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Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland

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Abstract

Northern peatlands contain up to 25% of the world's soil carbon (C) and have an estimated annual exchange of CO_2-C with the atmosphere of 0.1–0.5 Pg yr^{-1} and of CH_4-C of 10–25 Tg yr^{-1}. Despite this overall importance to the global C cycle, there have been few, if any, complete multiyear annual C balances for these ecosystems. We report a 6-year balance computed from continuous net ecosystem CO_2 exchange (NEE), regular instantaneous measurements of methane (CH_4) emissions, and export of dissolved organic C (DOC) from a northern ombrotrophic bog. From these observations, we have constructed complete seasonal and annual C balances, examined their seasonal and interannual variability, and compared the mean 6-year contemporary C exchange with the apparent C accumulation for the last 3000 years obtained from C density and age-depth profiles from two peat cores. The 6-year mean NEE-C and CH_4-C exchange, and net DOC loss are -40.2 ± 40.5 (± 1 SD), 3.7 ± 0.5, and 14.9 ± 3.1 g m^{-2} yr^{-1}, giving a 6-year mean balance of -21.5 ± 39.0 g m^{-2} yr^{-1} (where positive exchange is a loss of C from the ecosystem). NEE had the largest magnitude and variability of the components of the C balance, but DOC and CH_4 had similar proportional variabilities and their inclusion is essential to resolve the C balance. There are large interseasonal and interannual ranges to the exchanges due to variations in climatic conditions. We estimate from the largest and smallest seasonal exchanges, quasi-maximum limits of the annual C balance between 50 and -105 g m^{-2} yr^{-1}. The net C accumulation rate obtained from the two peatland cores for the interval 400–3000 BP (samples from the anoxic layer only) were 21.9 ± 2.8 and 14.0 ± 37.6 g m^{-2} yr^{-1}, which are not significantly different from the 6-year mean contemporary exchange.

Key words: carbon balance, DOC, methane, net ecosystem exchange, peatland

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Introduction

Northern peatlands store between 200 and 450 Pg of carbon (C; Gorham, 1991; Turunen *et al.*, 2002) and the rate of C accumulation over the last 6–8 thousand has been estimated to be between 20 and 30 g C m^{-2} yr^{-1} (Gorham, 1991, 2003; Vitt *et al.*, 2000; Turunen *et al.*, 2002, 2004). The C balance of peatlands is of interest for several reasons. While the exchange of CO_2 between peatlands and the atmosphere is a relatively small component of the contemporary terrestrial exchange ($\approx$0.1–0.5 Pg yr^{-1} compared with $\approx$60 Pg for the net terrestrial exchange Schimel, 1995), the fate of the large store of C in peatland is of concern (e.g. Moore *et al.*, 1998) given the spatial pattern and magnitude of current and simulated changes in climate (Albritton &

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Meira Filho, 2001). Peatland regions are experiencing, and are expected to experience in the future, well above average winter and summer temperatures and significantly greater winter precipitation. There is less agreement among the climate models of what might happen to summer precipitation in northern regions, particularly over northern Europe. The C balance of peatlands should also be of interest for palaeoclimatic modelling (e.g. Brovkin *et al*., 2002), since the store of 200–450 Pg C exists because of a slow, varying, but persistent, C uptake over the last 10 000 years.

There are far fewer measurements of the contemporary exchange of C for northern peatlands than there are estimates of the past C accumulation rate (CAR) derived from peat cores. The contemporary measurements are also more varied, but this is in part due to differences in methods of measuring the exchange, the completeness of the measurement of inputs and outputs, and the short duration of observations – seasons to 1 or 2 years. Most studies measure only net ecosystem CO_2 exchange (NEE) using continuous micrometeorological methods (e.g. Shurpali *et al*., 1995; Suyker *et al*., 1997; Vourlitis & Oechel, 1997; Nordstroem *et al*., 2001; Schulze *et al*., 2002; Friborg *et al*., 2003) or chamber methods combined with empirical interpolation and spatial extrapolation techniques (e.g. Whiting, 1994; Bubier *et al*., 1999). With only a very few exceptions, NEE measurements are rarely extended throughout the winter season or for more than 1 or 2 years (cf. Lafleur *et al*., 2001, 2003; Arneth *et al*., 2002; Aurela *et al*., 2002, 2004). Further, the loss of C from the peatland by methane (CH_4) and dissolved organic C (DOC) export (cf. Waddington & Roulet, 2000; Billett *et al*., 2004) are seldom included, even though they are of the same order of magnitude as the long-term rate of C accumulation (Gorham, 1991).

The annual change in C, ΔC_{org}, for a peatland is given as

$$\Delta C_{org} = NEP + F_{CH_4} + netDOC_{EX}, \quad (1)$$

where NEP, net ecosystem production, is equal to the difference between the gross uptake and release of CO_2 by photosynthesis and ecosystem respiration integrated over the year (i.e. −NEE), F_{CH_4} is the loss or gain of C through the annual integrated flux of CH_4, and $netDOC_{EX}$ is the net gain or loss of DOC in water inputs and runoff (Lovett *et al*., 2006: where F_{CH_4}–$netDOC_{EX} = E$). Gorham (1991) provided a range of estimates for the various components of ≈ -20 to -30, 5, and 5–20 g C m^{-2} yr^{-1} for NEP, F_{CH_4}, and $netDOC_{EX}$, respectively: a negative sign indicates a loss to the atmosphere or a gain to the ecosystem. Gorham (1991) was also very clear that these estimates were based on an inadequate amount of data, and a mix of contemporary (e.g. CH_4 fluxes and DOC losses) and inferred net primary production, NPP, from peat accumulation rates.

It is well established that many peatlands can lose a substantial amount of C during the winter (e.g. Alm *et al*., 1999a; Lafleur *et al*., 2003; Roehm & Roulet, 2003). There is a wide range of annual NEE-C estimates from peatlands from a sink of −60 to a source of 90 g m^{-2} yr^{-1}, but most of these values are from short-term studies. Long-term measurements in a single peatland show large year-to-year variability and switches among years from sources to sinks (Arneth *et al*., 2002; Aurela *et al*., 2002; Lafleur *et al*., 2003).

Most reported annual C exchanges are for fens (e.g. Lafleur *et al*., 1997; Suyker *et al*., 1997, Vourlitis & Oechel, 1997; Alm *et al*., 1999b; Aurela *et al*., 2002; Schulze *et al*., 2002; Friborg *et al*., 2003) or for bogs where human activity, either on the peatland itself or in the surrounding catchment (e.g. Worrall *et al*., 2003; Billett *et al*., 2004), may have had some impact. Alm *et al*. (1999a, b) report a C loss of 90 g C m^{-2} yr^{-1} for a boreal bog due to an exceptionally dry summer, while Lafleur *et al*. (2003) report NEE-C ranging from −60 g m^{-2} yr^{-1} in wet years to near 0 in dry years for a raised bog. Arneth *et al*. (2002) found the NEE-C from a Siberian bog ranged from ≈ -60 to -36 g m^{-2} yr^{-1}, over a 2-year period, but the fluxes were measured only in the summer and the winter losses were modelled.

One of the unique characteristics of peatland ecosystems is that they retain a long-term, indirect record of NEP in the form of accumulating peat. Using age-depth relationships, peat densities, and C contents from the deeper anoxic portion of peatlands (referred to as the catotelm Ingram, 1978, which starts deeper than −0.3 to −0.5 m) the average long-term apparent rate of C accumulation (LORCA) can be obtained (Tolonen & Turunen, 1996; Clymo *et al*., 1998). While there have been many estimates of LORCA for peatlands (e.g. Vitt *et al*., 2000; Turunen *et al*., 2002; Gorham *et al*., 2003), as far as we know there has been no study that has compared a multiyear NEP and the CARs for the past for the same peatland. Schulze *et al*. (2002) compared NEP, ignoring CH_4, and DOC losses, with recent apparent rates of C accumulation (RERCA; Turunen *et al*., 2004) from the top 0.5 m of peat for a Siberian appa mire. However, estimates of RERCA grossly overestimate LORCA (e.g. Turunen *et al*., 2004) as the peat is still actively decomposing in these surface layers.

The objectives of the study are: (1) to present an annual C balance for a northern peatland over a 6-year period based on, as near as possible, complete-year measurements of all the major inputs and outputs to the ecosystem; and (2) to compare the contemporary multiyear mean C balance with the long-term C accumulation of the last few thousand years.

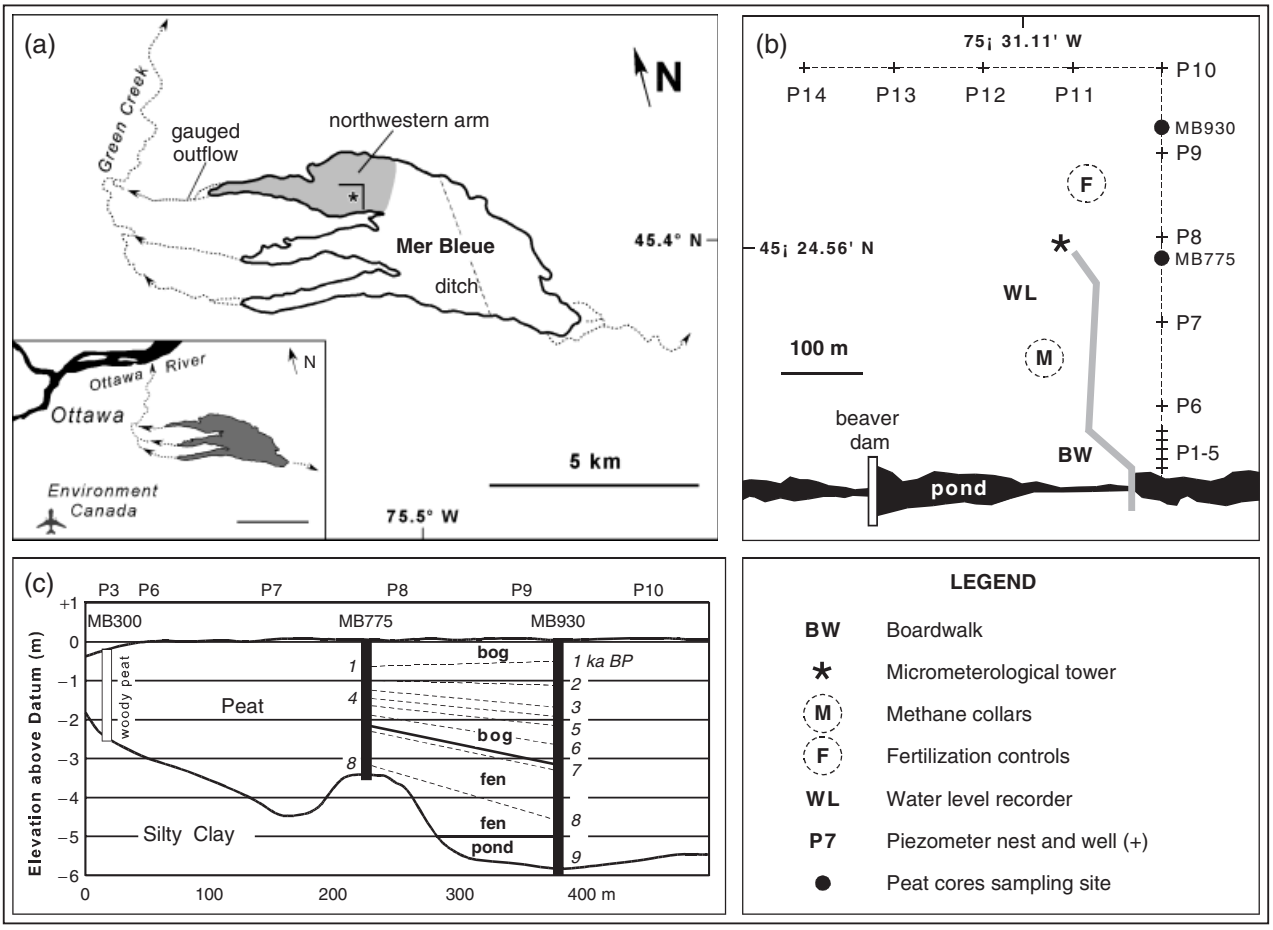

Fig. 1 Location of the study peatland (upper left), the location of the tower and where the peat cores were sampled (right panels), and the peat stratigraphy and age in cross section along the main axis piezometer network (lower left).

Methods

Site description

Mer Bleue peatland is located 10 km east of Ottawa, Ontario (45.41°N latitude, 75.48°W longitude, 69 m a.m.s.l.; Fig. 1). The climate of the region is cool continental, with a 30-year (1971–2000) mean annual temperature of 6.0 ± 0.8 °C and annual precipitation of 943 mm, 235 mm of which falls as snow between December and March. Total precipitation is fairly evenly spread among the 12 months, with a minimum of 58 mm in February and a maximum of 90 mm in July. The coldest month is January (-10.8 ± 2.9 °C) and the warmest month is July (20.9 ± 1.1 °C). The mean monthly air temperature is above 0 °C from April through November, and above 10 °C from May to September.

The Mer Bleue peatland lies in a postglacial channel system that was eroded into the floor of the former Champlain Sea basin. Regional ice retreat occurred shortly before 13 200 years ago and the Lower Ottawa River Lowlands were then invaded by Glacial Lake Iroquois (Anderson, 1988) depositing laminated silt and clay over sandy, silty gravel, and limestone outcrops. Around 13 100 years ago (Anderson, 1988; Richard & Occhietti, 2005), silty clay marine sediments 40–50 m thick were laid down over the glacio-lacustrine sediments as Champlain Sea rapidly invaded the isostatically depressed Saint-Lawrence River Lowlands. Marine waters lasted some 2500 years in the Central Lowlands, ending around 10 600 years ago when freshwaters dominated again in the basin (Lampsilis Lake phase, Elson & Elson, 1969). Modern contours of the Ottawa and St. Lawrence Rivers were attained around 7800 years ago. The postglacial channel system, now occupied by the Mer Bleue peatland basin, was carved by fluvial outbursts from the Ottawa River, during the emplacement of the early upper Great Lakes between 12 000 and 9500 years ago. The oldest organic (lake) sediments in the Mer Bleue basin date back some 9000 years ago. The peatland formed over the past 8400 years, beginning as a fen, and switching to the bog

phase ca. 7100–6800 cal. years BP (Auer, 1930; Mott & Camfield, 1969; P. J. H. Richard, unpublished radiocarbon dates).

The present Mer Bleue peatland covers approximately 28 km^2 and is roughly oval shaped with an east–west orientation. Two longitudinal lobes of fluvial sand/gravel material dissect the western end of the bog creating three separate arms (Fig. 1). The northwest arm, used in this study, is a slightly domed bog (Joyal, 1970), with peat depths varying from 5 to 6 m near the centre decreasing to <0.3 m at the margins with a narrow band of beaver ponds surrounding the bog. The bog surface has a hummock–hollow microtopography. The dominant evergreen (*Chamaedaphne calyculata, Ledum groenlandicum, Kalmia angustifolia*), and deciduous (*Vaccinium myrtilloides*) shrubs have an average height of 0.2–0.3 m and leaf area index (LAI) of $\approx$1.3 (Moore *et al*., 2002). Sedges (*Eriophorum vaginatum*) comprise a sparse cover and a few small trees (*Picea mariana, Larix laricina, Betula populifolia*) are present on hummocks. Hummocks and hollows are covered by *Sphagnum* mosses (*S. capillifolium, S. magellanicum*). Total aboveground and belowground biomass for vascular species, measured in 1999 and 2004, averaged 356 ± 100 g m^{-2} (Moore *et al*., 2002) and 433 g m^{-2} (Bubier *et al*., 2006), and 1820 ± 660 g m^{-2} (Moore *et al*., 2002) respectively, and *Sphagnum* capitulum biomass was 144 ± 30 g m^{-2} (Moore *et al*., 2002) to 158 g m^{-2} (Bubier *et al*., 2006).

Contemporary C balance measurements

Measurements began at Mer Bleue in May 1998, but for the purposes of the calculation of the annual C balance, we consider the C year to be from 1 November to 31 October: we present measurements from 1 November 1998 to 31 October 2004. In this section, we provide a brief but thorough summary of the measurements involved and indicate where more details can be found. NEE exchange measurements and data processing are described in Lafleur *et al*. (2001, 2003) but in our previous publications we used the period 1 June to 31 May for the C year, so there are slight differences in NEE totals. The assessment of the runoff hydrology and water borne export of DOC are discussed in detail in Fraser *et al*. (2001a, b). We have not published the CH_4 fluxes from Mer Bleue, but we used the same methods, procedures, instrumentation, and measurement protocols as described by Bubier *et al*. (2005). Our analysis of the C balance was restricted to the hydrologic catchment of the northwest arm of Mer Bleue: $\approx$4.8 km^2 (Fraser *et al*., 2001b; Fig. 1). This constraint was necessary because NEE and CH_4 flux are measured and computed on a areal (i.e. m^{-2}) basis, thus, a catchment boundary is necessary to convert the mass flux of dissolved C measured at an outflow into a unit area loss.

NEE. The main instrument site was an 8 m tower located 250 m north of the southern edge of the bog (Fig. 1). Fetch surrounding the tower site was limited only to the south (200–300 m), the least frequent wind direction. For all other bearings, fetch ranged from 500 to >1500 m. The eddy covariance (EC) technique was used to measure the net flux of CO_2 at a height of 3.0 m from the mean elevation of the hummock tops. Before 1 September 2000 the instrumentation consisted of a sonic anemometer–thermometer (model Solent 1012R3, Gill Instruments Ltd., Lymington, UK), and closed-path infrared gas analyser (IRGA, model 6252, LI-COR Inc., Lincoln, NB, USA), krypton hygrometer (Model KH20, Campbell Scientific, Inc., Logan, UT, USA), and a fine wire thermocouple. Air was drawn at 6.5 L min^{-1} through a sampling tube to the main instrument hut approximately 16.5 m away from the tower where the IRGA was stored. In September 2000 the IRGA was moved to an insulated, temperature-controlled box at the base of the tower with air drawn through a 4 m long sampling tube. Signals from all instruments were logged on a data logger (model CR7X, Campbell Scientific Inc., Logan, UT, USA) with a scan rate of 10 Hz and fluxes computed every 30 min from two 15 min subsampling intervals using the data logger covariance programme. Half-hour NEE was computed as the sum of the CO_2 flux and the rate of change of CO_2 storage in the air column below the height of the EC instrumentation. Details of flow corrections, WPL procedure, calibrations, quality control, and assurance are all outlined in Lafleur *et al*. (2003). Beginning January 2004 flux measurements were obtained using an upgraded system consisting of a model Solent R3-50 (Gill Instruments) sonic anemometer–thermometer and a model LI7000 closed-path IRGA (LI-COR) with air drawn through the 4 m sampling tube at 15 L min^{-1}. Digital signals from these sensors were recorded at 20 Hz using a computer. All CO_2 fluxes for the 6-year period were calculated from the covariance of the CO_2 mixing ratio and vertical velocity having undergone a three-axis co-ordinate rotation (Tanner & Thurtell, 1969). The changes in the EC system in 2004 were expected to improve the CO_2 flux measurements in part by reducing the loss of the high-frequency portion of the flux. The old and new systems were run concurrently and 30 min CO_2 fluxes obtained during rain-free periods in May and June 2004 were compared using linear regression. A correction factor of 1.25 for the old system fluxes ($n = 1533$, $r^2 = 0.91$) was found and applied to fluxes obtained before

January 2004, reflecting the average proportion of flux lost due to damping of high-frequency fluctuations as a result of the previously lower flow rates in the intake tube, slower sampling rates and slower IRGA response rates. Throughout the 6-year period, calibration of the IRGA was done manually every 2–4 weeks. The Fluxnet-Canada measurement and processing protocols were used in our analysis (Protocols for EC Flux Measurements, pp. 8–17, in Fluxnet-Canada Measurement Protocols, August 2003: http://www.fluxnet-canada.ca/).

A variety of environmental measurements were made in support of the flux data (Lafleur *et al*., 2001, 2003). These measurements included above canopy incoming photosynthetically active radiation (PAR), air temperature at 2.0 m from the bog surface and soil temperatures from 0.01 to 2.5 m below the top of one hummock and one hollow with arrays of copper–constantan thermocouples embedded in wood dowels. Depth to the water table was measured in two wells (one in a hollow and one in a hummock) using a float and counterweight system attached to a potentiometer.

On average, 42% of the half-hour NEE measurements were removed from each year's data set due to instrument malfunction or quality control procedures described by Lafleur *et al*. (2003). Of the removed data, 31% were due to calm conditions when friction velocity fell below 0.1 m s^{-1} at night or during the cold season, or both; 62% were due to concerns over data quality and instrument malfunctions, and 7% were due to a C uptake at night or during the cold season when 5 cm soil temperatures were below freezing. We assumed under the latter condition both the moss and the bulk of the roots would be frozen thus inhibiting photosynthesis. In order to obtain seasonal and annual sums of NEE, the gaps in measurements were filled using the same procedure for each calendar year of the 6-year period. First, gaps of one and two half-hours were linearly interpolated (on average, 10% of the gaps). An exponential relationship was then derived for the negative of nighttime half-hour NEE (assumed to be equivalent to ecosystem respiration, ER) and 5 cm soil temperature greater than 0 °C. Estimates of ER using this relationship were adjusted to match the seasonal variations in ER using a multiplier found by regressing modelled values against measured values for 200 consecutive half-hour measurements (between 7 days and 2 months) moving through the year in increments of 40 half-hours (e.g. Barr *et al*., 2004). For daytime and nighttime periods during winter when 5 cm soil temperature was below 0 °C, missing NEE was filled with the mean NEE from 200 consecutive half-hour measurements. Next, daytime estimates of gross ecosystem production (GEP) when soil temperatures were above 0 °C were estimated by adding measured and modelled ER to measured NEE. A rectangular hyperbolic relationship between GEP and PAR was evaluated for 15 June to 15 July of each year. GEP computed from this relationship was then adjusted to match the seasonal variations in GEP using the same procedure for ER above. Missing daytime NEE were filled using the difference between modelled ER and GEP.

The uncertainty associated with annual estimates of NEE was computed. We applied the Morgenstern *et al*. (2004) approach for an annual error estimate associated with a 20% random error on each half-hour value of NEE computed using propagation of errors. The uncertainty from the empirical relationships used for gap-filling was assessed using a resampling technique with replacement for 1000 repetitions (see Humphreys *et al*., 2005). Finally, as the majority of the gaps are biased to periods of C loss during the night or during the winter, the strategy for estimating ER for filling gaps was modified and used to recompute two additional sets of annual NEE. These included estimating ER using only a running mean and using a single-unadjusted annual relationship with 5 cm soil temperature.

Water borne loss of C. Discharge from Mer Bleue was measured at a culvert that passed under Anderson Road at the western end of the northwest arm (see Fig. 1 and Fraser *et al*., 2001a). Cross-sectional velocity was measured at the down stream end of the culvert using a Pygmy current meter (Gurley Precision Instruments, Troy, NY, USA) and discharge was calculated by the velocity-area method. Water level above the culvert was measured continuously using a float potentiometer connected to a data logger from 1998 through to 2002. Beaver activity (i.e dam construction and subsequent submergence of data loggers) meant that rating curves had to be recalibrated frequently. In 2002 a pressure transducer replaced the float-potentiometer measurements. Fraser *et al*. (2001b) determined there was a strong relationship between water table measured at the tower in the northwestern arm and discharge at the culvert outflow (Fig. 4a; Fraser *et al*., 2001b) and we used this relationship to estimate runoff during times when the water level record at the outflow was missing (~25% of the time).

DOC in the outflow water was sampled weekly or more frequently in 1998, 1999, and 2003 and 2004, but sampling was sporadic between 2000 and 2003. Samples were placed in clean Nalgene bottles, filtered through 0.45 μm membrane filters and the filtrate was analysed on a Shimadzu 5050 Total Organic Carbon analyser using Ultra-Zero air (<1.0 ppm CO_2) as the carrier gas. Samples were acidified with 2 N HCl to pH 2–4

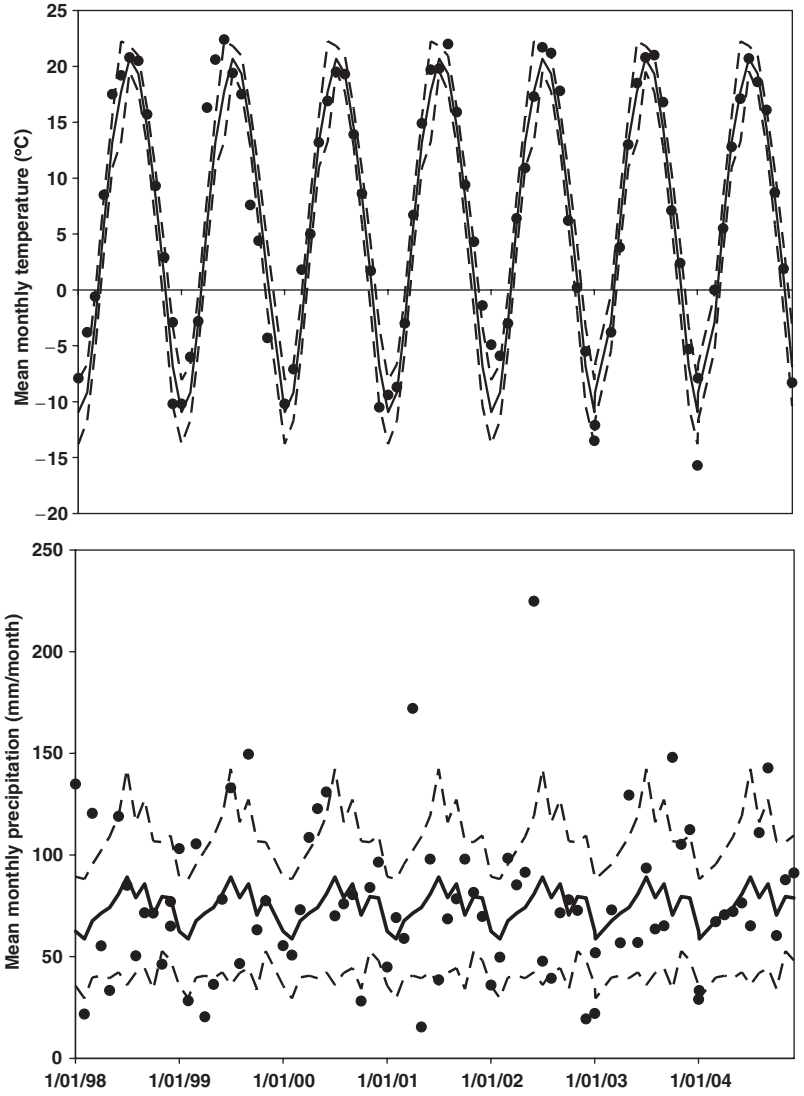

Fig. 2 Comparison between the mean monthly air temperature (top panel) and precipitation (lower panel) during the 6 years of the study (1998–2004) and the means derived from a 66-year period (1938–2004). All data were recorded at the Macdonald International Airport 12 km southwest of the Mer Bleue peatland. The circles are the monthly values, the solid line is the 66-year monthly means, and the dashed lines represent 1 SD above or below the 66-year monthly means.

to convert carbonates to CO_2 and sparged with N_2 for 10 min to release the CO_2. The samples were then combusted over a platinum catalyst at 680 °C to produce CO_2 gas, which was measured by an infrared gas analyser. An average of three injections per sample were made but sometimes a maximum of six injections were performed to obtain a coefficient of variance $<5\%$.

We chose Method-5 (Dawson *et al*., 2004) to calculate DOC export because, similar to Hope *et al*. (1997) and Dawson *et al*. (2004), we found no relationship between DOC and discharge (Fraser *et al*., 2001b). For the periods where there were too few DOC measurements to interpolate, we used the mean seasonal concentrations of DOC obtained from the 3 years when the sample size was large and the measured discharge for the desired time to estimate DOC loss. Fraser *et al*. (2001b) estimated overall error in annual DOC loss from Mer Bleue by combining the errors associated with discharge, the chemical analysis of DOC, and interpolation among sample points to be approximately $\pm 40\%$.

We did not measure DOC input in rainfall, which is fairly small but not insignificant. To compute the input of DOC in precipitation, we assumed an average concentration of DOC of 2.0 mg L^{-1} based on the results of studies at Hubbard Brook (Likens & Bormann, 1995) and near Montreal, Quebec (Dalva &

Moore, 1991) and multiplied this by the total amount of precipitation received at Mer Bleue during the period of interest.

CH_4 fluxes. CH_4 emissions were measured by a static chamber method at two locations in the northwest arm: one site, containing 20 collars, was between the tower and the peatland margin (Fig. 1: M), and the other site, containing 12 collars, was closer to the centre of the peatland (Fig. 1: F). A large number of measurements were made in 4 of the 6 years and few measurements were made in 1999 and 2001. CH_4 emissions were measured using two different chambers (volumes 0.018 and 0.045 m^3, and areas of 0.05 and 0.03 m^2) placed on water-sealed collars inserted $\approx$0.1 m into the peat (see Bubier *et al*., 2005). The air in the enclosure was sampled every 5 min for 25 min through a septum and stopcock, and the samples were analysed on a Shimadzu Mini II gas chromatograph (Shimadzu Scientific Instruments, Columbia, MD, USA) equipped with a flame ionization detector. The GC was calibrated for each sample period with three standards and periodically checked to ensure the calibration had a reproducibility of $\pm$1%. The fluxes of CH_4 were calculated from the slope of the regression between CH_4 concentration and time.

The seasonal emissions of CH_4 for each location were estimated by interpolating between sample dates. It was assumed for the purposes of determining the annual fluxes that the annual emission period was 180 days. It has been shown that in many peatlands there is a winter flux of CH_4 that can amount to between 2% and 10% of the annual CH_4 emissions (e.g. Melloh & Crill, 1996; Alm *et al*., 1999b) but for the purposes of our C balance we have assumed that winter fluxes were zero.

Past C balance measurements

The many past CARs obtained from peat core studies are less variable than contemporaneous ΔC_{org} estimates due to the numbers of years compressed into even 1 cm increments of cores and the low number of cores taken in an individual peatland. When multiple cores are taken in a single peatland, the estimates of CAR can vary considerably between cores (Korhola *et al*., 1996; Lavoie & Richard, 2000a, b). We sampled two peat cores from the area near the tower dominated today by *Sphagnum* moss and *C. calyculata*, to reconstruct the palaeoecology of the peatland and to determine the temporal variability in LORCA (Fig. 1). The upper 1.44 m (core MB930) and 2.00 m (core MB775) were sampled with a 2 m long and 0.1 m inner diameter Coüteaux sampler (Coüteaux, 1962): the remaining

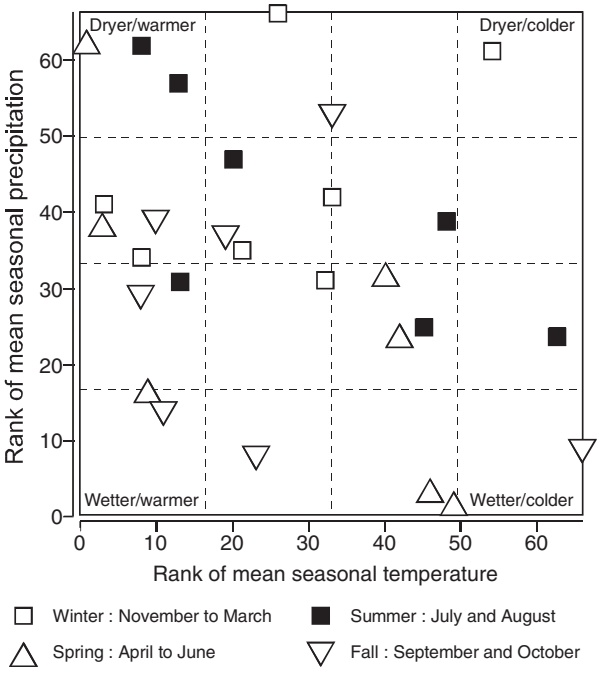

Fig. 3 Rank of the seasonal temperature and precipitation for the 6 years of the study, 1998–2004, relative to the rank of all seasons from the full 66 years of record (1938–2004). The winter, spring, summer, and autumn are November–March, April–June, July–August, and September–October, respectively.

1.5–3.0 m was sampled with a 1 m long, 0.075 m inner diameter Russian corer (Jowsey, 1966) yielding hemicylindric cores, down to 5.97 m (MB930) and 3.47 m (MB775). CARs were established from an age-depth relationship combined with fine resolution measurements of density and C concentration in the cores.

Fifteen age determinations were used for core MB930, either from radiocarbon dates ($N = 5$) or from palynostratigraphical correlation with other radiocarbon dated pollen diagrams in the Montreal–Ottawa area ($N = 10$). The age for core MB775 was obtained through correlation against the pollen diagram from core MB930 ($N = 8$ palynostratigraphically correlated samples). Samples (1 cm^3) of fresh peat were dried at 105 °C, weighed, and ignited at 600 °C, to determine density and organic matter content (Dean, 1974; Beaudoin, 2003). C concentration was estimated to be 50% of the organic matter content. Turunen *et al*. (2004) analysed the top 0.60 m for 48 cores from 24 different bogs in eastern Canada and obtained a mean of 46%. We used this C concentration in our calculations. Measurements from core MB930 were made every 0.01 m from the surface to 1.44 m, and every 0.04 m from 1.44 to 5.97 m and for the MB775 core, every 0.02 m from 0 to 2.00 m, and every 0.04 m

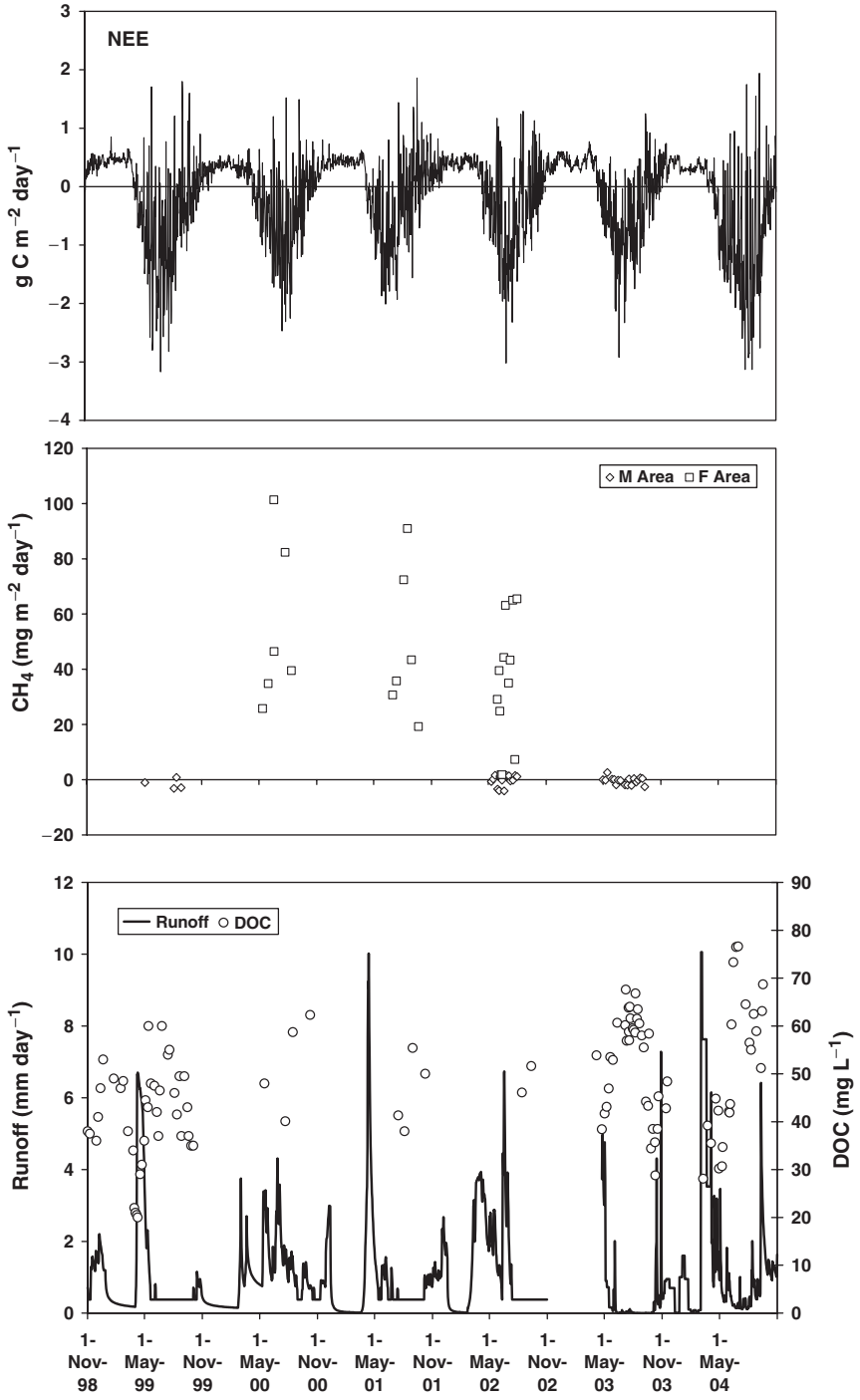

Fig. 4 Time series of the eddy covariance net ecosystem CO_2 exchange (NEE; direct observations and in-filled; top panel), instantaneous CH_4 flux (middle panel), and discharge and dissolved organic carbon (DOC) concentrations at the outflow of the Mer Bleue peatland (bottom panel). In the case of the CO_2 exchange the atmospheric sign convention as been adopted – i.e. a negative is a loss from the atmosphere or a gain by the peatland.

from 200 to 347 cm for the MB930 core. Long-term rates of C accumulation (LORCA) were calculated using a smoothed, age-depth model for each core, the estimated C concentration for each sample, and the interpolated deposition time of each depth increment (e.g. either 0.01 or 0.04 m). LORCA was determined for the period between 3000 and 400 years ago to avoid including the acrotelm portion of the cores where the CARs are

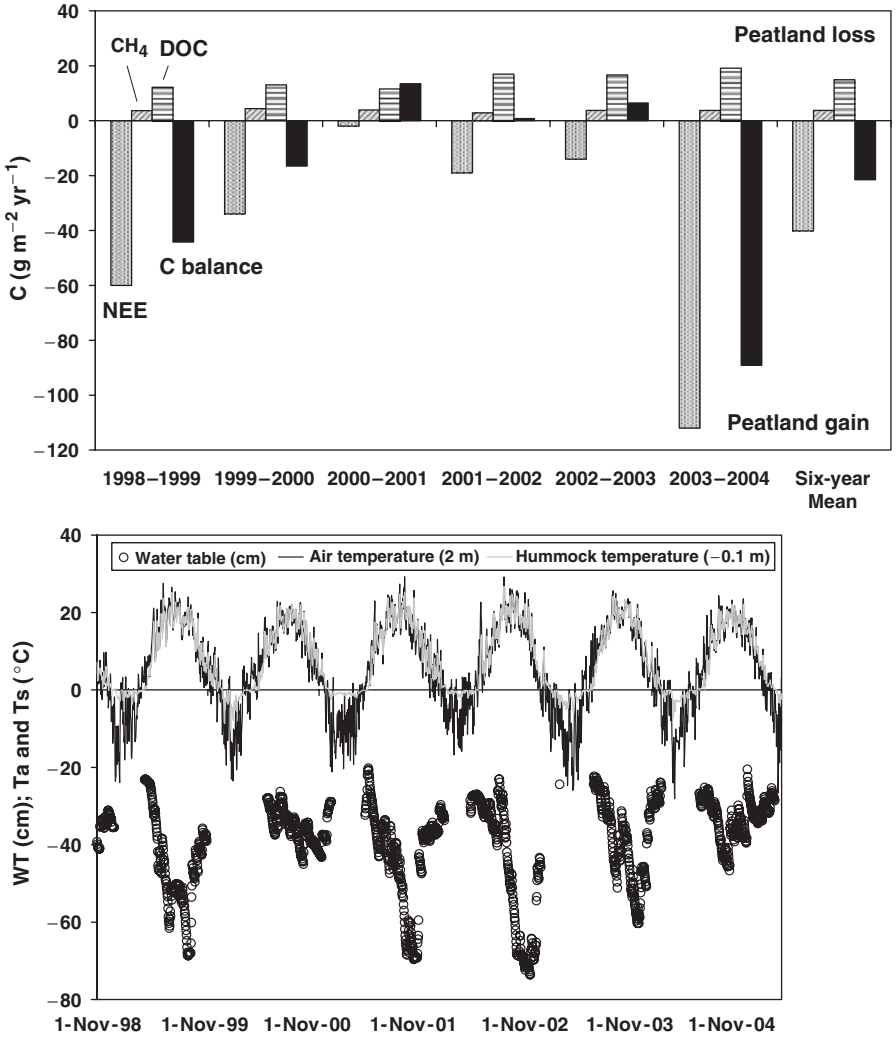

Fig. 5 Components of the annual carbon balance (top panel) and the trends on air, hummock peat temperature and water table for the 6 years (1 November 1998 to 31 October 2004) for the Mer Bleue peatland (bottom panel).

not representative of the long-term rates because the peat is still actively decomposing in the oxygenated, unsaturated zone (Turunen *et al.*, 2004). Peat age of 400 years corresponds to depths of 0.32 m in core MB930 and 0.45 m in core MB775, and zero depth corresponds to the base of living *Sphagna*. Deposition time within this window varies between 16 and 42 yr cm^{-1} for the MB930 core and between 19 and 31 yr cm^{-1} for the MB775 core.

Results

Annual and seasonal climate variations

The climate for 1998–2004 was quite variable (Fig. 2): over half the mean seasonal temperatures and total precipitation were greater than 1 SD from the long-term mean and totals for the 66-year record at the Ottawa Macdonald-Cartier International Airport (45.19°N latitude, 75.40°W longitude, 114 m a.m.s.l.), approximately 12 km southwest of the Mer Bleue peatland (Fig. 1). We ranked the seasonal temperature and precipitation within the 66 years of record (Fig. 3). The winters of 2002 and 2004, the spring of 1999, the summers of 2001 and 2002, and autumn 2000 received significantly (i.e. in the upper or lower quartile) less precipitation, while the springs of 2000 through 2002, and the autumns of 1999, 2003, and 2004 experienced precipitation closer to the norm. Only three seasons were colder than normal (summer and autumn 1999, and winter 2002), while in 11 of the remaining 21 seasons, or 45% of the study period, the temperatures were in the top quartile. Six out of a possible 24 seasons experienced both large temperature and precipitation anomalies (drier/wetter and warmer/cooler).

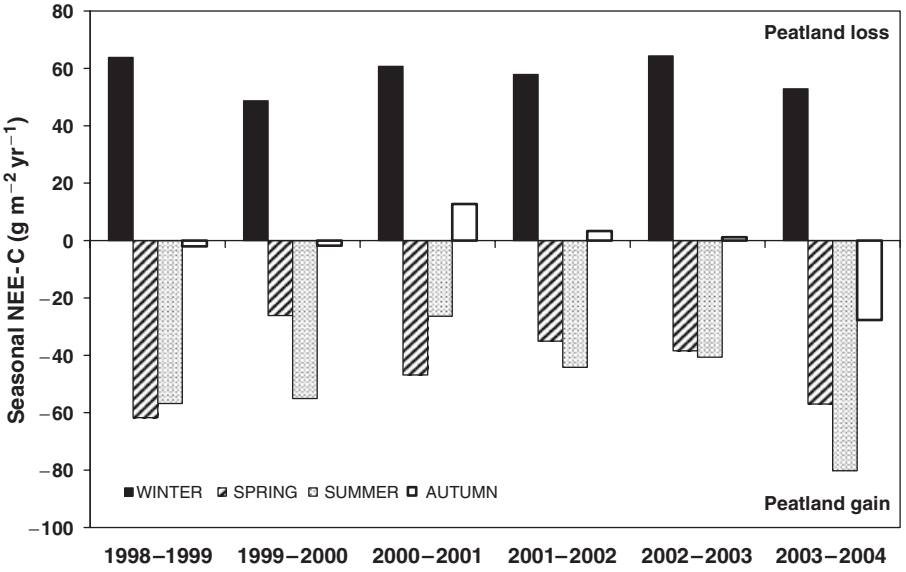

Fig. 6 Seasonal NEE from 1 November 1998 to 31 October 2004 for the Mer Bleue peatland. The seasons were defined in the caption for Figure 3.

Contemporary annual C balance

The NEE, CH_4 fluxes, runoff, and DOC concentration for the period 1 November 1998 to 31 October 2004, for the Mer Bleue peatland are shown in Fig. 4. NEE-C ranges from a maximum uptake $>2.5\,g\,m^{-2}\,day^{-1}$ in June or early July in each year to a maximum loss of $>1\,g\,m^{-2}\,day^{-1}$ (Fig. 4a). Mer Bleue took up CO_2 between mid-April to mid-October. The shift from the winter loss of CO_2 to net uptake in the spring was well defined in most years (April 16 ± 5 days), but the switch from net uptake to release in the autumn (October 3 ± 17 days) was more variable among years. Mer Bleue released CO_2-C over the winter [mean loss 58.1 ± 6.2 (± 1 SD) $g\,m^{-2}\,t^{-1}$; maximum 64.4, minimum 48.7, where 't' indicates the duration of the season in question which varied among years] and experienced an uptake through the spring, summer, and autumn (mean net uptake $-97.1 \pm 38.7\,g\,m^{-2}\,t^{-1}$; maximum -164.8, minimum -76.0). The annual cumulative NEE-C ranged from a minimum of -2 (2000–2001) to a maximum of $-112\,g\,m^{-2}\,yr^{-1}$ (2003–2004) and the 6-year mean annual cumulative NEE-C was $-40.2 \pm 40.5\,g\,m^{-2}\,yr^{-1}$ (Fig. 5).

The CH_4 flux from Mer Bleue ranged from a maximum uptake of $-4.1\,mg\,m^{-2}\,day^{-1}$ to a maximum emission of $101.4\,mg\,m^{-2}\,day^{-1}$. The CH_4 flux differed considerably between the two sites (Fig. 4b). In the area M the CH_4 fluxes were on average a small uptake (mean $-0.1 \pm 3.6\,mg\,m^{-2}\,day^{-1}$; maximum 21.2, minimum -4.1). However, closer to the centre of the peatland (area *F*) there was a consistent net emission (mean $43.5 \pm 23.2\,mg\,m^{-2}\,day^{-1}$; maximum 101.4, minimum -1.8). To estimate the annual flux of CH_4 we assumed, based on visual inspection of various images of Mer Bleue, that these separate areas made up 40% and 60% of the surface area of the bog. The annual loss of C as CH_4 ranged from 2.8 to $4.4\,g\,m^{-2}\,yr^{-1}$, with a 6-year mean of $3.7 \pm 0.5\,g\,m^{-2}\,yr^{-1}$ (Fig. 5).

We have 5 years of reasonably good estimates of runoff and 3 years of DOC concentration (1998–1999 and 2002–2004; Fig. 4c). The arithmetic mean concentration of DOC at the peatland outflow was $47.5 \pm 12.6\,mg\,L^{-1}$ (maximum 76.6, minimum 20.0). There was a marked seasonal pattern in DOC concentration, from lower in the spring when runoff was greatest (20.0–47 $mg\,L^{-1}$) to higher in the summer during periods of negligible flow (47–76 $mg\,L^{-1}$). Runoff varied considerably from year-to-year (mean $391 \pm 67\,mm\,yr^{-1}$; maximum 472, minimum 316), and followed differences in annual precipitation. Over 55% of the annual runoff occurred in March and April from snow melt. Combining runoff and DOC concentrations yielded a net mean annual loss of C via DOC export of $16.4 \pm 3.4\,g\,m^{-2}\,yr^{-1}$ (maximum 21.0, minimum 13.2). The mean annual input of DOC in precipitation was estimated to be $1.8 \pm 0.1\,g\,m^{-2}\,yr^{-1}$ (maximum 1.9, minimum 1.6), giving a mean annual net DOC export of $14.9 \pm 3.1\,g\,m^{-2}\,yr^{-1}$ (maximum 19.1, minimum 11.5; Fig. 5).

Combining the annual import and export of C for the Mer Bleue peatland resulted in a mean 6-year C balance

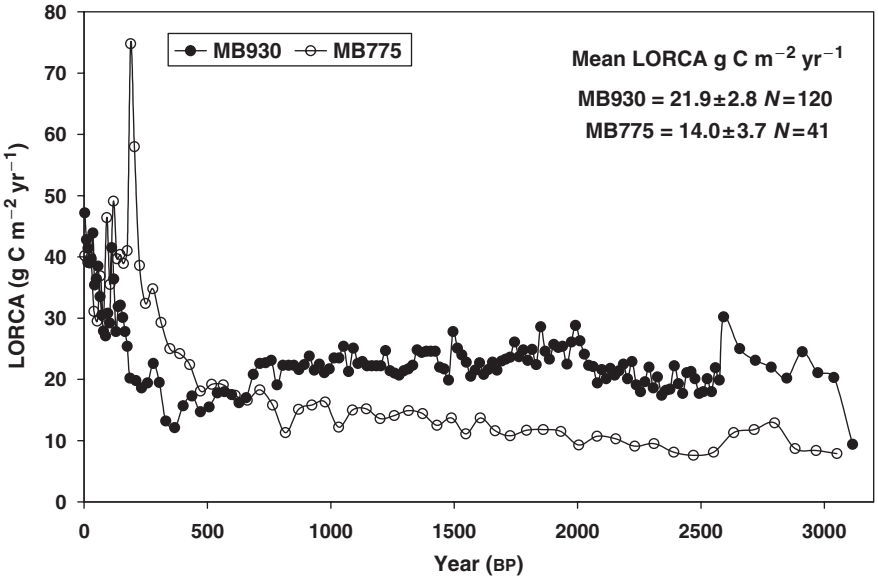

Fig. 7 Average long-term apparent rate of carbon accumulation for the last 3000 years for the Mer Bleue peatland. The mean and standard deviations of long-term apparent rate of C accumulation (LORCA) are based on accumulation rates from below the acrotelm/catotelm boundary only (i.e. >400 BP).

of $-21.5 \pm 39.0\,g\,m^{-2}\,yr^{-1}$ (Fig. 5). In 3 of the 6 years (2000–2001, 2001–2002, 2002–2003) the net C loss at Mer Bleue ranged from 13.5 to $0.8\,g\,m^{-2}\,yr^{-1}$. All 3 of these years experienced quite low water tables from mid to late summer through into the autumn (Fig. 5). In the other 3 years, the net sink for C ranged from -16.5 to $-89.2\,g\,m^{-2}\,yr^{-1}$: two of which had higher water tables throughout the summer and into the autumn. NEE is the largest and most variable (CV = 100%) component of the balance. However, while the loss of C by CH_4 in Mer Bleue is quite small, the loss of C via DOC export is an important component of the annual C balance. In fact, in no year was the NEE positive, but in 3 years the loss of C via DOC resulted in there being a net loss of C from the Mer Bleue peatland. CH_4 and DOC losses equate, on average, to 9% and 37% of mean NEE. If CH_4 and DOC were ignored, the uptake of C in the Mer Bleue peatland would be overestimated by 40% to 80% in those years that net uptake occurred, and a net loss of C would not have been estimated for the other 3 years.

Reliability of the 6-year mean C balance

Given the large variation in the C exchanges we have measured it is important to consider the robustness of the 6-year mean exchange. The uncertainty associated with each estimate of annual NEE varies depending on the nature of the error. For random errors, the uncertainty in the C balance is less than $1.6\,g\,m^{-2}\,yr^{-1}$. The 95% confidence intervals on annual estimates of NEE computed with the resampling technique gives an indication of the influence of individual C measurements on the parameters of the empirical relationships used for gap-filling were all less than $\pm 2\,g\,m^{-2}\,yr^{-1}$. The systematic biases associated with the gap-filling strategy resulted in the greatest uncertainties. Estimating ER using only a running mean generally resulted in less annual C uptake by $22 \pm 4\,g\,m^{-2}\,yr^{-1}$ on average (NEE-C increased by 13–39 $g\,m^{-2}\,yr^{-1}$). By using a single unadjusted annual relationship with 5 cm soil temperature, annual C uptake was generally greater by $7\,g\,m^{-2}\,yr^{-1}$ (NEE-C decreased by 33 to $-5\,g\,m^{-2}\,yr^{-1}$ for the 6 years). In most cases, the differences among years remained similar regardless of the gap-filling technique used.

Although we reduced the uncertainty in the observations as much as possible there was still a large uncertainty associated with the inherent variability in the C exchanges. To significantly reduce the SD many more years of observations would be needed. For example, assuming that the variance of the C balance we observed is representative of the 'normal' range, to reduce the SD to approximately equal to that of the mean ΔC_{org} would require $\approx$20 years of observations. The variability is a function of different weather conditions from year-to-year and season-to-season. An important question for determining the robustness of our observations is whether the period of measurement covers the possible range of climatic conditions. Ecosystems do not respond to changes in mean conditions as much as to changes in seasonal conditions, such as warmer/colder winters and depth of snow, and warm/cooler, wetter/

drier spring, summer, and autumn. Partitioning the annual NEE into seasonal NEE indicates there are large differences among the seasons over the 6 years (Fig. 6). The seasonal variation, expressed as SDs, of the winter, spring, summer, and autumn C exchanges are respectively ± 6.2, 13.6, 18.2, and $13.5\,g\,m^{-2}\,t^{-1}$. Winter showed the least variability. To approximate a potential maximum and minimum NEP, we combined all the seasons with the lowest and the maximum C exchange and this produced a range of -25 to $121\,g\,m^{-2}\,yr^{-1}$. We then combined this with the maximum and minimum losses for CH_4 and DOC to bracket the possible ΔC_{org} between 50 and $-105\,g\,m^{-2}\,yr^{-1}$.

Long-term C accumulation

Cores MB930 and MB775 estimate average, LORCA (obtained from samples below the acrotelm–catotelm boundary) of 21.9 ± 2.8 and of $14.0 \pm 3.7\,g\,C\,m^{-2}\,yr^{-1}$, respectively, between 3000 and 400 years ago (Fig. 7). The lower LORCA for MB775 is due to the position of the (overall) shorter core on a ridge at the bottom of the Mer Bleue basin (Fig. 1), affecting the long-term rate of decomposition until about 1800 years ago, after which both cores showed similar vegetational development.

Discussion

Six-year C balance of Mer Bleue

Our measurements show that the portion of Mer Bleue we examined has an average annual contemporary C accumulation around $21\,g\,m^{-2}\,yr^{-1}$, but the peatland C balance is inherently variable ranging from a source of 14 to a sink of $89\,g\,m^{-2}\,yr^{-1}$. In only one of the 6 years (1999–2000) was the annual C balance ($-16.5\,g\,m^{-2}\,yr^{-1}$) close to the 6-year mean. The large SD clearly demonstrates that attempting to establish the contemporary C balance of a peatland based on 1–2 years of data is not reliable. Equally important, our results show that ignoring the CH_4 and net DOC losses of C will lead to over estimating the C sink between ≈ 16 and $23\,g\,m^{-2}\,yr^{-1}$, which encompasses the value of the 6-year mean C sink. In our study, the CH_4 flux is a much smaller loss than DOC. The CH_4 flux is similar to those reported for many other bogs (e.g. 1–8 $g\,m^{-2}\,yr^{-1}$), but lower than the CH_4 losses reported for wetter, mineral-rich peatlands (e.g. 3–30 $g\,m^{-2}\,yr^{-1}$; Moore & Roulet, 1995; Nilsson *et al*., 2001). The DOC export from Mer Bleue is consistent with that observed for other peatlands (e.g. Waddington & Roulet, 1997; Worrall *et al*., 2003; Billett *et al*., 2004) and to that originally inferred by Gorham (1991).

To the best of our knowledge, this is the first full C balance constructed from multiyear measurements on any peatland, where the components NEE, CH_4, and DOC have been measured for more than 2 years. Waddington & Roulet (1997, 2000) estimated a C balance for a poor fen in northern Sweden based on chamber measurements of CO_2, CH_4 and estimates of groundwater flow and DOC concentrations. The NEE-C, CH_4-C, and DOC inputs and outputs between the 2 years of study were -10.3 and -3, 4.1 and 3.9, and 4.2 and $6.7\,g\,m^{-2}\,yr^{-1}$, respectively, yielding a near neutral C balance in both years. However, this balance had considerable uncertainty due to the sensitivity of the ecosystem scale exchange to the spatial extrapolation of exchanges at the topographic unit scale (Waddington & Roulet, 1997). In the present study, the uncertainties are much less than in Waddington & Roulet (1997) because the NEE flux obtained by eddy covariance is already spatially averaged and the DOC loss and runoff were measured at the catchment outflow, and not inferred from flownet analysis. Worrall *et al*. (2003), working on an upland peatland in England, arrived at values similar to ours, but their balance was made up from information on various components from different years and different peatlands. Based on the variations in NEE, CH_4, and DOC export from our study and among other peatland reported in the literature, we question whether this is a good approach.

Comparison of contemporary C balance and past C accumulation

Our results from two cores demonstrate the need for multiple core assessments of past CARs in order to assess LORCA adequately in a given peatland. Most studies on past C accumulation in peatlands are based on single, central cores. At Mer Bleue, in the vicinity of the tower, the two cores, MB930 and MB775, give some indication of the variability that can exist within the central part of a peatland. Based on a palynological study by Mott & Camfield (1969) between the northwestern and central arm of Mer Bleue (see Fig. 1 in Fraser *et al*., 2001a), 5.2 m of peat were retrieved dating back ca. 8500 years ago; we are confident that the much higher resolution MB930 core data are effectively representative of the overall CAR for most of the nontreed central part of the peatland. Consequently, a mean LORCA of about $20\,g\,C\,m^{-2}\,yr^{-1}$ probably applies to the entire peatland between 3000 and 400 years ago, and to the vicinity of the tower.

In a synthesis of C accumulation in western Canadian peatlands, Vitt *et al*. (2000) estimate a mean rate of $19.4\,g\,m^{-2}\,yr^{-1}$, but there was no disaggregation of accumulation rates by peatland type. Turunen *et al*.

(2004) reports a mean LORCA for 15 ombrotrophic bogs in eastern Canada of $19 \pm 8\,g\,m^{-2}\,yr^{-1}$, while Gorham *et al*. (2003) report a mean and median dry matter accumulation rate of 47 and $50\,g\,m^{-2}\,yr^{-1}$, respectively, for a widely dispersed sample of 32 North American peatlands. Assuming a 50% C concentration, they are equivalent to a CAR of 24 and $25\,g\,m^{-2}\,yr^{-1}$, or 22 and $23\,g\,m^{-2}\,yr^{-1}$ if a C concentration of 46% is used, as we have done. Turunen *et al*. (2002) analysed peat depth, age and C contents for over 1000 Finnish peatlands and estimated an overall CAR for undrained peatlands of $18.6\,g\,m^{-2}\,yr^{-1}$, of which bogs with a CAR of $20.8\,g\,m^{-2}\,yr^{-1}$, formed a subset of the sample. Based on these estimates, the Mer Bleue CARs are close to the mean for northern hemisphere bogs and fit well within the variance and range reported in regional surveys.

We know of no other studies that have directly compared a multiyear contemporary C accumulation estimate with a palaeoaccumulation estimate for the same peatland. For the Mer Bleue peatland the 6-year mean contemporary CAR is not statistically different from the LORCA obtained from the two peatlands cores (i.e. no difference between the contemporary C balance and the past C accumulation of the last 3000 years). It would be very difficult to obtain a statistical difference given the large interannual variability in NEE, but it is not likely that we would be able to obtain a sufficiently long record of contemporary C exchange to reduce the variance to much less than $20–30\,g\,m^{-2}\,yr^{-1}$.

Conclusions

In this paper, we report the results from an intensive multiyear study of a single peatland in the midcontinental cool-temperate climate zone of North America. How applicable are the results of this study to northern peatlands in general? Mer Bleue represents an ombrotrophic peatland, which is ubiquitous throughout northern North America, Europe, and Asia. These peatland ecosystems share similar developmental and ecological characteristics due to a certain degree of self-regulatory feedback between their hydrology and the processes that control peat accumulation (Gorham, 1991; Hilbert *et al*., 2000; Belyea & Baird, 2006). However, within the context of this generality, ombrotrophic peatland can display a wide variety of morphologies depending on their specific climatic and physiographic setting. Mer Bleue has a midcontinental location. We, therefore, would not expect our results to apply to ombrotrophic peatlands located in Maritime settings were there is a large annual precipitation excess (500 to $>1000\,mm\,yr^{-1}$) over evapotranspiration. Despite this last qualification, a recent CO_2 exchange study on an Atlantic blanket bog in western Ireland has a very similar NEE to Mer Bleue (Sottocornola & Kiely, 2005) even though the ecology of the blanket bog is very different than a continental bog.

We draw two conclusions that should apply generally to all ombrotrophic peatlands, and an additional conclusion more specific to Mer Bleue, but that should be tested widely by others on a variety of northern peatlands:

1. To determine the contemporary C balance of a peatland, NEE, CH_4 flux, and DOC export are all required. As DOC export and net C accumulation can be the same size in a given year, neglecting DOC in a peatland C balance prohibits determining whether the balance is significantly different from 0: the measurement of DOC input and export is as important as the continuous record of NEE. Unlike Mer Bleue, where CH_4 emission is relatively small, the magnitude of the CH_4 flux in many peatlands is of the same order as DOC and ΔC_{org}, and its neglect raises the same concern.
2. The estimates of exchanges produced in this study after 6-years of continuous and extensive measurements are quite close to those inferred by Gorham (1991), even though he had very little data on which to draw. He had to assume that the past CAR was a reasonable estimate of the contemporary rate, since when he did his synthesis there were no reliable estimates of NEE for northern peatlands. Our study provides quantitative confirmation of Gorham's inferences, at least for one bog. It would not be reasonable to assume that our results are representative for other peatlands where there has been no disturbance or a major shift in climate and/or the physical/ecological setting. Unfortunately, with analysing peat cores and constructing a peatland C balance as we have done in this study, there is no obvious way to conclude *a priori* whether or not the past CAR is applicable to the present. Testing the universality of no significant difference between the past and present CAR requires replications of our study across a diverse set of ecoclimatic regions and other peatland types.
3. We cannot determine if we have measured the components of the C balance of Mer Bleue long enough to determine an acceptably accurate contemporary mean. Using 5 of the 6 years, either individually or in combination, we would have come to very different conclusions about the sink/source function of Mer Bleue than what the 6-year mean suggests. The conclusions could have ranged from a contemporary sink three to four times greater than the past accumulation rates (e.g. $-70–90\,g\,C\,m^{-2}\,yr^{-1}$) to a net source of C (e.g. $10–20\,g\,C\,m^{-2}\,yr^{-1}$). The combination of climate conditions Mer Bleue experienced

over the 6 years of study captures a wide range of precipitation, but is biased towards warmer conditions. However, this is not something we are likely to avoid given the trend in increasing temperatures observed over most of the northern hemisphere for the last century, and particularly, the last 40–50 years.

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