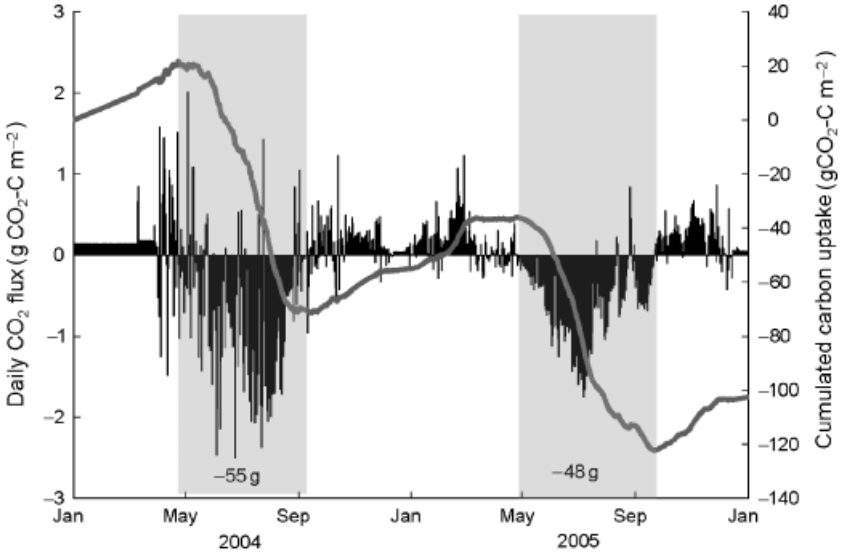

Fig. 4 Net CO_2-C exchange during 2004 and 2005 based on Eddy covariance measurements. Daily values represented by black bars, and the cumulative carbon accumulation by the cumulative curve (line). Gray shaded zones represent net uptake periods of CO_2-C.

the carpet plant community. The CH_4-flux rates were generally higher from the carpet than from the lawn, especially during 2004 (Fig. 5a and b). The CH_4-fluxes from the carpet during the snow free season of 2004 ranged from 2 to 6 mg CH_4-C m^{-2} h^{-1} while those from the lawn were <2 mg CH_4-C m^{-2} h^{-1} for most of the time. The CH_4-emissions during the snow free season of 2005 from the two plant communities were more similar, but those from the carpet community were still slightly higher (3–5 mg CH_4-C m^{-2} h^{-1}) than those from the lawn plant community (generally 2–4 mg CH_4-C m^{-2} h^{-1}).

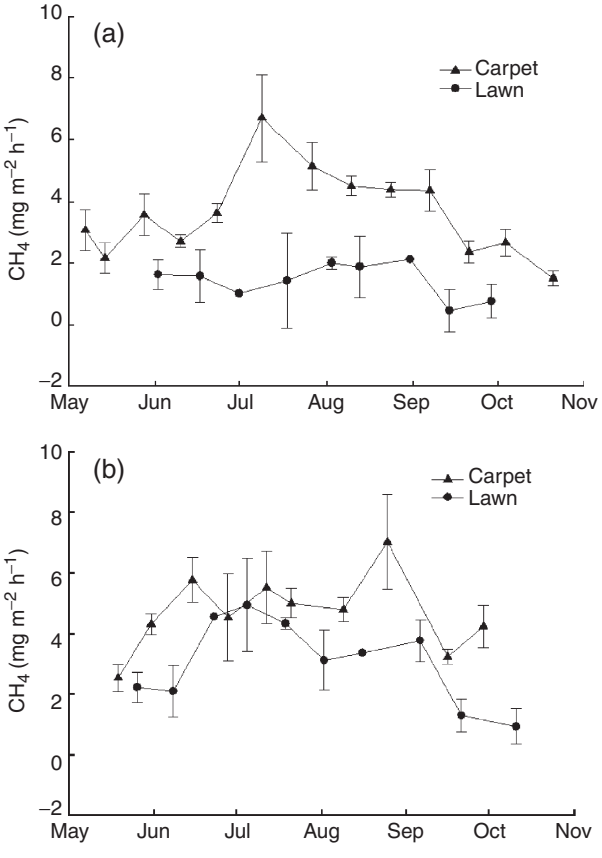

Fig. 5 Methane emission rates from lawn plant and carpet plant communities (average ± SE): (a) 2004 (b) 2005.

To estimate the annual fluxes, we assumed that the flux during the season from 25 May to 5 October constituted 80% of the annual flux from the mire. The estimated total methane losses were 9 ± 1.8 (± SD) g CH_4-C m^{-2} during 2004 and 14 ± 2.5 (± SD) g CH_4-C m^{-2} during 2005.

Carbon loss via runoff

The catchment area drained by the Vargstugbäcken stream was estimated to be 3.1 km^2, of which 69% is mire. The specific discharge from the total catchment was 369 mm (i.e. L m^{-2}) during 2004 and 343 mm during 2005. The specific discharges from the mire area alone were estimated to be 455 and 441 mm in 2004 and 2005, respectively, resulting in forest-specific discharges of 178 and 125 mm, respectively. The measured average TOC, DIC and CH_4-C concentrations in the runoff water during 2004 and 2005 were 25.3 ± 1.8, 9.6 ± 3.6 and 0.5 ± 0.4 mg L^{-1}, respectively, and the estimated mire-specific concentrations were 30.3 ± 2.2, 10.3 ± 4.4 and 0.6 ± 0.5 mg L^{-1}, respectively. The total mire-specific C-exports during 2004 and 2005 were 20.4 ± 2.1 and 15.1 ± 1.7 g C m^{-2}, respectively. The mire-specific runoff C-export was dominated by TOC, but CO_2 also made

Table 2 Net ecosystem carbon balance (NECB) at Degerö Stormyr during 2004 and 2005, divided into net-uptake and net-loss seasons and the entire years (cumulated ± SE)

	2004			2005		
Entity	NL*-season	NU†-season	Total‡	NL-season	NU-season	Total
Land–atmosphere CO_2-C exchange ($g C m^{-2}$)	37	−92	−55 ± 1.9	38	−86	−48 ± 1.6
Precipitation TOC ($g C m^{-2}$)	−0.6	−0.6	−1.2	−0.5	−0.9	−1.4
Land–atmosphere CH_4-C exchange ($g C m^{-2}$)	2	7	9 ± 1.7	3	11	14 ± 2.5
Stream total C-export ($g C m^{-2}$)	10.9	9.5	20.4 ± 1.7	4.1	11.0	15.1 ± 1.4
Stream TOC export ($g C m^{-2}$)	8.1	5.9	14.0 ± 1.5	3.0	8.9	11.9 ± 1.3
Stream CO_2 export ($g C m^{-2}$)	3.5	2.5	6.0 ± 0.8	0.8	2.3	3.1 ± 0.4
Stream CH_4 export ($g C m^{-2}$)	0.2	0.2	0.4 ± 0.06	0.03	0.07	0.1 ± 0.01
Total C exchange ($g C m^{-2}$)	49	−76	−27 ± 3.1§	45	−65	−20 ± 3.3§

*The net-loss (NL) season is defined as the period with a land–atmosphere net CO_2 efflux: 2004, 235 days from 1 January to 6 May and from 15 September to 31 December; 2005, 217 days from 1 January to 25 April and from 22 September to 31 December, (see Fig. 4).

†The net-uptake (NU) season is defined as the period with a land–atmosphere net CO_2 uptake: 2004, 130 days from 7 May to 14 September; 2005, 148 days from 26 April to 21 September, (see Fig. 4).

‡Sum of the net uptake and net loss periods.

§Square root of the sum of squares of the SDs included.

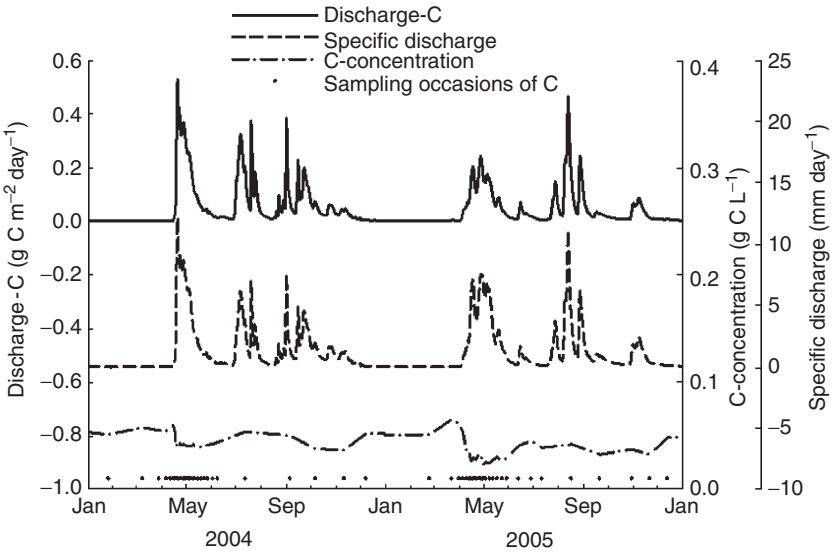

Fig. 6 Temporal variations in stream export of total C (upper graph), water discharge (middle graph), concentrations of total C (lower graph) and the collection times of water samples for analysis of the carbon content (dots at bottom of graph).

a significant contribution in both years, while the amount of carbon lost as methane was negligible (Table 2).

The C-export through runoff at Degerö Stormyr was dominated by high runoff episodes (Fig. 6). The proportion of the annual C-export that occurred in episodes with specific discharge $>0.55\,mm\,day^{-1}$ amounted to 94% in 2004, and such flows occurred during 46% of the year. During 2005, 91% of the runoff-C was exported during episodes with specific discharges $>0.55\,mm\,day^{-1}$, which occurred during 42% of the year. The spring high flow ($>0.55\,mm\,day^{-1}$) periods during 2004 and 2005 constituted just 14 ± 2% of the total time during the 2 years, but accounted for 39 ± 1% of the annual C-discharge.

The annual net ecosystem carbon balance

The NECBs during 2004 and 2005 were −27 ± 3.4 and $-20 \pm 3.4\,g\,C\,m^{-2}\,yr^{-1}$, respectively (Table 2). The annual NEE was $-55 \pm 1.9\,g\,CO_2\text{-}C\,m^{-2}\,yr^{-1}$ during

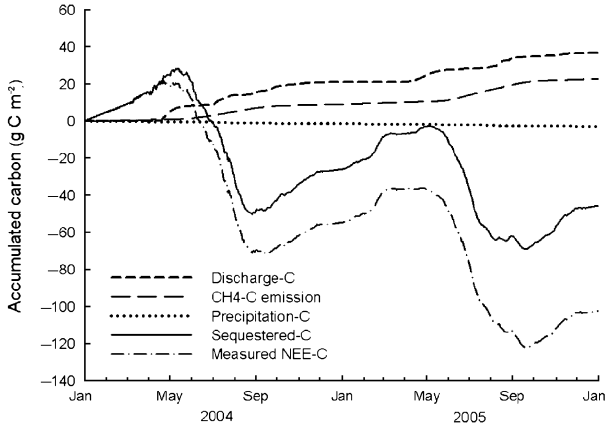

Fig. 7 Data on cumulative C-flux components during the measurement period.

2004 and $-48 \pm 1.6\,g\,CO_2\text{-}C\,m^{-2}\,yr^{-1}$ during 2005. The amount of organic carbon added to the mire through precipitation was on average $1.3 \pm 0.14\,g\,C\,m^{-2}\,yr^{-1}$ during the 2 years. The net uptake (denoted by a negative sign) of atmospheric carbon dioxide was partly counterbalanced by the emission of methane to the atmosphere and C-export through runoff (Table 2, Fig. 7). The inclusion of precipitation-C, CH_4 C-emission and runoff C-export increased the NEE source strength of the net-loss period in 2004 from 37 to $49\,g\,C\,m^{-2}\,yr^{-1}$ and during 2005 from 38 to $45\,g\,C\,m^{-2}\,yr^{-1}$. The sink strength (NEE + precipitation-C) during the net-uptake season in 2004 decreased by 17 to $-76\,g\,C\,m^{-2}\,yr^{-1}$ and during 2005 by 22 to $-65\,g\,C\,m^{-2}\,yr^{-1}$.

Discussion

Fluxes to the atmosphere

The vertical NEE of CO_2 during the 2 years studied (2004, 2005) was similar to the annual NEE from the same site during 2001–2003, which was -48 ± 1.1, -61 ± 4.4, $-56 \pm 2.1\,g\,C\,m^{-2}\,yr^{-1}$, respectively (Sagerfors *et al*., 2008). The average NEE for the 5 years was $-54\,g\,C\,m^{-2}\,yr^{-1}$ with a total uncertainty (SD, including both the within-year measurement error and the climatic interannual variability) of $\pm 5.6\,g\,C\,m^{-2}\,yr^{-1}$. Multiyear measurements of annual NEE from mire ecosystems are still scarce, but Roulet *et al*. (2007) obtained an average estimate, based on 6 years EC measurements, for the bog Mer Bleu in southern Canada of $-40 \pm 40\,g\,C\,m^{-2}\,yr^{-1}$, and Aurela *et al*. (2004) obtained an estimate based on 6 years of measurements, for the average NEE of a subarctic fen in northern Finland of $-22 \pm 20\,g\,C\,m^{-2}\,yr^{-1}$. In addition, based on measurements over one-and-a-half years (including two growing seasons) the average annual NEE at a boreal oligotrophic fen in southern Finland was estimated to be $-56 \pm 5.6\,g\,C\,m^{-2}$ (Aurela *et al*., 2007), a lowland temperate peatland in Scotland yielded a 2-year average of $-28 \pm 25\,g\,C\,m^{-2}\,yr^{-1}$ (Billett *et al*., 2004), and Sottocornola & Kiely (2005) obtained estimates of annual NEE from an Atlantic blanket bog for 2 years of -49 and $-61\,g\,C\,m^{-2}\,yr^{-1}$, respectively. These comparative values indicate that the values we obtained for the minerogenic oligotrophic mire Degerö Stormyr are among the highest estimates of annual net uptake NEE based on Eddy covariance measurements recorded at any mire ecosystems. However, the 5-year average we obtained is similar to the NEE at the boreal oligotrophic fen, Siikaneva in southern Finland (Aurela *et al*., 2007) that represents the same mire type as Degerö Stormyr.

The rates of methane emission from the lawn plant community found in this study are close to the snow free season rate averages (gross average over 3 years, $2.2 \pm 7\,mg\,CH_4\text{-}C\,m^{-2}\,h^{-1}$) recorded at the same site during 1995–1997 (Granberg *et al*., 2001a). The estimates of the annual methane release are in the average range of rates reported from other poor minerogenic mires (Nykänen *et al*., 1998; Huttunen *et al*., 2003). They are also close to the recently published estimate of annual methane emission ($13\,g\,m^{-2}\,yr^{-1}$), based on continuous Eddy covariance measurements, from the boreal minerotrophic fen, Siikaneva, in Finland (Rinne *et al*., 2007). The long-term averages for oligotrophic minerogenic mires for 1980–1997 were estimated to be 12 ± 5 and $8 \pm 4\,g\,CH_4\text{-}C\,m^{-2}\,yr^{-1}$, respectively (average $\pm$ 95% confidence limits) for the Swedish regions relevant to Degerö Stormyr, with respect to climate (Nilsson *et al*., 2001). The estimated annual methane releases for 2004 and 2005 from Degerö Stormyr are thus similar to these long-term averages for oligotrophic mires in neighboring regions.

Fluxes through runoff

The estimated mire-specific carbon loss as stream TOC ($\approx 13\,g\,C\,m^{-2}\,yr^{-1}$) from the study site are in the upper range of export rates reported from boreal streams and rivers in other regions of the world, which typically range between 1 and $10\,g\,C\,m^{-2}\,yr^{-1}$ [see Hope *et al*. (1994) for a review]. The mire-specific average TOC export from 22 catchments in Finland, based on multiyear data, was $8.5\,g\,C\,m^{-2}\,yr^{-1}$ [calculated from data in Kortelainen *et al*. (1997)]. However, if the average mire-specific TOC export from the Finnish catchments is recalculated for the same annual mire-specific discharge as at Degerö Stormyr ($\sim 450\,mm\,a^{-1}$) the average annual C-discharge becomes $12.5\,g\,C\,m^{-2}\,yr^{-1}$; this is

similar to the export from Degerö Stormyr ($\sim 13\,g\,C\,m^{-2}\,yr^{-1}$). Recent studies of streams in the Degerö Stormyr region have measured annual TOC export ranging from 1.5 to $9.9\,g\,C\,m^{-2}\,yr^{-1}$ (Laudon *et al*., 2004; Ågren *et al*., 2007), and positively correlated ($r^2 \geq 0.7$) with the area of wetlands (Laudon *et al*., 2004). Using a regression model based on these data, we calculated the mire-specific annual export of TOC (i.e. extrapolated the regression model to 100% wetland) and found it to be $12\,g\,C\,m^{-2}\,yr^{-1}$. The recalculated, runoff-adjusted, annual mire-specific discharge export of TOC corresponds well with the annual mire-specific runoff export in the form of TOC from this study, namely $14.0 \pm$ (SD) 1.5 and $11.9 \pm 1.3\,g\,C\,m^{-2}\,yr^{-1}$ for 2004 and 2005, respectively. These findings imply that most of the variability in runoff export of TOC from boreal continental mires originates from variations in the annual specific discharge, rather than TOC concentration.

It should be noted that our calculation of C export in mire-specific runoff is dependent in part upon the C concentration contribution to total stream runoff estimated for the forested portion of the catchment. The forest-specific stream C concentrations, in contrast to all the other measurements in this study, were not obtained directly at the Degerö Stormyr site but instead used data from a forested site 10 km away. As this site had very similar vegetation, soil and Quaternary geology characteristics to the forested areas in the Degerö Stormyr catchment, it is believed to be a reasonable representation of the C inputs. However, as noted previously, any mixing of data from disparate sites or time periods introduces error. Our analysis accounted for the uncertainty in the forest-specific C runoff value, as with other data in this study, in a Monte Carlo error analysis.

Stream export of inorganic carbon (mainly as dissolved CO_2) accounted for 30% and 20% in 2004 and 2005, respectively, of the total stream flux of carbon. The origins (minerogenic weathering or mineralization of organic material) of inorganic carbon in mire runoff probably vary substantially, depending on factors such as the mire type, catchment topography and topography of the mineral soil underlying the peat. For instance, Billet *et al*. (2007) found differences in signatures in ^{14}C-age and ^{13}C-signatures between DOC and CO_2 from peatlands in the UK, which they concluded were probably related to minerogenic origins of the CO_2. However, information acquired from other studies in the same area as Degerö Stormyr suggests that the measured DIC in the discharge at Degerö Stormyr emanates from mineralization of the mire peat rather than from the underlying mineral soil. Notably, in a study of 15 streams in the Krycklan catchment 10 km NE of Degerö Stormyr, DIC concentrations and fluxes were much higher in headwater mire than headwater forested streams (Wallin, 2005), suggesting a high contribution of stream CO_2 from the mires. This observation was substantiated by direct measurements of soil solution C that indicated increases in DIC when subsurface water flow paths intersected areas of peat (Grip, 1994). The concentration of CO_2 from mire peat pore water in the same region (Nilsson & Bohlin, 1993) has also been found to be even higher [35 ± 3.5(SE) $mg\,CO_2\text{-}C\,L^{-1}$] than in the upwelling water leaving Degerö Stormyr, further indicating that the bulk of the CO_2-C in the stream leaving the mire likely originates from the mire peat. The inorganic C export is of the same order as in other published studies. For example, Billett *et al*. (2004) found that inorganic carbon comprised 7% of the total stream export from a peatland in Scotland, whereas Dawson *et al*. (2001) found that inorganic carbon accounted for 31% of the total stream carbon export from wetlands in Wales.

That high discharge associated with hydrological episodes corresponds to high stream export of carbon is well recognized. In northern regions, long, snow rich winters generate snow melt episodes that often dominate the water and carbon budgets (Laudon *et al*., 2004; Finlay *et al*., 2006; Ågren *et al*., 2007). In this study, this is corroborated by the findings that 38% and 40% of the stream carbon export occurred during 4 weeks of snow melt in the springs of 2004 and 2005, respectively.

Carbon species

The average annual NEE at Degerö Stormyr during the net uptake period was $-89\,g\,C\,m^{-2}\,yr^{-1}$, while the average NECB for the 2 years was $-24 \pm 4.9\,g\,C\,m^{-2}\,yr^{-2}$. The amount of organic C added through precipitation was equivalent to $<2\%$ of the annual C input. The annual C-loss term was mainly (56%) attributed to CO_2 loss during the net-loss season, but CH_4-C emissions and runoff-C also contributed substantial losses (17% and 27%, respectively). Thus, the single most important determinant of the annual CO_2 NEE in the mire we examined appears to be the ratio between the lengths of the CO_2-net uptake and net loss seasons, in accordance with the conclusion of other authors (Lafleur *et al*., 2001; Aurela *et al*., 2002). Based on data from 2001–2005 (Sagerfors *et al*., 2008; this paper), we calculated that if the CO_2 net uptake period at Degerö Stormyr started 1 week earlier, the annual NEE would increase by 11%. However, the C-losses through methane emissions and runoff-C also constitute significant components, together responsible for 44% of the annual net C-loss. The relative importance of NEE, methane emission and runoff-C for the annual

net carbon exchange in mires certainly differs between mire types, and because the factors influencing these variables differ between mires, the effects of different weather conditions on mire net C-exchange will also differ considerably between them.

Relationship between current NECB and Holocene carbon accumulation

Most of the published data on Holocene peat C accumulation refer to LARCA, for which a global estimate of $29\,g\,C\,m^{-2}\,yr^{-1}$ (Gorham, 1991) and area-weighted values for oligotrophic mires in the two climate regions of Finland with the most similar climates to that in our study area of 20 ± 8.3 and $16 \pm 4.3\,g\,C\,m^{-2}\,yr^{-1}$ have been published (Turunen *et al*., 2002). Based on Clymo's peat accumulation model (Clymo, 1984; Clymo *et al*., 1998), several attempts have been made to convert apparent C accumulation rates to the current, true rate of carbon accumulation (TRACA). Using global or close to global datasets, the TRACA was estimated to be $23\,g\,C\,m^{-2}\,yr^{-1}$, representing 79% of LARCA, by Gorham (1991), and $21\,g\,C\,m^{-2}\,yr^{-1}$ by Clymo *et al*. (1998) based on parameters estimated from 1125 peat cores from Finland (Tolonen & Turunen, 1996). However, because of potential bias in the data used by Clymo *et al*. (1998), the authors argued that the true current sequestering rate in boreal mires could be 30–40% less than their calculated values. At a patterned fen 70 km away from Degerö Stormyr, the average apparent accumulation of peat-C in a carpet plant community (*S. majus* dominated) during AD 1200–1600 (excluding data for 'the little ice age', in the 16th–18th century, when net C accumulation dropped to $10\,g\,C\,m^{-2}\,yr^{-1}$) was $25\,g\,C\,m^{-2}\,yr^{-1}$ (Oldfield *et al*., 1997). Using average values for the proportion TRACA represents of the apparent C accumulation (Clymo *et al*., 1998) the true rate of C accumulation was estimated to be $20\,g\,C\,m^{-2}\,yr^{-1}$. The estimated mire net C-exchange of $24\,g\,C\,m^{-2}\,yr^{-1}$ at Degerö Stromyr is very close to these estimated average values of the TRACA during the Holocene. Thus, although the estimate for NECB at Degerö Stormyr covers only 2 years, it is not lower than apparent long-term accumulation rates for similar mires and it does not indicate that mire NECB has declined in recent years.

Roulet *et al*. (2007) also concluded that the 6-year average NECB ($21 \pm 39\,g\,m^{-2}\,yr^{-1}$) for the ombrotrophic mire Mer Blue was not different from the Holocene average measured at the same mire. It should also be noted that the two average NECB's for the ombrotrophic mire Mer Bleu ($21 \pm 39\,g\,m^{-2}\,yr^{-1}$) and the minerogenic mire Degerö Stormyr ($24 \pm 4.9\,g\,m^{-2}\,yr^{-1}$) are very similar. Despite different plant community composition, different hydrology and different climate, the current net carbon accumulation seems to be very similar.

TOC and atmospheric fluxes

It should be noted that the loss of carbon as TOC through runoff from a mire plays a different role than loss to the atmosphere. When constructing a current mire net C budget for comparison with apparent C accumulation, the runoff export of TOC should be treated in the same way as the NEE and methane emission to the atmosphere. However, to assess the net effect on the mire–atmosphere exchange, the runoff export of TOC should be partitioned into mineralization to CO_2 and permanent sedimentation, i.e. long-term burial of organic carbon in lake sediments (Algesten *et al*., 2004). Current estimates and calculations suggest that mineralization is several times greater (average = eight times) than the sedimentation of the exported TOC (Molot & Dillon, 1996; Algesten *et al*., 2004). The longer the water turnover time in lakes, the larger the proportion of TOC that is respired. The estimated C-loss as TOC for the 2 years was $13\,g\,C\,m^{-2}\,yr^{-1}$. If we apply the average mineralization proportion (Molot & Dillon, 1996; Algesten *et al*., 2004), to our study, then two of the $13\,g\,C\,m^{-2}\,yr^{-1}$ will be buried in lake sediments rather than returned to the atmosphere. The annual net effect of mire C-uptake from the atmosphere should, thus be augmented by an additional $2\,g\,C\,m^{-2}\,yr^{-1}$, increasing the current estimate for Degerö Stormyr from 24 to $26\,g\,C\,m^{-2}\,yr^{-1}$.

Conclusions

The oligotrophic minerogenic mire Degerö Stormyr represented a net C-sink of $24 \pm 4.9\,g\,C\,m^{-2}\,yr^{-1}$ ($\pm$ SD) during 2004 and 2005. The CO_2-C net uptake during the growing season was reduced by the non-growing season CO_2-C loss (56%), methane emission (17%) and runoff export of CH_4, CO_2 and TOC (27%). Both the emission of methane and the runoff export of carbon contributed substantially to the NECB at Degerö Stormyr. The NECB response of the mire to a changing climate will, therefore, depend on the response of each of the three flux components: NEE, methane emission and discharge C-export. However, because the climatic conditions during the 2 years studied were close to long-term average conditions, this mire is still probably generally a net sink for atmospheric carbon. Our results also indicate that the current NECB of the mire is in the same range as, or maybe higher than, the long-term carbon accumulation rates for the region.

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