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How strong is the current carbon sequestration of an Atlantic blanket bog?

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Abstract

Although northern peatlands cover only 3% of the land surface, their thick peat deposits contain an estimated one-third of the world's soil organic carbon (SOC). Under a changing climate the potential of peatlands to continue sequestering carbon is unknown. This paper presents an analysis of 6 years of total carbon balance of an almost intact Atlantic blanket bog in Glencar, County Kerry, Ireland. The three components of the measured carbon balance were: the land-atmosphere fluxes of carbon dioxide (CO_2) and methane (CH_4) and the flux of dissolved organic carbon (DOC) exported in a stream draining the peatland. The 6 years C balance was computed from 6 years (2003–2008) of measurements of meteorological and eddy-covariance CO_2 fluxes, periodic chamber measurements of CH_4 fluxes over 3.5 years, and 2 years of continuous DOC flux measurements. Over the 6 years, the mean annual carbon was -29.7 ± 30.6 (± 1 SD) $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ with its components as follows: carbon in CO_2 was a sink of $-47.8 \pm 30.0\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$; carbon in CH_4 was a source of $4.1 \pm 0.5\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ and the carbon exported as stream DOC was a source of $14.0 \pm 1.6\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$. For 2 out of the 6 years, the site was a source of carbon with the sum of CH_4 and DOC flux exceeding the carbon sequestered as CO_2. The average C balance for the 6 years corresponds to an average annual growth rate of the peatland surface of $1.3\,\mathrm{mm\,yr^{-1}}$.

Keywords: carbon balance, carbon sequestration, dissolved organic carbon, methane, net ecosystem exchange, peatland

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Introduction

Northern peatlands account for about 3% of the earth's land area and have accumulated 20%–30% of the world's estimated global soil carbon (C) pool which corresponds to 270–450 Pg of C (Gorham, 1991; Turunen *et al.*, 2002). A recent study reported that the northern circumpolar permafrost region contains approximately 50% of the global belowground organic carbon pool (Tarnocai *et al.*, 2009). Peatlands are generally less productive than other ecosystems making their contribution to the current terrestrial exchange relatively small ($\approx$ 0.1–0.5 $\mathrm{Pg\,C\,yr^{-1}}$ compared with $\approx 60\,\mathrm{Pg\,C\,yr^{-1}}$ for the net terrestrial exchange, Schimel, 1995) so that it is more the future of their large soil C pool to be of concern (Moore *et al.*, 1998). Globally only 3% of the peat area is covered by blanket bogs, but locally they can be very important. In the Republic of Ireland blanket bogs cover about 13% of the land area containing an estimate of about 28%–45% of the nation soil C stock (Tomlinson, 2005; Eaton *et al.*, 2008). Blanket bogs are largely ombrotrophic peatlands, thus receive water and nutrients only through atmospheric deposition and typically develop independently from basins in temperate regions with annual rainfall greater than 1250 mm (Hammond, 1981).

The net ecosystem carbon balance (NECB, after Chapin III *et al.*, 2006) of peatlands comprises: net ecosystem exchange (NEE, the difference between fixation of C via photosynthesis and emission of C through ecosystem respiration); net methane (CH_4) consumption or efflux; and the net gain or loss of C in water inputs and runoff (including total organic carbon, dissolved inorganic carbon and CH_4). There are only few peatland NEE studies that are extended for more than 1 or 2 years. These show a wide range of annual NEE between sites and between years of the same site (Aurela *et al.*, 2004; Roulet *et al.*, 2007; Nilsson *et al.*, 2008; Lund *et al.*, 2009; Sottocornola & Kiely, 2010). In addition to NEE, the CH_4 emissions (Granberg *et al.*, 2001; Roulet *et al.*, 2007; Nilsson *et al.*, 2008) and the fluvial losses of C as dissolved organic carbon (DOC) (Dawson *et al.*, 2004; Roulet *et al.*, 2007; Nilsson *et al.*, 2008) in peatlands vary between sites and from year to year. The seasonal and interannual variation (IAV) of all C flux components reflects the strong influence and sensitivity to present

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climate conditions as well as site-specific characteristics (e.g., vegetation, chemical status and microform patterns). To our knowledge, only two studies have combined all C flux components with measurements at the same time and space with the aim to estimate the total annual C balance for a peatland (Roulet *et al.*, 2007; Nilsson *et al.*, 2008). In the longest known peatland C balance study, in Mer Bleue, an ombrothropic continental raised bog in Canada, Roulet *et al.* (2007) measured a mean annual C balance of $-21.5 \pm 39.0\,\mathrm{g\,m^{-2}}$ during a 6 years time period (a negative sign is the micrometeorological convention indicating C sequestered by the ecosystem). Multiannual measurements of C balances from individual peatland sites are important to elucidate the uncertainty about their current role in C sequestration. Furthermore, continuity of these measurements is essential if progress is to be made in modelling the peatland's C balance for future climate change scenarios.

The objectives of this study are to present the annual C balance for an Atlantic blanket bog over a 6 years period including the three main inputs and outputs to the ecosystem (NEE, CH_4, and DOC) and to study their interannual and seasonal variability.

Materials and methods

Site description

The study site is located in an Atlantic blanket bog near Glencar in southwest Ireland (51°55′N, 9°55′W, about 150 m above sea level). This peatland is typical of Atlantic blanket bogs in the maritime regions of northwestern Europe in terms of both vegetation and water chemistry (Sottocornola *et al.*, 2009). The surface of the bog is a mosaic of microforms that differ in relative altitude, plant composition and water table depth. Four classes were distinguished: hummocks (6%), high lawns (62%), low lawns (21%) and hollows (11%) (Laine *et al.*, 2006) with an elevation difference of 20–40 cm between the highest and lowest microform. The peat depth ranged from about 0.5 m (at the margins and on the steepest slopes) to over 5 m (Sottocornola *et al.*, 2009; C. Lewis, personal communication).

A stream draining the peatland was monitored to measure the fluvial loss of DOC (Koehler *et al.*, 2009). The stream has its boundaries inside the bog on the west, east and north and is delimited by a small country road on the south. The catchment area of the stream is approximately 74 ha; 85% of which is relatively intact bog (Sottocornola *et al.*, 2009) and 15% is on a hill slope covered by patches of grassland and peaty soils.

The experimental arrangement consists of a micrometeorological tower equipped with meteorological sensors and an eddy-covariance (EC) system for CO_2 flux measurements between the biosphere and the atmosphere. The small stream draining the peatland was monitored for flow and water chemistry. The meteorological and EC station was located in the central part of the peatland near the northeastern border of the stream's catchment while the stream monitoring system was located at the northern outfall of the catchment.

Environmental measurements

The meteorological station (established in 2002, Kiely *et al.*, 2009) included a sensor for Q_{PAR}, photosynthetically active radiation (PAR Lite; Kipp & Zonen, Delft, the Netherlands), a shielded probe for air temperature measurements at 2 m height (HMP45C; Vaisala, Hilsinki, Finland), and probes for soil temperature recordings at different depths (107; Campbell Scientific, Loughborough, UK). Precipitation in the study site was measured with two tipping bucket rain gauges (an ARG100; Environmental Measurements Ltd., Sunderland, UK and an Obsermet OMC-200; Observator BV, Ridderkerk, The Netherlands) while water table level was measured with a pressure transducer (PCDR1830; Campbell Scientific).

Stream height was recorded every 30 min since January 2007 using a pressure transducer (1830 Series; Druck Ltd., Leicester, UK). Manual measurements of instantaneous discharge were carried out at a range of stream heights using an OTT current meter (OTT Messtechnik GmbH & Co KG, Kempten, Germany). The manual discharge measurements were used to establish a rating curve [Eqn (1)], which converted the continuously recorded stream height to discharge:

$$Q = 0.6946 \times (\mathrm{SH} - 0.08071)^{1.441}, \quad r^2 = 0.9986, \mathrm{RMSE} = 0.005, \tag{1}$$

where Q is discharge in $\mathrm{m^3\,s^{-1}}$ and SH stream height in m. The total discharge was calculated by integrating the 30 min discharge data. Error analysis for Q and drainage basin area was performed using the approach of Fraser *et al.* (2001). The discharge error was determined from the standard error of the rating curve (± 0.005), such that minimum and maximum Q were calculated using stages that ranged ±0.005 m about the best-fit line. Furthermore, a drainage basin error of 5% was included (Fraser *et al.*, 2001). The error of Q was taken into account for the calculation of the measured DOC flux in 2007 and 2008.

Current C flux measurements

For the calculation of the annual C balance, the six calendar years between January 1, 2003 and December 31, 2008 were considered. A summary of the methods and time periods of measurements for CO_2, CH_4 and DOC fluxes are given in the following sections. Seasonal variation in the fluxes was investigated with the seasons defined as: winter (December–February), spring (March–May), summer (June–August), and autumn (September–November).

NEE. The EC technique was used to measure the net flux of CO_2 at a height of 3.0 m above the high lawn vegetation (since September 2002, and to continue till at least 2011). The EC system consists of a 3-D sonic anemometer (Model 81000; R. M. Young Company, Traverse City, MI, USA) and an open-path CO_2/H_2O infrared gas analyser (LI-7500; LI-COR, Lincoln, NE, USA). Data were recorded at 10 Hz and those passing an automatical online quality check were Reynolds-averaged over 30 min. The postfield data processing included a double rotation and air density variation corrections (Webb *et al*., 1980); filters were then established to discard bad fluxes separately for day and nighttime data sets (a threshold of incoming radiation of $10\,\mathrm{W\,m^{-2}}$ was used to distinguish day and nighttime fluxes). After the data processing, the amount of good remaining CO_2 fluxes was 59% for the daytime and 26% for the nighttime on average over the 6 years. The under-representation of nighttime data prevalently occurred outside the growing season, when a large part of the CO_2 fluxes were discarded because negative, likely due to the heating effect of the Licor-7500 (Burba *et al*., 2008), which anyway did not affect the reliability of the EC flux measurement and computation in Glencar (Sottocornola & Kiely, 2010). The gaps arising in the time series were filled by nonlinear regression equations relating CO_2 flux to either Q_{PAR} or temperature for monthly to bimonthly periods. Details of the postfield processing and gap-filling procedures can be found in Sottocornola & Kiely (2005) and Sottocornola & Kiely (2010).

The uncertainty associated with annual estimates of NEE was computed as follows. A 20% random error was applied to each 30 min value of NEE and an annual error estimate was computed using propagation of errors (Morgenstern *et al*., 2004). The uncertainty due to the nonlinear relationships used for gap-filling was assessed through a bootstrap approach (Humphreys *et al*., 2005), so that each monthly to bimonthly period in every year was resampled with replacement and the nonlinear relationship was determined and used to gap-fill the original data set. This procedure was repeated 1000 times, the annual sums of NEE were calculated and their 95% confidence interval determined. In this paper the annual NEE values are the median of the 1000 repetitions.

Methane fluxes (CH_4). The closed chamber method was used to estimate the flux of CH_4 from the peatland. Methane measurements conducted from August 2003 until September 2005 are described in Laine *et al*. (2007). Further CH_4 chamber measurements were carried out at biweekly to monthly intervals during 2008. Owing to relatively mild winters with little frost it was possible to sample all the year round. Four replicate plots were sampled for each of the three microforms: hummock, high lawn and low lawn. Different to Laine *et al*. (2007) the hollows were further divided into hollows with a mud bottom, hollows covered by mosses only, by vascular plants without *Menyanthes trifoliata* or by vascular plants including *M. trifoliata*. Four replicates were sampled for each defined hollow type. As it was not possible to install collars at four of the hollow plots, the chamber size was reduced from $0.6 \times 0.6 \times 0.25$ to $0.3 \times 0.3 \times 0.3$ m to use floating chambers. Except for the size, the remaining chamber features and additional measurements of soil temperature at different depths and water table depth for each plot were the same as in Laine *et al*. (2007). Accordingly the same nonlinear regression approach as in Laine *et al*. (2007) was used to reconstruct CH_4 fluxes for the period 2003–2008:

$$CH_4 = (c + d \times \mathrm{WTL})(\exp(b \times T_{\mathrm{soil\,20\,cm}})), \qquad (2)$$

where b, c and d are parameters, WTL is water table level and $T_{\mathrm{soil\ 20\,cm}}$ soil temperature at 20 cm depth. Equation (2) was parameterised for each sample plot separately based on the periodic chamber measurements between 2003 and 2005 and during 2008 and then used to estimate the CH_4 flux for the whole period 2003–2008. If the linear function describing the relationship of WTL to CH_4 flux did not increase the explanatory power of Eqn (2), it was replaced with a constant a. Four plots had to be taken out of the final flux calculation as the fit of the nonlinear regression was not satisfactory; nevertheless at least three replicates were available for each microform. For the CH_4 flux integration, continuous (30 min) time series of $T_{\mathrm{soil\ 20\,cm}}$ and *WTL* for each sample plot were reconstructed from the $T_{\mathrm{soil\ 20\,cm}}$ and *WTL* continuously measured at the meteorological station. The annual CH_4 flux was calculated through an up-scaling based on the known average distribution of the microforms around the EC tower (as defined by Laine *et al*., 2006).

The standard error of the average annual CH_4 flux from each microform type was computed and weighted according to the microform distribution to estimate an error for the annual CH_4 fluxes (Laine *et al*., 2007).

DOC. Continuous measurements (30 min interval) of DOC in the stream began in January 2007 using a spectroanalyser (spectro::lyser™, scan Messtechnik GmbH, Vienna, Austria) (see Koehler *et al*., 2009). The DOC flux was computed as the product of DOC concentration and discharge. For the years 2003–2006, the measured stream height and DOC concentration were not available and were therefore modelled as follows. The monthly discharge was regressed against monthly precipitation (data 2007–2008):

$$\begin{gathered} Q = precip \times 0.896 + 6.138\,, \\ r^2 = 0.90, \mathrm{RMSE} = 35.7, \end{gathered} \qquad (3)$$

where Q is discharge and *precip* is the precipitation, both in mm. The best relationship for DOC concentration was an s-shaped function of binned daily mean air temperature (T_{air} in °C) and daily mean DOC concentration (DOC in mg $\mathrm{L^{-1}}$) (data 2007–08, Fig. 1):

$$\mathrm{DOC} = 3.763 + \frac{5.144}{1 + \exp(-0.6888 \times T_{\mathrm{air}} + 7.387)}, \quad (4)$$
$$r^2 = 0.92,\ \mathrm{RMSE} = 0.63.$$

An error estimate for Eqns (3) and (4) was computed as described for the relationship between stream height and discharge [Eqn (1)] (Fraser *et al.*, 2001), resulting in a lower and upper estimate of the DOC flux for the period 2003–2006. To calculate the DOC flux for the period 2003–2006, the estimated daily DOC concentration was averaged over the month and multiplied by the estimated monthly discharge resulting in estimates of $12.6 \pm 3.2\,\mathrm{g\,C\,m^{-2}}$ for 2007 and $15.8 \pm 3.2\,\mathrm{g\,C\,m^{-2}}$ for 2008, compared with our measured values of 11.9 ± 1.2 and $15.0 \pm 1.3\,\mathrm{g\,C\,m^{-2}}$ for 2007 and 2008, respectively.

Additionally, DOC concentration in precipitation was measured over a 1-year period ($n = 7$) with three replicates each time using a funnel with an attached bottle. The bottles were left out in the field for up to 3 days during a rainy period and were analysed for DOC concentration thereafter as described below. The product of the mean DOC concentration over the 1-year period and the annual amount of precipitation was used to estimate the DOC input in precipitation for each year. For the stream water, a 24-bottle auto-sampler (6712 portable sampler; Teledyne Isco Inc., Lincoln, NE, USA) was used every 6–8 weeks and the samples were analysed for DOC and total organic C using a TOC-V cpH (SHIMADZU Scientific Instruments, Columbia, MD, USA). The flux of particulate organic carbon (POC), which is the difference between total and DOC was estimated using the average percentage of POC calculated from the bottle auto-sampler results.

Bulk density

Samples for bulk density were taken using a peat core sampler (Eijkenkamp Agrisearch Equipment BV, Giesbeek, the Netherlands) at four different locations in the bog, at half-meter intervals, three replicates at each depth. The peat samples were oven-dried to a constant mass at 55 °C and weighted; bulk density was calculated by dividing the dry mass by the fresh volume.

Results

Current environmental conditions

The study of the 6 years measurements showed a wide range of environmental conditions. We ranked the seasonal temperature and precipitation from 2003 to 2008 from the nearest synoptic weather station (Valentia, located ca. 30 km West of Glencar, http://www.meteireann.ie/climate/valentia.asp) within their past long-term record (1940–2008) as done by Roulet *et al.*

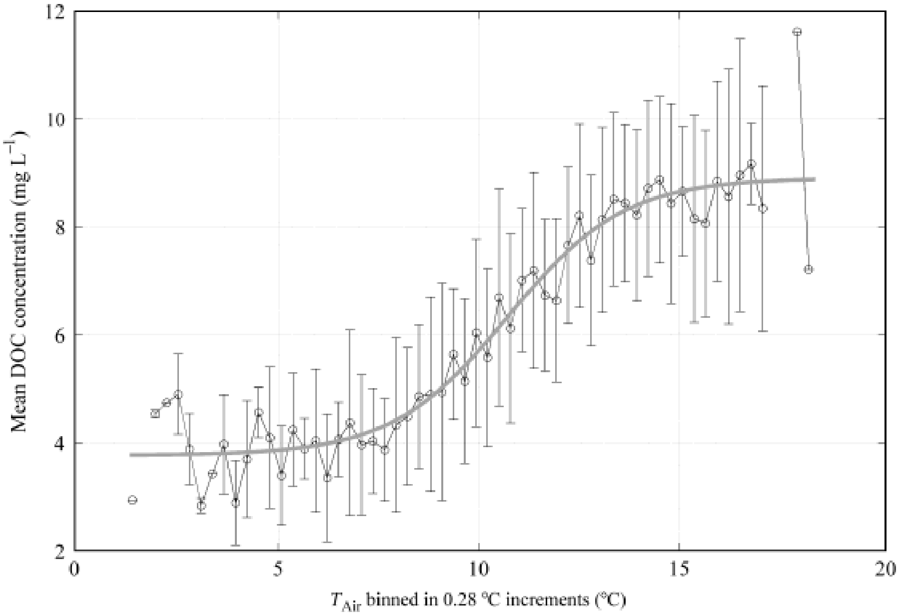

Fig. 1 S-shaped relationship of binned mean daily air temperature (T_{air}) and corresponding mean daily dissolved organic carbon (DOC) concentration.

(2007) (Fig. 2). Only two out of 23 seasons experienced no significant temperature and/or precipitation anomaly, i.e., not in the upper or lower quartile (winter 2005/2006 and summer 2004). On the contrary seven seasons experienced both temperature and precipitation anomalies (drier/wetter and warmer/cooler). In total, eight seasons received significantly higher precipitation with spring being the season with most precipitation anomalies (Fig. 2). Lower precipitation was observed only for four seasons. In general, precipitation at the Glencar peatland showed a large IAV over the 6 years observation period from 2235 mm in 2007 up to 2952 mm in 2006 (which corresponds to a 32% increase over the driest year) as well as a high inter-seasonal variation (Fig. 3c). The average number of wet days (i.e., $>1\,\mathrm{mm\,day^{-1}}$) was 209. Temperature showed an even higher number of anomalies than precipitation with 65% of the study period (thus 15 seasons) experiencing temperatures in the top quartile (Fig. 2). Only one single season was colder than normal. The average annual air temperature over the period 2003–2008 was 10.6 ± 0.2 (± 1 SD) °C with a mean average air temperature from May to October of 13.3 ± 0.4 °C and from November to April of 7.8 ± 0.4 °C. Daytime Q_{PAR} showed low IAV with slightly higher standard deviation during the summer than the winter time (Fig. 3a). During 2003–2008 the water level fluctuations ranged between 2 cm above and 17 cm below the low lawn surface with low standard deviation during the winter and higher standard deviation during the summer time (Fig. 3d) resulting in a mean annual difference over the 6 years of 3 cm.

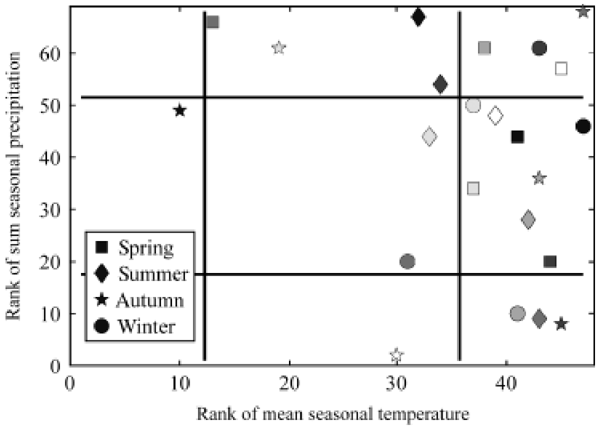

Fig. 2 Rank of the seasonal temperature and precipitation of the period 2003–2008, relative to the rank for the past 47 years for temperature and past 68 years for precipitation. 2003 is in white and the colour shading is getting darker for each following year until 2008 is shown in black.

Annual NECB

The measured annual cumulative NEE ranged from a minimum uptake of $12.5\,\mathrm{g\,C{-}CO_2\,m^{-2}}$ in 2006 to a maximum uptake of $84.0\,\mathrm{g\,C{-}CO_2\,m^{-2}}$ in 2005 with a 6 years mean annual cumulative NEE of -47.8 ± 30.0 (± 1 SD) $\mathrm{g\,C{-}CO_2\,m^{-2}\,yr^{-1}}$ (Fig. 4, Tables 1 and 2). The uncertainty associated with each estimate of annual NEE is less than $0.8\,\mathrm{g\,C{-}CO_2\,m^{-2}\,yr^{-1}}$ for random errors and the error associated with individual C measurements on the gap-filling technique ranged between ± 2 and $\pm 5\,\mathrm{g\,C{-}CO_2\,m^{-2}\,yr^{-1}}$ within the 6 years (Table 1). On a seasonal basis, winter NEE was always positive, i.e., a loss of C to the atmosphere ranging from 13 to $26\,\mathrm{g\,C{-}CO_2\,m^{-2}}$ while the summer showed always an uptake of C in the order of $42{-}88\,\mathrm{g\,C{-}CO_2\,m^{-2}}$ (Fig. 5a). Spring as well as autumn showed an average close to zero while varying between uptake and loss of C between the years (Fig. 5a). The largest variation was observed for spring and summer (Fig. 5a).

Methane flux from the peatland differed between microform type (Laine *et al.*, 2007). Integrating the flux from all microforms according to their spatial distribution within the EC footprint, the annual emission of CH_4 ranged from 3.6 to $4.6\,\mathrm{g\,C{-}CH_4\,m^{-2}\,yr^{-1}}$ with a 6 years mean of 4.1 ± 0.5 (± 1 SD) $\mathrm{g\,C{-}CH_4\,m^{-2}\,yr^{-1}}$ (Fig. 4, Tables 1 and 2). The standard errors of the average annual CH_4 flux varied between years and microforms (Table 1). Flux from hollows including *M. trifoliata* had the highest variation between replicate plots (6 years average $\pm 2.6\,\mathrm{g\,C{-}CH_4\,m^{-2}\,yr^{-1}}$) and hollows with moss cover the lowest (6 years average $\pm 0.6\,\mathrm{g\,C{-}CH_4\,m^{-2}\,yr^{-1}}$). The weighted error across all microforms ranged from 1.6 to $2.0\,\mathrm{g\,C{-}CH_4\,m^{-2}\,yr^{-1}}$ over the 6 years (Table 1). On a seasonal basis the flux increased in the order winter < spring < autumn < summer and with increased flux also the variation among the 6 years increased (Fig. 5b).

Discharge from the catchment of the peatland stream always exceeded $1900\,\mathrm{mm\,yr^{-1}}$. For the 2 years of DOC measurements (2007 and 2008), the average DOC concentration was 6.5 ± 2.0 (± 1 SD) and $6.1 \pm 2.7\,\mathrm{mg\,L^{-1}}$ resulting in an annual loss of C as DOC of 11.9 and $15.0\,\mathrm{g\,C\,m^{-2}}$ in 2007 and 2008, respectively (Fig. 4). The annual error associated with the discharge measurements and the basin area were ± 1.2 and $\pm 1.3\,\mathrm{g\,C\,m^{-2}}$ for 2007 and 2008, respectively (Table 1). For the years 2003–2006, the modelled DOC flux [Eqns (3) and (4)] and error estimates ranged between 13.1 ± 3.1 and $16.5 \pm 3.2\,\mathrm{g\,C\,m^{-2}}$ (Fig. 4, Table 1). This results in an annual average DOC flux estimate of 14.0 ± 1.6 (± 1 SD) $\mathrm{g\,C\,m^{-2}}$ (Fig. 4, Table 2). On a seasonal basis the DOC flux did not show a clear pattern but for the 6 years average it increased in the order spring < summer

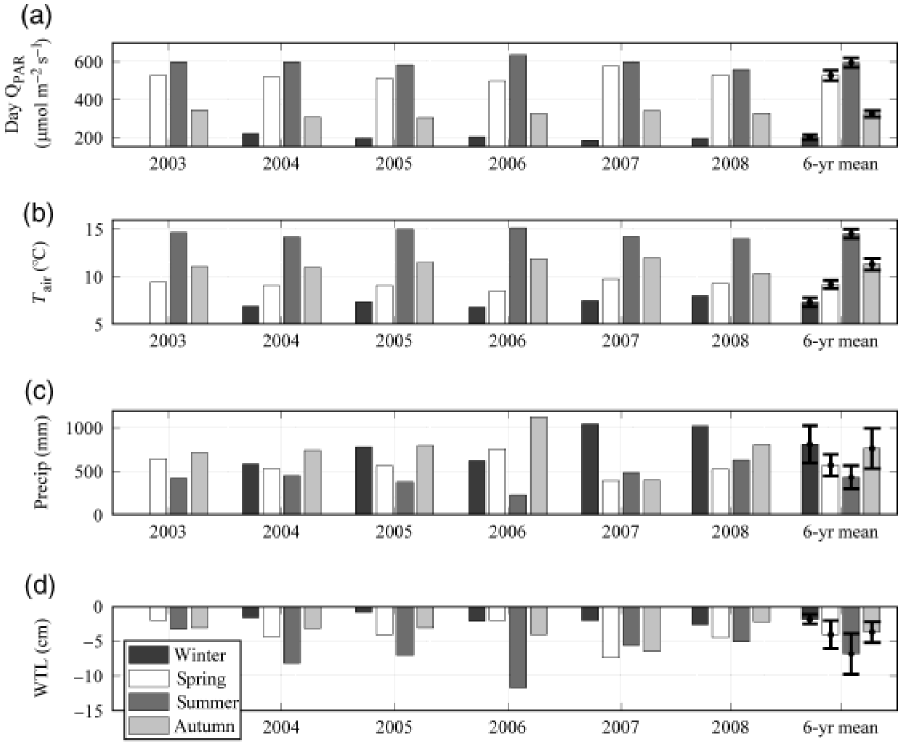

Fig. 3 Seasonal variation for the years 2003–2008 and average over the 6 years for daytime Q_{PAR} (a), air temperature (b), precipitation (c) and water table level (d).

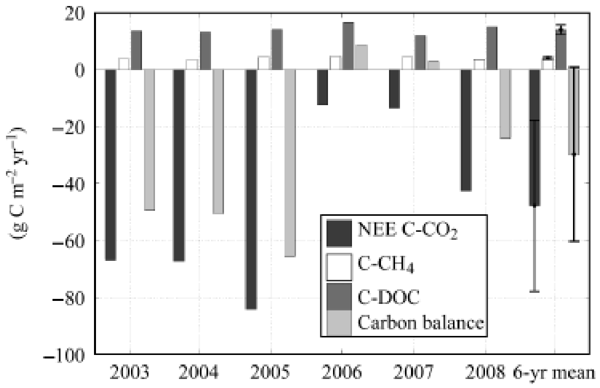

Fig. 4 Sums of the annual carbon balance components for 2003–2008 and their 6 years mean and standard deviation. The flux of dissolved organic carbon (DOC) only includes the loss of DOC in the stream.

$<$ winter $<$ autumn with the highest interseasonal variation in autumn and similar ranges for the other three seasons (Fig. 5c). On average, the concentration of POC in the stream was 6.5% of the total organic C, which equates to a loss of POC from the catchment of about $1.0\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$. The peatland received carbon as DOC through precipitation with a mean concentration of $0.7\,\mathrm{mg\,L^{-1}}$ adding between 1.7 and $2.2\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ (average $1.9\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$) in the years 2003–2008. In the following C balance discussion, the input of C through rain and the loss through POC were not taken into account as they approximately cancel each other out.

Combining the annual import and export of C for the Glencar bog resulted in a mean 6 years C balance of -29.7 ± 30.6 ($\pm$1 SD) $\mathrm{g\,m^{-2}\,yr^{-1}}$ with NEE being the largest and most variable component of the C balance (Fig. 4, Tables 1 and 2). During the 6 years NEE was always negative (Fig. 4, Table 1), i.e., a net uptake of CO_2. The calculation of the total C balance (C–CO_2 + C–DOC + C–CH_4) showed that the 2 years 2006 and 2007 were small C sources while the remaining 4 years were sinks for C (Fig. 4, Tables 1 and 2). On average, the C loss as CH_4 and DOC accounted for about 9% and 29% of the mean NEE, respectively. As done by Roulet *et al*. (2007) we combined all the seasons with the lowest and the highest NEE, CH_4 and DOC to bracket the potential maximum and minimum carbon balance between $+15$ and $-85\,\mathrm{g\,m^{-2}\,yr^{-1}}$. This estimate might overestimate the range of the C balance since this approach improperly considers that the distribution of the three fluxes is independent.

Bulk density samples from Glencar did not show any significant variation with depth and had an average

Table 1 NEE, CH_4, DOC and C balance for Glencar for the years 2003–2008 based on measurements and predictions

	NEE ($g\,C–CO_2\,m^{-2}\,yr^{-1}$)	CH_4 ($g\,C–CH_4\,m^{-2}\,yr^{-1}$)	DOC ($g\,C\,m^{-2}\,yr^{-1}$)	C balance ($g\,C\,m^{-2}\,yr^{-1}$)
2003	−66.8 ± 5.2	3.8 ± 1.6	13.5 ± 3.2	−49.6 ± 6.3
2004	−67.2 ± 3.0	3.6 ± 1.6	13.1 ± 3.1	−50.5 ± 4.6
2005	−84.0 ± 4.8	4.5 ± 1.9	13.9 ± 3.2	−65.6 ± 6.1
2006	−12.5 ± 3.4	4.6 ± 2.0	16.5 ± 3.2	8.6 ± 5.1
2007	−13.5 ± 2.3	4.2 ± 1.9	11.9 ± 1.2	2.8 ± 3.2
2008	−42.7 ± 4.7	3.6 ± 1.6	15.0 ± 1.3	−24.1 ± 5.1

The given error estimate for each flux is calculated as described in 'Materials and methods'.
NEE, net ecosystem exchange; CH_4, methane; DOC, dissolved organic carbon.

Table 2 NEE, CH_4 and DOC (TOC for Degerö Stormyr) (±1 SD) for Glencar, Mer Bleue and Degerö Stormyr and their estimated C balance including the three fluxes

	Glencar (Ireland)	Mer Bleue (Canada)	Degerö Stormyr (Sweden)
NEE ($g\,C–CO_2\,m^{-2}\,yr^{-1}$)	−47.8 ± 30.0	−40.2 ± 40.5	−51.5 ± 4.9 (5 years −53.6 ± 5.6)
CH_4 ($g\,C–CH_4\,m^{-2}\,yr^{-1}$)	4.1 ± 0.5	3.7 ± 0.5	11.5 ± 4.9
DOC (TOC) ($g\,C\,m^{-2}\,yr^{-1}$)	14.0 ± 1.6	14.9 ± 3.1	13.0 ± 1.5
C balance ($g\,C\,m^{-2}\,yr^{-1}$)	−29.7 ± 30.6	−21.5 ± 39.0	−27.1 ± 7.0

NEE, net ecosystem exchange; CH_4, methane; DOC, dissolved organic carbon; TOC, total organic carbon.

value of $0.045\,g\,cm^{-3}$ (C. Lewis, unpublished results). Using this bulk density value and assuming that soil organic carbon (SOC) in organic matter is about 50%, a rough estimate of the peat height growth at the surface can be calculated. The 6 years average carbon balance was converted into a height growth rate of $1.3\,mm\,yr^{-1}$ ranging from a loss of peat of $0.4\,mm\,yr^{-1}$ (2006) to a growth of $2.9\,mm\,yr^{-1}$ (2005).

Discussion

The Glencar blanket bog showed an average annual C accumulation rate of $-29.7\,g\,C\,m^{-2}\,yr^{-1}$ with a large IAV ranging from a source of 8.6 to a sink of $-65.6\,g\,C\,m^{-2}\,yr^{-1}$ within the 6 years period (Fig. 4, Table 1). Precipitation and temperature exhibited a wide range as well but were biased towards wetter and warmer conditions compared with the period 1961–2000, raising the question on the representativeness of the measured time period as mean C accumulation rate of the long-term climatic conditions. The sum of the CH_4 and DOC flux was greater than NEE in 2 of the 6 years, confirming that not including the CH_4 and DOC fluxes can largely overestimate the C sink status of a peatland ecosystem. One of the 6 years (2006) had a fluvial loss of DOC even greater than NEE.

Sottocornola & Kiely (2010) presented a detailed analysis of the variation in NEE related to environmental conditions in Glencar for the 5 years October 2002 to September 2007. They found that the IAV of the annual NEE correlated positively with an earlier onset of the growing season but not with any other hydro-meteorological parameter. On a seasonal basis, the CO_2 uptake showed a preference for wet conditions in autumn and winter and for intermediate environmental conditions (not too wet, not too dry; not too cold not too hot) during the summer (2005, Figs 3 and 5a).

The flux of CH_4 in Glencar seemed to be more strongly related to temperature than to changes in water table level. The inclusion of the water table level in the nonlinear regression model [Eqn (2)] increased the explanatory power only for the wettest plots. Hence, spring, summer and autumn with the highest (lowest) CH_4 flux corresponded to the years with the warmest (coldest) seasons (Figs 3b and 5b). Winter CH_4 flux only showed a very small IAV due to its very low flux.

In Glencar, the highest monthly DOC flux did not occur at the same time as the highest DOC concentrations in the stream, which occurred during the summer time (Koehler *et al*., 2009). While in Glencar the DOC concentration showed a strong relationship to temperature (Fig. 1), the DOC flux is controlled by the discharge (Koehler *et al*., 2009). Therefore, no clear seasonal pattern can be observed for the DOC flux, but the highest flux corresponded to the season with the highest precipitation (autumn 2006) (Figs 3c and 5c).

To our knowledge, there are only two comparable studies presenting a multiannual C balance of a peatland ecosystem: Roulet *et al*. (2007) examined 6 years C balance of the Mer Bleue peatland, an ombrotrophic continental raised bog in southeast Canada, while Nilsson *et al*. (2008) presented 2 years C balance from the

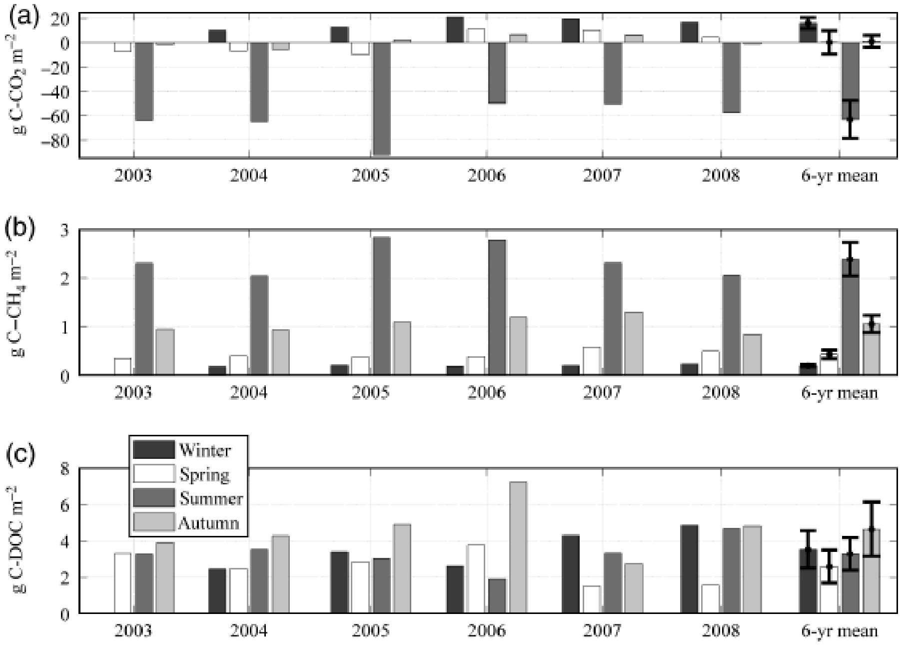

Fig. 5 Seasonal variation and average over the 6 years (2003–2008) of (a) net ecosystem exchange (NEE), which was entirely based on measurements; (b) CH_4 flux, which was estimated from periodic chamber measurements in 2003–2005 and in 2008; and (c) DOC flux, which was assessed based on measurements in 2007 and 2008.

Degerö Stormyr peatland, a minerogenic oligotrophic mire in northern Sweden. Despite differences in plant functional types, hydrology (runoff of about 400 and 450 mm yr^{-1} for Mer Bleue and Degerö Stormyr, compared with $>$1900 mm yr^{-1} in Glencar), chemical character and climatic conditions (continental and maritime settings), each having an influence on the single C flux components, the average C balance of the three peatlands showed very similar results (Table 2). Glencar and Mer Bleue's C balance showed a large IAV of similar order ranging from a sink to a source of C, while Degerö Stormyr's C balance exhibited a low IAV and was a sink in each year of measurement (Table 2). Also the partitioning of the single fluxes and their IAV was very similar for Glencar and Mer Bleue but somewhat different for Degerö Stormyr (Table 2).

For all three sites, NEE was the main component of the C balance for most years. The average annual NEEs were very similar, with Glencar and Mer Bleue exhibiting a much larger IAV than Degerö Stormyr (5 years NEE record, Nilsson *et al.*, 2008; Sagerfors *et al.*, 2008) (Table 2). Even though similar on an annual scale, seasonally Glencar and Degerö Stormyr showed a lower C loss during the winter and a smaller uptake during the growing season than Mer Bleue. Although there are multiple factors influencing NEE, the lower summer uptake in Glencar might be mainly attributed to a lower leaf area index (LAI) compared with Mer Bleue (Glencar: 0.6 m^2 m^{-2}, Mer Bleue: 1.3 m^2 m^{-2}) while the lower loss in winter in Glencar is likely due to some uptake by mosses and evergreen vascular plants, since winters are mild and often suitable for photosynthesis (Sottocornola & Kiely, 2010). The authors are not aware of LAI measurements for Degerö Stormyr. The importance of LAI was recently indicated in a NEE comparative study including 12 wetland sites across Europe and Northern America that found high CO_2 uptake at sites with high LAI (Lund *et al.*, 2009).

The flux and IAV of CH_4 are larger in Degerö Stormyr compared with Glencar and Mer Bleue where they showed similar values (Table 2). The low CH_4 flux in Mer Bleue is likely due to the dryness of the site [water table between 20 and 70 cm below the surface (Roulet *et al.*, 2007)], compared with Glencar and Degerö Stormyr [water tables ranging between the surface to about 15 and 20 cm below the surface, respectively (Fig. 3) (Nilsson *et al.*, 2008)]. Even so, the CH_4 flux in Glencar is surprisingly only slightly higher than in Mer Bleue considering Glencar's high water table level, large proportion of sedges, higher pH (Glencar: 4.5 $>$ Degerö Stormyr: 4 $>$ Mer Bleue: 3.9) and no extreme soil sulphate concentration (0.52–3.81 mg L^{-1}) compared with measurements in other peatlands in Ireland, the United Kingdom and Canada (1.9–9.6 mg L^{-1}) (Wind-Mulder *et al.*, 1996; Adamson *et al.*, 2001; Proctor, 2006). These factors are all in favour of CH_4 flux. The higher

CH_4 flux in Degerö Stormyr compared with Glencar might depend on Degerö Stormyr being dominated by lawn and carpet plant communities, microforms that were responsible for the highest efflux in Glencar (see also Laine *et al.*, 2007). Besides, it has to be noted that the used technique might introduce possible bias in the comparison. All three sites used the chamber technique measuring fluxes at the plot (covering $<1\,m^2$) and not ecosystem scale with time intervals being at best weekly and lacking diurnal variations. Furthermore different annual flux calculation models (Glencar, nonlinear regression; Mer Bleue and Degerö Stormyr, linear interpolation) and winter flux estimations were used (based on measurements in Glencar, zeroed in Mer Bleue, considered 20% of annual flux in Degerö Stormyr). Moreover, the CH_4 flux might be underestimated as ebullition is possible to occur which is not well captured with chambers (Christensen *et al.*, 2003).

The annual flux of DOC is similar in the three sites though revealing major differences when investigating the combination of concentration and discharge. In Glencar, the mean annual DOC concentration is very low ($6.3\,mg\,L^{-1}$, with DOC being about 93.5% of TOC) compared with Mer Bleue ($47.5\,mg\,L^{-1}$) and Degerö Stormyr (TOC concentration of $27.8\,mg\,L^{-1}$). The low mean and small absolute range of DOC concentration in Glencar (Koehler *et al.*, 2009) together with the high discharge ($>1900\,mm\,yr^{-1}$) supports the suggestion that Glencar does not accumulate DOC in the soil as it is continuously flushed due to frequent rain events (even in the summer). For Degerö Stormyr and Mer Bleue, a build up of DOC in the soil may occur during the summer time due to extended dry periods resulting in a flushing of DOC after rain events in late summer and autumn so that storage of DOC varies over the year more considerably than in Glencar. Despite these different patterns, the annual DOC exports are similar in the three sites. In Glencar frequent heavy rains are accompanied with low DOC concentrations resulting in high DOC flux throughout the year, whereas in Mer Bleue and Degerö Stormyr the DOC concentrations are higher and the discharge lower on an annual basis and the annual C export results from episodes with high flow rates, most importantly the spring snow melt and the late summer and autumn intense rains (Roulet *et al.*, 2007; Nilsson *et al.*, 2008).

While the degassing of CH_4 from the stream was found to be negligible (Billett *et al.*, 2004; Dawson *et al.*, 2004; Nilsson *et al.*, 2008), both Glencar and Mer Bleue C balances lack the inclusion of the fluvial loss of inorganic C, which was estimated to account for up to 7%–31% of the total stream C export (Dawson *et al.*, 2001; Billett *et al.*, 2004; Nilsson *et al.*, 2008). The use of this estimate for the loss of inorganic carbon would result in an additional loss of C for Glencar of 1.0–$7.4\,g\,C\,m^{-2}\,yr^{-1}$ considering the lowest and highest annual DOC flux.

For Glencar, the average annual C balance for the 6 years was converted into an approximate growth rate of the peatland surface of $1.3\,mm\,yr^{-1}$ using bulk density measurements of $0.045\,g\,cm^{-3}$. This value can not be directly compared with peat core studies of peat accumulation rates such as those over the past 400 years of $0.4\,mm\,yr^{-1}$ for the Mer Bleue bog (Roulet *et al.*, 2007). Turunen *et al.* (2004) gives an average bulk density for 23 Canadian peatlands, including Mer Bleue, of 0.042 and $0.051\,g\,cm^{-3}$ for hummocks and hollows, respectively, which would convert the average C balance of Mer Bleue to a peat height growth of 0.8–$1.0\,mm\,yr^{-1}$.

Summarizing, Glencar, Mer Bleue and Degerö Stormyr showed similar average C balances with NEE being the main component for most of the years. Despite differences in peatland types, climatic and geographic location, most NEE studies report multiple year averages between 20 and $60\,g\,C\,m^{-2}\,yr^{-1}$ (Limpens *et al.*, 2008) even if single years can vary largely as observed for Glencar and Mer Bleue. An important factor controlling the rate of carbon sequestration was found to be the peatland surface structure (Belyea & Malmer, 2004). Eppinga *et al.* (2009a) suggested that different combinations of structuring mechanisms (peat accumulation, water ponding and nutrient accumulation) lead to the development of similar peatland surface patterns, which could explain the development of different peatland types into similar stable structures (Eppinga *et al.*, 2009b). It has been argued that these similar structures might then exert a form of top-down control on peatland development in which large scale features (i.e., peatland size and shape) may constrain processes operating at a smaller scale (as acrotelm transmissivity, peat formation rate) leading to similar self-regulating processes (Belyea & Baird, 2006). This might determine comparable peat accumulation rates in different peatland types as observed for Glencar, Mer Bleue and Degerö Stormyr.

Conclusions

In this paper, we present the results of a multiannual C balance study for the Glencar Atlantic blanket bog in County Kerry, southwest Ireland. We showed that NEE is not the only important component of the peatland C balance but that also the CH_4 flux and stream water DOC flux are crucial components. NEE accounts for about 73% of the average C balance, while the CH_4 flux and stream water DOC flux contribute with about 6% and 21%, respectively. However, for two of the 6 years, the sum of the CH_4 and DOC flux exceeded the NEE, making the site a source of carbon. NEE had a significant IAV while both the CH_4 flux and stream water DOC flux showed low IAV. Therefore, the annual behaviour of NEE is the most important component determining the bog's annual C status. The existence of similar self-regulating processes in peatlands was suggested in the literature to be a possible mechanism determining comparable peat accumulation rates in different peatland types as observed for Glencar, Mer Bleue and Degerö Stormyr. For further investigation of these processes and an understanding of the impact of the climate change on peatland ecosystems, it is recommended to continue the current C balance studies and to extend the measurements of the total C balance to other peatland sites.

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