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Hydro-meteorological controls on the CO_2 exchange variation in an Irish blanket bog

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ABSTRACT

Northern peatlands contain an estimated 1/3 of the world's soil carbon pool. This large carbon pool is of concern due to its uncertain future in a changing climate. Blanket bogs are peatlands that occur in temperate maritime regions where precipitation is much greater than evapotranspiration. We describe five years (1 October 2002 to 30 September 2007) of eddy-covariance (EC) carbon dioxide (CO_2) flux measurements in an Atlantic blanket bog in Ireland. The measured net ecosystem CO_2 exchange (NEE) was partitioned into its components of ecosystem respiration (ER) and gross ecosystem production (GEP). The inter-annual variation of the CO_2 fluxes was investigated using correlation coefficient analyses with measured hydro-meteorological parameters. The annual NEE was negative for all five years (thus the peatland was a sink of CO_2), ranging between -16.5 ± 5.1 and -96.5 ± 23.2 g C-CO_2 m^{-2} (average of -54.9 ± 15.6 g C-CO_2 m^{-2}). During the study period, NEE was negative for the same five months in each year (May–September). NEE showed the highest CO_2 uptake (due to the highest GEP) in the summer with intermediate rather than extreme meteorological conditions, thus with low vapour pressure deficit, intermediate soil water content, air temperature and light radiation, which might be partly explained by the role of the bryophyte community. Under climate change predictions of higher temperature, the inter-annual variation analysis suggests that ER might increase in winter. Furthermore, the predicted lower precipitation and higher temperature in the summer are expected to lead to lower GEP. The resulting increase in NEE (thus lower CO_2 uptake) will be partly compensated by a higher GEP in warmer winters and in dryer autumns. Moreover, the CO_2 uptake will benefit by a longer growing season, while wetter conditions will likely lower the ecosystem respiration in the spring. The length of the growing season was found to be driven by warmer winter and September soil temperatures.

1. Introduction

The eddy-covariance (EC) method is now well established as the most suitable technique for long-term carbon dioxide (CO_2) flux measurements at an ecosystem level (Baldocchi, 2003). The pioneering studies using this technique in forests have now ten or more years of measurement data (e.g. Dunn et al., 2007; Grünwald and Bernhofer, 2007; Urbanski et al., 2007). Long time series provide the opportunity to deepen our understanding of ecosystem functioning by focusing on the mechanisms (e.g. climate, ecology and management) driving the inter-annual variation (IAV) in carbon fluxes. The IAV of CO_2 fluxes has been typically studied with either modelling approaches (e.g. Higuchi et al., 2005; Hui et al., 2003; Ito et al., 2005; Richardson et al., 2007) or correlation coefficient (or regression) analyses together with hydro-meteorological variables (e.g. Aubinet et al., 2002; Aurela et al., 2004; Barr et al., 2007; Carrara et al., 2003; Wohlfahrt et al., 2008b). Furthermore, the partitioning of net ecosystem CO_2 exchange (NEE) and the separate study of the ecosystem respiration (ER) and gross ecosystem production (GEP) have been shown to be essential to asses the vulnerability of ecosystems to climate change (Barr et al., 2007; Dunn et al., 2007; Krishnan et al., 2008; Saigusa et al., 2005).

Although Northern peatlands are generally of low productivity, they are important ecosystems because they contain 1/3 (~455 Gt of C) of the world's estimated soil carbon (C) pool (Gorham, 1991). The future of this C reservoir is of key interest as many regions (e.g. the arctic tundra) are experiencing a C status change from sink to source due to global warming (Oechel et al., 2000), with the additional risk of a positive feedback. Climate warming is expected in peatlands to affect the hydrology (Roulet et al., 1992), the vegetation zones and plant composition (Weltzin et al., 2003): all factors influencing the C dynamics. Mid-century climate change

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scenarios for Ireland predict: mean monthly temperature increases between 1.2 and 1.4 °C (highest in the summer and autumn); a decrease in summer precipitation (of 5–10%); and an increase in winter precipitation (of 5–10%) (Dunne et al., 2008; Fealy and Sweeney, 2007).

Despite their role in the global carbon cycle, relatively few peatland sites have been monitored for CO_2 fluxes using the EC system (Arneth et al., 2002; Aurela et al., 2004, 2007; Friborg et al., 2003; Lund et al., 2007; Roulet et al., 2007; Valentini et al., 2000) and only very few have been continuously studied for multi-year periods (Aurela et al., 2004; St-Hilaire et al., 2008). Moreover, most of the EC studies are being conducted in boreal, subarctic or arctic regions and the only EC measurements in a blanket bog were reported in short-term studies (Laine et al., 2006; Sottocornola and Kiely, 2005). These researches have shown that peatland ecosystems are generally a small sink of CO_2, but that they have a very wide inter-annual variation (e.g. Aurela et al., 2004; St-Hilaire et al., 2008).

Blanket bogs have some features similar to raised bogs, others to minerotrophic fens. Blanket bogs are largely ombrotrophic, thus receiving water and nutrients only from atmospheric deposition, similarly to raised bogs. Nevertheless they have a vegetation rich in herbaceous vascular plants and brown mosses as minerotrophic fens, while poorer in shrubs and *Sphagnum* mosses (bog mosses), typical of raised bogs. Blanket bogs are usually found in flat to moderately sloping terrain in regions with a temperate maritime climate. They have a persistently high water table and a high sea-origin ion concentration and pH due to the proximity of the sea (Proctor, 1992; Sottocornola et al., 2009). In the global context, blanket bogs are rare ecosystems, accounting only for ca. 3% of the world peatland area (Foss et al., 2001), but locally they can be very important. In the Republic of Ireland, blanket bogs cover about 13% of the national land area and contain about 45% of the national soil C stock (Eaton et al., 2008; Kiely et al., 2008).

The objectives of this study were (1) to quantify the seasonal and inter-annual variability of NEE and of its components, ER and GEP, in an Atlantic blanket bog and (2) to assess the role and relative importance of different hydro-meteorological parameters in driving this variability.

2. Methods

2.1. Site description

The experimental site is a relatively intact Atlantic blanket bog located near Glencar, County Kerry, in Southwest Ireland (Latitude: 51°55′N, Longitude: 9°55′W) at an elevation between 145 and 170 m above sea level. This peatland was described as typical of Atlantic blanket bogs in the maritime regions of North-western Europe (Sottocornola et al., 2009). The characteristic feature of the bog is a spatially heterogeneous surface, with a mosaic of microforms, which differ in relative altitude, plant composition and water table depth. We divided these microforms into four classes based on their relative elevation: hummocks, high lawns, low lawns and hollows (Laine et al., 2006; Sottocornola et al., 2009). The elevation difference between the highest and lowest microform is typically 20–40 cm. Hollows are 50–300 cm oblong depressions covered by standing water for most of the year. The distribution of microform composition inside the eddy-covariance footprint was estimated as: 6% hummocks; 62% high lawns; 21% low lawns; and 11% hollows (Laine et al., 2006). Vascular plants cover about 30% of the bog surface during the summer, the most common species being *Molinia caerulea* (purple moor-grass), *Calluna vulgaris* (common heather), *Erica tetralix* (cross-leaved heath), *Narthecium ossifragum* (bog asphodel), *Rhynchospora alba* (white beak-sedge), *Eriophorum angustifolium* (common cotton grass), *Schoenus nigricans* (black-top sedge) and *Menyanthes trifoliata* (buckbean). The bryophyte component is not widespread, about 25% of the bog surface, and the principal species include a brown moss, *Racomitrium lanuginosum* (woolly-hair moss), and *Sphagnum* mosses (bog mosses), both occurring in the peatland with similar abundance (Sottocornola et al., 2009). The peat depth is >2 m in most parts of the EC footprint.

2.2. Meteorological measurements

The experimental arrangement consists of a meteorological station and an EC system for CO_2, water and energy fluxes, situated in the middle of the bog. The meteorological equipment included a net radiometer (CNR 1, Kipp & Zonen, The Netherlands) and a sensor for Q_{PAR}, photosynthetically active radiation (PAR Lite, Kipp & Zonen, The Netherlands). Air temperature (T_{air}) and relative humidity were measured at 2 m height with a shielded probe (HMP45C, Vaisala, Finland). Soil temperature was recorded with a probe (107, Campbell Scientific, UK) at 5 cm ($T_{soil\_5\ cm}$, since 11 March 2005) and at 20 cm ($T_{soil\_20\ cm}$, for the whole period) below the high lawn vegetation. The missing $T_{soil\_5\ cm}$ was modelled with a multiple regression based on T_{air} and $T_{soil\_20\ cm}$ [$r^2 = 0.90$; root mean squared deviation (Piñeiro et al., 2008), RMSD = 1.55 °C]. Soil water content (SWC) at 5 cm depth was recorded with a time domain reflectometer (CS615, Campbell Scientific, UK). The reflectometer was not calibrated but the SWC data were obtained from an equation for mineral soil set to peak at 0.96 (see Admiral et al., 2006). Precipitation was measured with two tipping bucket rain gauges (an ARG100, Environmental Measurements Ltd., UK and an Obsermet OMC-200, Observator BV, The Netherlands), while the water table level (WTL) was continuously measured with a pressure transducer (PCDR1830, Campbell Scientific, UK) placed inside a porous metal well. A malfunction of the pressure transducer between November 2002 and May 2004 was corrected by detrending the recorded data based on interpolated manual measurements (Laine et al., 2007). Data from all the micrometeorological sensors were monitored every minute and averaged over a 30-min period by a CR23X data logger (Campbell Scientific, UK).

2.3. Eddy-covariance measurements and processing

The EC system consisted of a 3-D sonic anemometer (Model 81000, R.M. Young Company, USA) and an open-path CO_2/H_2O infrared gas analyser (LI-7500, LI-COR, USA) mounted at 3 m above the high lawn vegetation. The ground contours within the flux footprint are relatively flat. A fetch analysis following Hsieh et al. (2000) indicated that the site had a typical fetch of 300 m during daytime unstable conditions and of 750 m during stable night time conditions. Data were recorded at 10 Hz and automatically checked online for quality. The 10 Hz flux data were discarded if the CO_2 concentration was above or below predetermined realistic threshold values ($[CO_2] < 5\ \mu mol\ m^{-3}$; $[CO_2] > 35\ \mu mol\ m^{-3}$) or if the sonic temperature or the water vapour concentration were not similar to those measured and calculated from the Vaisala probe in the previous 30-min period (thus ± 3 °C and ± 200 mmol m^{-3}, respectively). Good 10 Hz flux data were then Reynolds-averaged (running means) over the half-hour. The post-field data processing included a double rotation, so that the mean horizontal wind speed was rotated into the mean wind direction and the mean vertical wind velocity was set to zero, by correcting the fluxes for the averaged 30-min angle between the horizontal and vertical axes. The CO_2 fluxes were then corrected for variations in air density (Webb et al., 1980). The flux data were subsequently partitioned into day and night sets, using a short-wave incoming radiation threshold of 10 W m^{-2} (46% of the five-year dataset comprised of day data). Filters were then established to discard bad flux estimates. Half-hour flux data were rejected if: (1) less than 95% of the 10 Hz data had passed the online

10 Hz filters; or if (2) the estimate of the vertical angle of wind speed gave unrealistic outputs (typically in low wind speed conditions at night); or if (3) less than 67% of the flux footprint length was estimated to have originated from the bog (see Laine et al., 2006 for details); or if (4) the fluxes were measured during rainy periods ($\geq$0.4 mm over the half-hour) or up to 1 h after rain, because the open-path CO_2/H_2O infrared gas analyser is unreliable during wet conditions; or if (5) the fluxes were above or below predetermined realistic seasonal threshold values. No clear correlation between the CO_2 fluxes and the friction velocity (u^*) was found in dry nights and so no u^* filter was applied. Night time CO_2 uptake estimates were rejected. After the data processing, the amount of good remaining CO_2 fluxes was 56%, 68%, 51%, 63% and 60% at day time and 23%, 26%, 23%, 29% and 28% at night time in the five annual periods 2002/03 to 2006/07, respectively. Negative night time fluxes occurred mostly outside the growing season and were likely caused by an overestimation of the sensible heat flux term of the Webb correction (Webb et al., 1980), due to the heating effect of the Licor 7500 (Burba et al., 2008). The use of the Burba et al. (2008) correction resulted in unrealistic fluxes (as was also found by Wohlfahrt et al., 2008a and by Lafleur and Humphreys, 2008), likely because our LI-7500 sensor was mounted at about 50° (to deflect rainfall) and not mounted near-vertically as required by Burba et al. (2008). In this paper, we therefore refrain from including the Burba's corrected fluxes and we decided to reject the negative night time CO_2 fluxes (accepting the risk to skew the normal distribution curve of the night time fluxes), which likely offset the possible bias of the fluxes due to the non performance of the Burba's correction. Indeed our data compared well with up-scaled CO_2 chamber fluxes (Laine et al., 2006), thus supporting the reliability of our measured and computed CO_2 fluxes. This chamber and EC comparison gave a very good correlation, especially for monthly NEE (the time frame for which we present most of our data here), although the EC fluxes were overestimated towards CO_2 uptake at daytime outside the growing season (Laine et al., 2006), when the CO_2 fluxes are in any case low.

The gaps in the time series were filled by nonlinear regression equations defined using the Curve Fitting Function of the MATLAB 7.0.1 software (MathWorks Inc., USA), relating the CO_2 flux to either Q_{PAR} or temperature. Separate gap-filling equations were established for day and night time data, for monthly or bimonthly periods, depending on the best fit. Most of the daytime fluxes were gap-filled relating the CO_2 flux response to light conditions, using either a rectangular hyperbola type of equation (Frolking et al., 1998) or polynomial equations in one variable of different orders, in those months when the high Q_{PAR} corresponded to a reduction of CO_2 uptake (see Sottocornola, 2007; Sottocornola and Kiely, 2005). The latter family of equations was also used to relate CO_2 fluxes to T_{air} when temperature explained the flux variation better than light. Night time data were gap-filled using two Lloyd and Taylor (1994) exponential equations, relating the CO_2 flux with $T_{soil\_20\ cm}$ (before 11 March 2005) or $T_{soil\_5\ cm}$ (after 11 March 2005).

No data were logged for the 10 days between 25 May and the 4 June 2003, due to an electricity outage. The missing meteorological data were replaced with the last five good days of data before the outage and the first five days of good data after the outage except for precipitation. Precipitation data were obtained from the averaged ratio between the slopes of the annual cumulative sums of precipitation in Glencar and in the nearby synoptic weather station at Valentia, County Kerry, 25 km west of the bog site. Shorter meteorological gaps were replaced either with interpolation (all data up to 4 h gaps, except radiation data) or with the average of the same half-hour in the previous and following seven days (radiation data, and all data for gaps longer than 4 h) (Falge et al., 2001). Missing short-wave incoming radiation (r^2 = 0.99; RMSD = 12.22 W m^{-2}) and net radiation (r^2 = 0.94; RMSD = 32.12 W m^{-2}) data were replaced by a relationship with Q_{PAR}. The EC system suffered three outage breaks (21 May to 26 June 2003, 21 January to 2 February 2005, 16 to 23 March 2005), which were replaced using the gap-filling equations based on meteorological data. In the five year, 58 days of EC data (thus 3.2% of time) were lost and therefore gap-filled.

The eddy-covariance data quality was assessed by dividing the source of error into random and systematic. The approach by Aurela et al. (2002) was used to estimate the random component of the error, which was 3.3% of the annual measured good NEE, on average. The error in the energy balance closure provided an estimate of the systematic error (e.g. Moureaux et al., 2008), which equalled 28%, on average. The combined error estimate, calculated following the Pythagorean theorem, was 30%, 28%, 24%, 29% and 31% for the five years 2002/03 to 2006/07, respectively.

We adopted the micrometeorological convention in which fluxes from the biosphere to the atmosphere are positive and we report on the data collected for the five years (1 October to 30 September) 2002/03 to 2006/07. The measured CO_2 flux was considered to correspond to the net ecosystem exchange, because the stored flux in the canopy was considered negligible in this treeless ecosystem (Lafleur et al., 2003).

2.4. CO_2 flux-partitioning

The NEE was partitioned into its component fluxes, considering night time NEE as ecosystem respiration and applying a night time derived ER model to the daytime, with the assumption that the temperature dependence of ER is the same during day and night. Ecosystem respiration was modelled based on $T_{soil\_20\ cm}$ following the approach of Reichstein et al. (2005), using the Lloyd and Taylor (1994) exponential regression:

$$\mathrm{ER} = R_{\mathrm{ref}} * e^{E_0(1/(T_{\mathrm{ref}}-T_0)-1/(T_{\mathrm{soil\_20\,cm}}-T_0))} \qquad (1)$$

where T_{ref} is the reference temperature (283.15 K) and T_0 is the regression parameter (227.13 K) (Lloyd and Taylor, 1994; Reichstein et al., 2005). R_{ref}, the respiration at T_{ref}, was calculated for four-day time periods and averaged at 0.56 g C-CO_2 m^{-2} day^{-1}, with a maximum of 2.10 g C-CO_2 m^{-2} day^{-1}. E_0 is the activation energy, which was set once (E_0 = 456.2 K) for the five-year period (E_0, long (Reichstein et al., 2005)). The linear regression relating the observed vs. predicted (Piñeiro et al., 2008) night time respiration had a low coefficient of determination (r^2 = 0.28; RMSD = 0.06 mg C-CO_2 m^{-2} s^{-1}), indicating a low precision of the model (Tedeschi, 2006). Nevertheless, the slope (1.03) and the small offset of the relationship from the zero (−0.02 °C) ensure an acceptable accuracy (Tedeschi, 2006) and therefore a satisfactory performance of the model over extended time periods of months or years. The gross ecosystem production was calculated as:

$$\mathrm{GEP} = \mathrm{ER} - \mathrm{NEE} \qquad (2)$$

The onset (OGS) and the end of the growing season were estimated as the first and last three consecutive days with a cumulative GEP > 4.5 g C-CO_2 m^{-2}. The cover of the vascular plants was assessed with regular measurements of the one-sided leaf area index (LAI) using a PAR/LAI Ceptometer (Accupur LP-80, Decagon, USA). The measurements started in October 2004 and were performed at 134 points inside the footprint, in conditions of diffused light, which ensures the good performance of the instrument (Garrigues et al., 2008).

2.5. Correlation coefficient analyses

The inter-annual variation of the CO_2 fluxes was examined with correlation coefficient analyses for annual and seasonal values. The hydro-meteorological measured variables used in this analysis were: T_{air}, $T_{soil\_5\ cm}$, daytime Q_{PAR}, daytime vapour pressure deficit

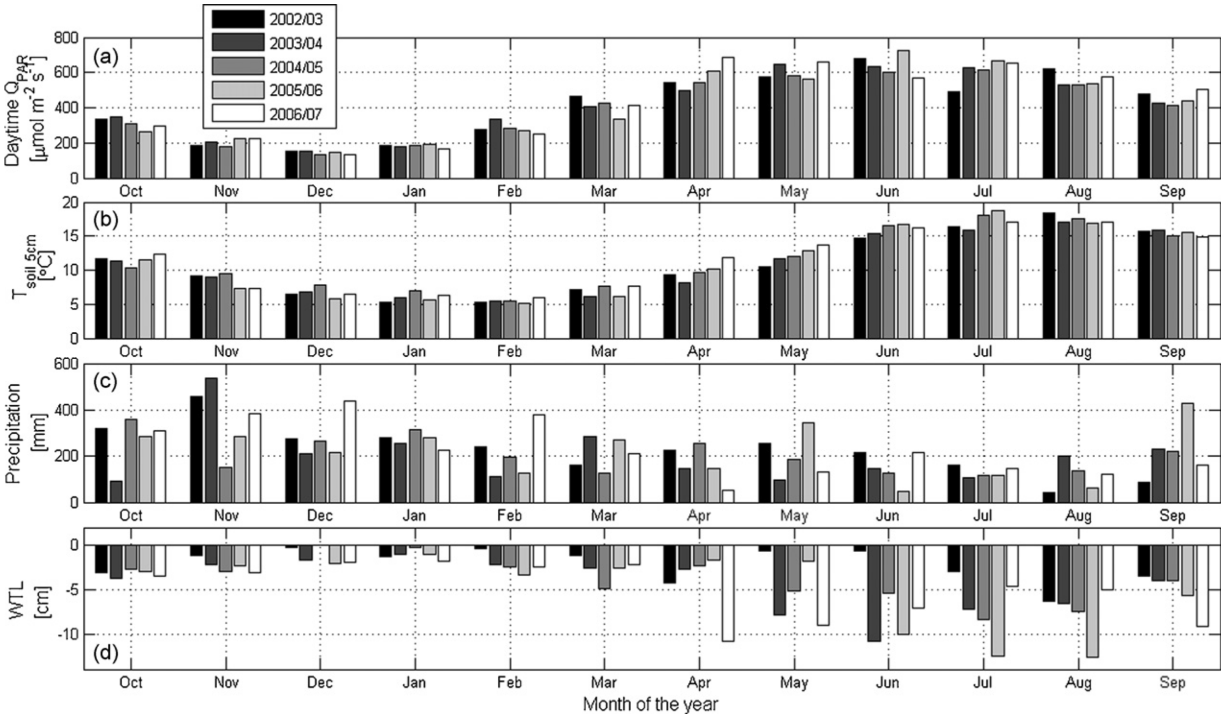

Fig. 1. (a) Monthly photosynthetically active radiation (Q_{PAR}) averaged for the daytime; (b) monthly averages of soil temperature at 5 cm depth ($T_{soil\_5\ cm}$); (c) monthly precipitation; (d) monthly averages of water table level (WTL), where zero is the ground level of a low lawn.

(VPD), water table level, precipitation, standardized precipitation frequency (SPF = number of wet days/potential ET, where a wet day has >1 mm precipitation) and evapotranspiration (ET). ET was computed from measurements of water vapour flux by the eddy-covariance system, while the Penman–Monteith equation with surface resistance set to zero was used as an estimate of the potential ET (for details, see Sottocornola, 2007; Sottocornola and Kiely, submitted).

3. Results

3.1. Inter-annual variation of hydro-meteorological variables

The daytime Q_{PAR} radiation showed little monthly variation in winter (December–February) while higher during the summer (June–August) (Fig. 1a). The monthly temperature showed fairly steady temperatures across the seasons (Fig. 1b), with daily T_{air} and $T_{soil\_5\ cm}$ averages ranging, over the five studied years, between a minimum of −0.9 and 1.0 °C and a maximum of 21.4 and 22.3 °C, respectively. Precipitation was very abundant in autumn (September–November) and winter and generally regular during the summer (Fig. 1c), varying between an annual sum of 2423 (2003/04) and 2776 mm (2006/07) (Table 1). The water table level (Fig. 1d) remained close to the soil surface throughout the years and followed the precipitation patterns, with half-hourly values ranging only between 2 cm above and 17 cm below the low lawn surface.

The five-year study period was characterized by a wide range of environmental conditions (Fig. 1). Particularly the spring (March–May) and summer of the last three years (2004/05 to 2006/07) presented a wide inter-annual variation in hydro-meteorological conditions. 2005/06 had the driest summer, with high Q_{PAR} and temperatures, but the wettest spring, while 2006/07 experienced the brightest, warmest and driest spring but the wettest summer. 2004/05 summer was also warm but had intermediate precipitation and the lowest Q_{PAR}. The coldest winter T_{air} and $T_{soil\_20\ cm}$ were recorded in 2002/03, while the warmest in 2004/05. The Met Eireann synoptic weather station at Valentia (ca. 30 km west of Glencar) recorded 1.0 °C warmer and ca. 5% wetter weather in the years 2003 to 2007 than for the 30-year average (1961–1990) (http://www.meteireann.ie/climate/valentia.asp).

The leaf area index within the footprint ranged between a minimum of about 0.2 m^2 m^{-2} in the winter and a maximum of 0.6 m^2 m^{-2} in the summer (not shown). The onset of the growing

Table 1

Annual (summer) averages of daytime photosynthetic active radiation (Q_{PAR}), daytime vapour pressure deficit (VPD), air (T_{air}) and soil temperature at 5 cm depth ($T_{soil\_5\ cm}$); annual (summer) precipitation, water table level (WTL) averages, onset (OGS) and length of the growing season (LGS), and net ecosystem exchange (NEE) values. Summer = June–August. The annual or summer mean values followed by a different letter within the same column were significantly different at $P < 0.05$ based on a non-parametric ANOVA, Kruskal–Wallis and Mann–Whitney tests (Shapiro–Wilk or Levene's test were significant for all variables), based on daily averages or sums. No test was applied to OGS and LGS because of a lack of repetitions for these variables.

	Daytime Q_{PAR} (μmol m^{-2} s^{-1})	Daytime VPD (hPa)	T_{air} (°C)	$T_{soil\_5\ cm}$ (°C)	Precipitation (mm)	WTL (cm)	OGS (LGS) (days)	NEE (g C-CO$_2$ m^{-2})
2002/03 (summer)	415^a (597^a)	2.92^a (3.64^a)	10.53^a (14.67^{ab})	10.84^a (16.43^a)	2724^a (420^a)	-2.13^a (-3.32^a)	158 (100)	-69.7^a (-57.7^{ab})
2003/04 (summer)	416^a (597^a)	2.77^a (3.58^a)	10.35^a (14.19^a)	10.72^a (16.12^a)	2423^a (451^a)	-4.38^b (-8.18^b)	147 (118)	-68.7^a (-65.9^a)
2004/05 (summer)	400^a (583^a)	2.58^b (3.26^{ab})	10.59^a (14.99^b)	11.40^a (17.42^b)	2454^a (378^{ab})	-3.83^b (-7.07^c)	140 (115)	-96.5^a (-90.6^c)
2005/06 (summer)	412^a (634^a)	2.85^a (4.30^c)	10.54^a (15.13^b)	11.03^a (17.44^b)	2607^a (227^b)	-4.89^b (-11.74^d)	164 (94)	-23.1^b (-48.6^d)
2006/07 (summer)	427^a (598^a)	2.83^a (3.18^b)	10.73^a (14.21^a)	11.40^a (16.84^c)	2776^a (485^a)	-5.07^c (-5.61^e)	157 (91)	-16.5^b (-48.6^{bd})

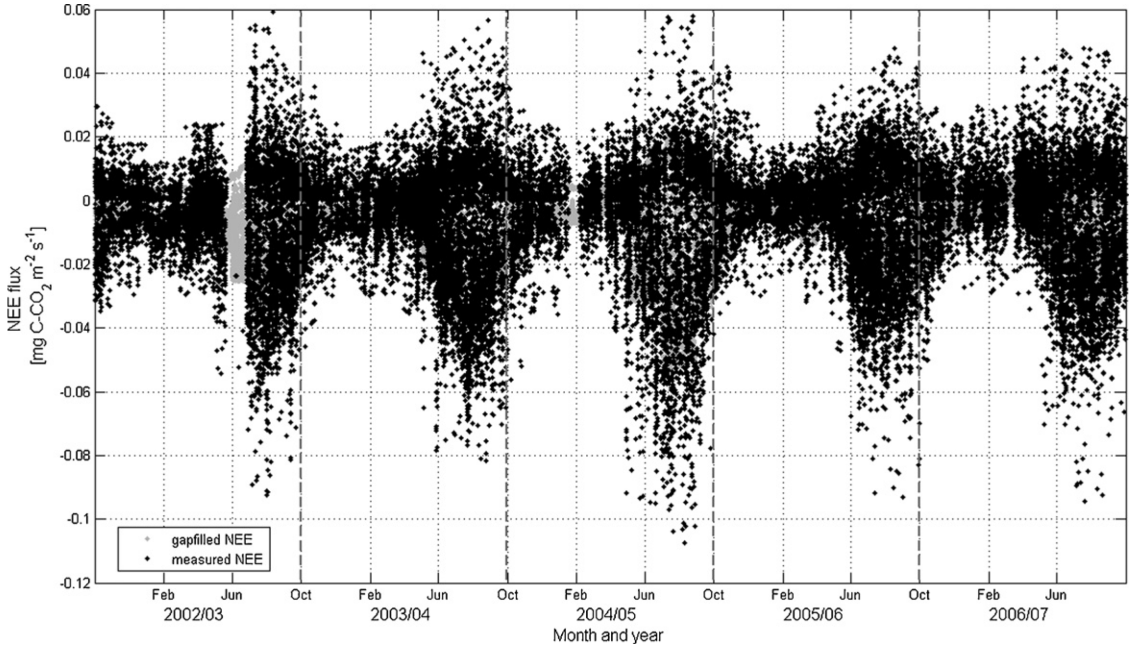

Fig. 2. 30-min measured and gap-filled NEE.

season ranged between 19 May in 2005 and 12 June in 2006. The end of the growing season varied little, between 4 September in 2007 and 20 September in 2004.

3.2. *Inter-annual variation of CO_2 fluxes*

The 30-min NEE ranged between a maximum uptake of CO_2 (negative NEE) of −0.11 mg $C\text{-}CO_2\ m^{-2}\ s^{-1}$ and a maximum release of CO_2 (positive NEE) of 0.06 mg $C\text{-}CO_2\ m^{-2}\ s^{-1}$, both in summer 2004/05. Half-hourly CO_2 uptake was typically recorded in wintertime as well, with maximum uptake of −0.03 mg $C\text{-}CO_2\ m^{-2}\ s^{-1}$, while the maximum winter CO_2 release generally ranged between 0.01 (in the cold 2002/03 winter) and 0.03 mg $C\text{-}CO_2\ m^{-2}\ s^{-1}$ (in the warm 2006/07 winter) (Fig. 2).

In all of the five studied years, the peatland was a net sink of CO_2 for the five months, May–September, and primarily a net source of CO_2 between October and April (Fig. 3), although slightly mixed monthly sums were observed in October, February, March and April. The highest inter-annual variation in monthly NEE occurred in July and August and in the spring months, while more similar fluxes were measured in winter and autumn. 2004/05 had the highest monthly CO_2 uptake between May and August (with a maximum uptake of −37.9 g $C\text{-}CO_2\ m^{-2}$ in July), while the lowest summer CO_2 uptake occurred in both the dry and warm 2005/06 and in the wet and cool 2006/07 summers. NEE showed the lowest winter CO_2 release in the cold 2002/03 winter while the highest winter and spring CO_2 releases were measured during the warm 2006/07 seasons (Figs. 3a and 4a). High spring net CO_2 loss also

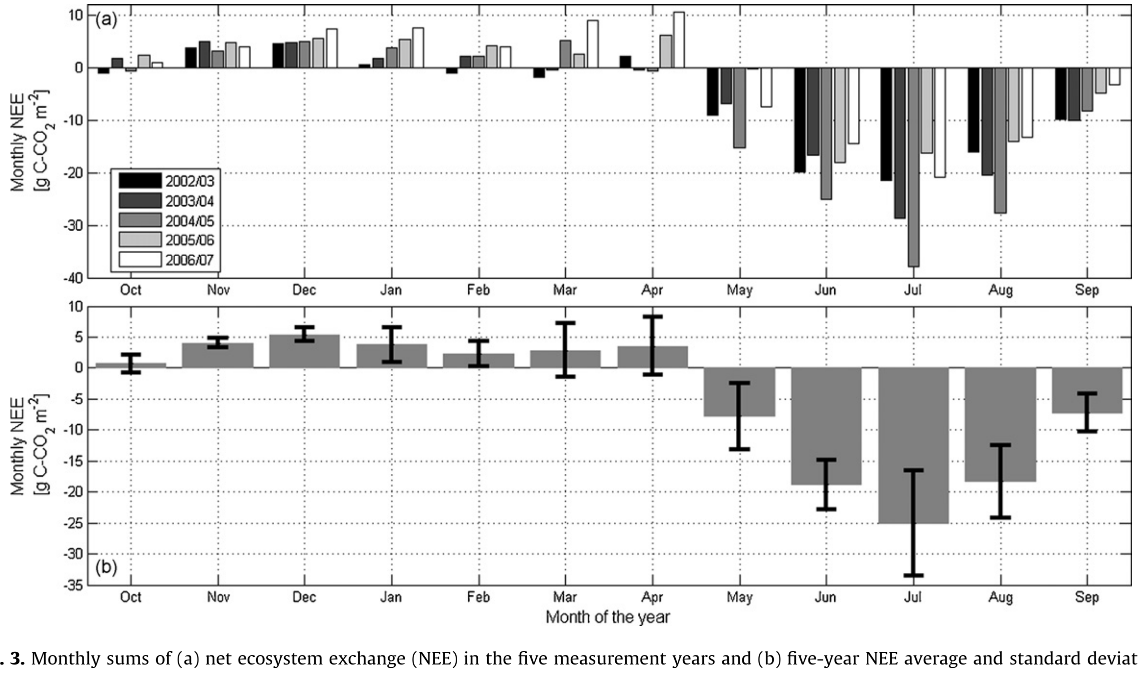

Fig. 3. Monthly sums of (a) net ecosystem exchange (NEE) in the five measurement years and (b) five-year NEE average and standard deviation.

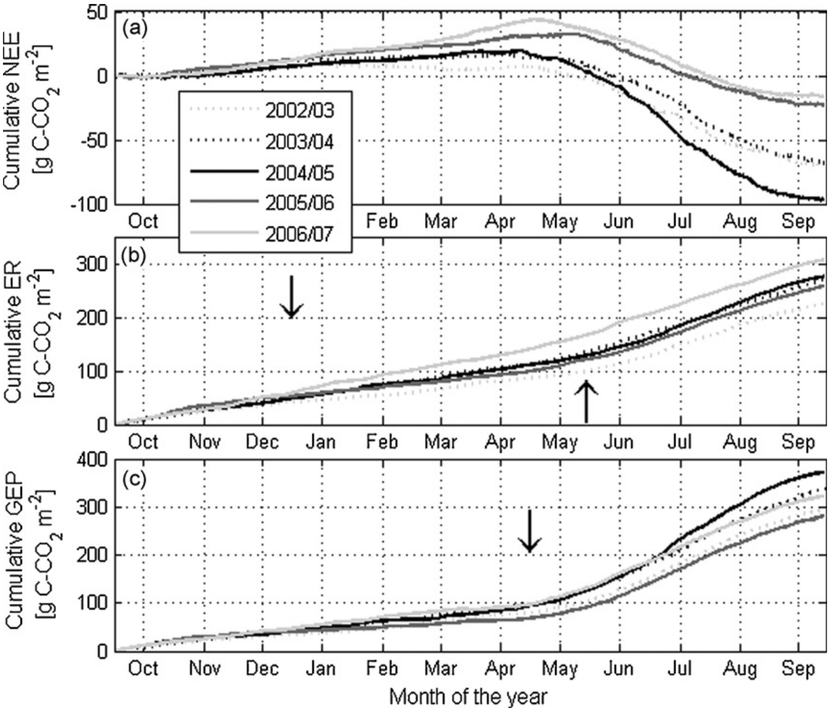

Fig. 4. Cumulative curves of (a) net ecosystem exchange (NEE), (b) ecosystem respiration (ER) and (c) gross ecosystem production (GEP). The arrows pointing downward indicate when the cumulative lines depart from each other; the arrow pointing upward indicates when the cumulative curves have a similar slope again.

occurred in the dry and warm March 2004/05 and April 2005/06. The peatland started acting as a sink of CO_2 between the end of April (in 2003/04 and 2004/05) and the end of May (in 2005/06), while the end of the uptake period ranged between the end of September (in 2002/03) and the second half of October (in 2004/05). The annual cumulative NEE resulted in a net CO_2 uptake in all five years and showed a high variation, ranging between a minimum of -16.5 ± 5.1 g C-CO_2 m^{-2} for the year 2005/06 and a maximum CO_2 uptake of -96.5 ± 23.2 g C-CO_2 m^{-2} in 2004/05, with an average of -54.9 ± 15.6 g C-CO_2 m^{-2} over the five years (Table 1 and Fig. 4a).

Both ER and GEP showed a high seasonal variation, ranging respectively between a monthly minimum of about 7 and 6 g C-CO_2 m^{-2} in winter to a maximum of 45 and 81 g C-CO_2 m^{-2} in summer (Fig. 5). The warm 2006/07 had the highest monthly ER between December and June, which was only partly balanced by the highest winter GEP. The unusually warm and dry spring of 2006/07 (9.69 °C and 393.7 mm of rain compared to an average of 9.00 °C and 624.6 mm, respectively, in the previous four years) resulted in a relatively low GEP in April, but the highest in May. In contrast winter and spring had a low ER and the lowest GEP in 2005/06. Overall the GEP followed the NEE pattern during the

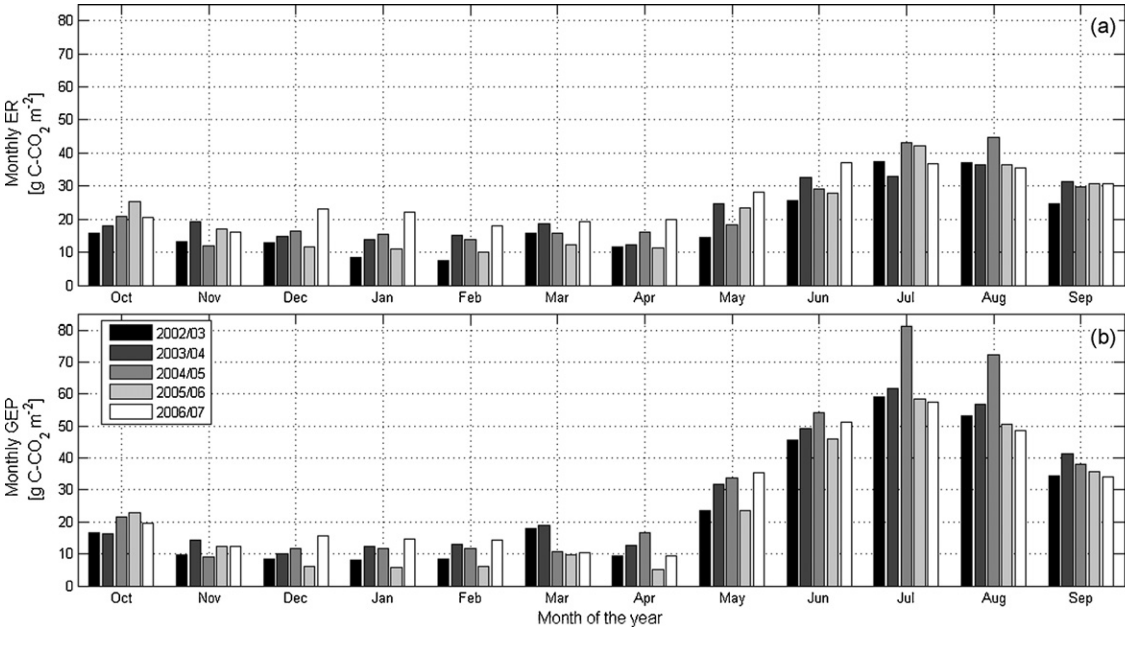

Fig. 5. Monthly sums of (a) ecosystem respiration (ER) and (b) gross ecosystem production (GEP).

summer (June–August), being highest in 2004/05, but rather small in both the warm and dry 2005/06 and wet and cool 2006/07 summers.

The ER showed a large inter-annual variation (Fig. 4b). The yearly ER cumulative curves seem to partition in three phases: (1) similar slopes from October to December; (2) different slopes from January to May and (3) similar slopes again from June to September (standard deviation of the cumulative curve slopes in the January–May period 20 and 5 times higher than in the previous and following periods, respectively). Annually, the ER ranged between 306.9 g C-CO_2 m^{-2} (in the warm 2006/07) and 224.8 g C-CO_2 m^{-2} (in the cold 2002/03). The cumulative GEP curves seem instead to partition into two phases: (1) similar slopes from October to April and (2) different slopes from May to September (standard deviation of the cumulative curve slopes in the May–September period 3 times higher than in the previous period). Thus the GEP cumulative curves were similar in the five years before the onset of the growing season and showed a bigger variation for the remainder of the year. The highest spring/summer GEP was measured in 2004/05, yielding an annual sum of 372.3 g C-CO_2 m^{-2}, mainly due to the highest GEP in July and August. The lowest spring/summer GEP was recorded in 2005/06, yielding an annual GEP of 281.8 g C-CO_2 m^{-2}. The lowest annual NEE (thus, CO_2 uptake, in 2004/05) was therefore associated with the highest annual GEP and an intermediate annual ER. The highest NEE (thus, CO_2 loss) was the result of either a low GEP during the growing season and an intermediate annual ER (in 2005/06, characterized by a dry and warm summer), or the highest winter and spring ER and an intermediate annual GEP (in 2006/07, characterized by a warm winter and spring, and a wet, cool summer).

3.3. Correlation coefficient analyses

The correlation coefficient analysis indicated that the CO_2 fluxes were strongly associated: the annual NEE correlated positively with both spring and summer NEE (Table 2), while the NEE and GEP were closely associated in summer, NEE and ER in the autumn, and ER and GEP in both autumn and winter (Table 3). Moreover, both annual NEE ($P < 0.1$) and GEP ($P < 0.01$) showed a higher uptake of CO_2 with an earlier onset of the growing season (not shown), the latter being determined by winter $T_{\mathrm{soil\_5\,cm}}$ average (Table 4) and by the maximum number of days with no rain (precipitation <1 mm day^{-1}) in February ($P < 0.01$) (not shown). No other significant correlation was found between the IAV of NEE and any measured hydro-meteorological parameters on an annual basis (Table 5), but CO_2 uptake showed a preference for wet conditions, since NEE correlated negatively with the standardized rain frequency in autumn and with the WTL in winter. Stronger correlations were found for ER and GEP. Wet conditions (e.g. high WTL) decreased the annual and spring ER, but benefit the annual GEP in the form of daytime VPD. Both ER and GEP were reduced by higher temperatures and rain frequency in autumn, while enhanced by temperature in winter. Annual and spring GEP correlated positively with ET.

Table 2
Correlation coefficients between the annual net ecosystem exchange (NEE) and the seasonal fluxes of NEE, ecosystem respiration (ER) and gross ecosystem production (GEP). NEE and ER follow the micrometeorological sign convention for fluxes, while GEP = ER − NEE.

	Annual NEE		
	vs. seasonal NEE	vs. seasonal ER	vs. seasonal GEP
Autumn	0.63	0.65	0.60
Winter	0.74	0.29	−0.03
Spring	0.97[a]	0.45	−0.61
Summer	0.90[b]	−0.21	−0.77

[a] Statistically significant at $P < 0.01$.
[b] Statistically significant at $P < 0.05$; $n = 5$.

Table 3
Correlation coefficients between the net ecosystem exchange (NEE), ecosystem respiration (ER) and gross ecosystem production (GEP) as annual and seasonal sums. NEE and ER follow the micrometeorological sign convention for fluxes, while GEP = ER − NEE.

	NEE vs. ER	NEE vs. GEP	ER vs. GEP
Annual	0.37	−0.64	0.48
Autumn	0.90[b]	0.72	0.95[b]
Winter	0.68	0.34	0.92[b]
Spring	0.53	−0.56	0.40
Summer	−0.60	−0.97[a]	0.78

[a] Statistically significant at $P < 0.01$.
[b] Statistically significant at $P < 0.05$; $n = 5$.

To study the hydro-meteorological controls on the summer NEE, the diurnal averages of NEE together with some environmental parameters in the last three studied summers (those having the most complete dataset) are shown in Fig. 6. NEE in the summer showed a higher CO_2 uptake with intermediate environmental parameters, while the CO_2 uptake was hindered by more extreme weather conditions. The lowest CO_2 uptake occurred in the 2005/06 and 2006/07 summers, when either the highest Q_{PAR}, T_{air}, VPD (June and July 2005/06) and the lowest soil water content (all summer 2005/06) or the lowest Q_{PAR} (in June 2006/07), T_{air} and the highest SWC (all summer 2006/07) were recorded. NEE had the highest CO_2 uptake in summer 2004/05, which was characterized by intermediate T_{air} (in June and July), SWC and Q_{PAR}. VPD was also a key parameter for NEE: the diurnal VPD average in 2004/05 was lower in the June mornings compared to 2006/07, when all other parameters were similar, likely driving the lower NEE.

Table 4
Correlation coefficients between the onset of the growing season (OGS) and the end of the growing season (EGS) with winter and spring or September hydro-meteorological parameters: air temperature (T_{air}), soil temperature at 5 cm depth ($T_{\mathrm{soil\_5\,cm}}$), daytime photosynthetic active radiation (Q_{PAR}), daytime vapour pressure deficit (VPD), water table level (WTL), precipitation (prec), standardized precipitation frequency (SPF, number of wet days/potential evapotranspiration; where a wet day has >1 mm precipitation).

	T_{air} (°C)	$T_{\mathrm{soil\_5\,cm}}$ (°C)	Q_{PAR} ($\mu mol\, m^{-2}\, s^{-1}$)	VPD (hPa)	WTL (cm)	Prec (mm)	SPF
OGS							
Winter	−0.44	−0.89[b]	−0.22	0.61	−0.48	0.09	0.83
Spring	−0.10	0.20	0.12	−0.06	0.26	0.39	0.33
EGS							
September	0.67	0.91[b]	−0.68	−0.47	0.77	0.22	0.34

[b] Statistically significant at $P < 0.05$; $n = 5$.

Table 5

Correlation coefficients between net ecosystem exchange (NEE), ecosystem respiration (ER) and gross ecosystem production (GEP) and some hydro-meteorological parameters as annual and seasonal data: air temperature (T_{air}), soil temperature at 5 cm depth ($T_{soil\_5\ cm}$), daytime photosynthetic active radiation (Q_{PAR}), daytime vapour pressure deficit (VPD), water table level (WTL), precipitation (prec), standardized precipitation frequency (SPF, number of wet days/potential ET, where a wet day has >1 mm precipitation) and evapotranspiration (ET). NEE and ER follow the micrometeorological sign convention for fluxes, while GEP = ER – NEE.

	NEE								ER								GEP							
	T_{air} (°C)	$T_{soil\_5\ cm}$ (°C)	Q_{PAR} (μmol $m^{-2} s^{-1}$)	VPD (hPa)	WTL (cm)	Prec (mm)	SPF	ET (mm)	T_{air} (°C)	$T_{soil\_5\ cm}$ (°C)	Q_{PAR} (μmol $m^{-2} s^{-1}$)	VPD (hPa)	WTL (cm)	Prec (mm)	SPF	ET (mm)	T_{air} (°C)	$T_{soil\_5\ cm}$ (°C)	Q_{PAR} (μmol $m^{-2} s^{-1}$)	VPD (hPa)	WTL (cm)	Prec (mm)	SPF	ET (mm)
Year	0.43	0.14	0.75	0.58	−0.62	0.64	−0.19	−0.62	0.48	0.67	0.31	−0.42	**−0.81**[c]	−0.00	−0.03	0.45	−0.01	0.42	−0.45	**−0.90**[b]	−0.09	−0.61	0.16	**0.96**[b]
Autumn	0.42	−0.53	0.27	0.77	−0.41	−0.17	**−0.94**[b]	0.12	0.39	**−0.85**[c]	−0.10	0.48	−0.52	−0.47	**−0.98**[a]	−0.09	0.33	**−0.96**[b]	−0.34	0.22	−0.54	−0.63	**−0.89**[b]	−0.22
Winter	0.61	0.08	−0.59	−0.08	**−0.83**[c]	0.44	0.40	0.10	**0.90**[b]	0.56	−0.51	−0.09	−0.41	0.68	−0.32	0.66	**0.83**[c]	0.68	−0.34	−0.07	−0.08	0.63	−0.63	0.80
Spring	0.03	0.73	0.45	0.08	−0.39	−0.13	0.14	−0.50	0.51	0.67	0.77	0.53	**−0.97**[a]	**−0.87**[c]	−0.60	0.38	0.47	−0.14	0.26	0.44	−0.53	−0.71	−0.74	**0.91**[b]
Summer	−0.24	−0.18	0.69	0.44	−0.10	−0.10	−0.01	−0.57	0.38	0.76	−0.31	−0.41	−0.17	−0.13	0.13	0.41	0.30	0.37	−0.64	−0.47	0.03	0.04	0.05	0.58

[a] Statistically significant at $P < 0.01$.

[b] Statistically significant at $P < 0.05$.

[c] Statistically significant at $P < 0.1$; $n = 5$.

4. Discussion

This study extends a previous two-year study, reported in a short paper (Sottocornola and Kiely, 2005), to five years of measurements of net ecosystem exchange in a relatively intact Irish Atlantic blanket bog. Compared to the previous study, the current work deepens the CO_2 flux analyses, including a stricter quality check of the 10 Hz data, and a filter on the footprint length, based on Hsieh et al. (2000) model, described in details in Laine et al. (2006). In addition, the present paper partitions the NEE into its components of ecosystem respiration and gross ecosystem production and examines the inter-annual variation of the CO_2 fluxes. Correlation coefficient analyses with hydro-meteorological variables were used to examine the key determinants of the inter-annual variation of the CO_2 fluxes using the wide range of both environmental parameters and fluxes over the study period (Figs. 1, 3 and 5).

4.1. Inter-annual variation of CO_2 fluxes

The 30-min NEE variation in Glencar was much lower than in other peatland ecosystems (Fig. 2). Maximum CO_2 uptake and release were about 25% of those measured in the Mer Bleue Canadian boreal raised bog (Lafleur et al., 2003) and 50% of those measured in the Kaamanen subarctic fen in Finland (Aurela et al., 1998). Despite its low productivity, Glencar had a five-year annual NEE average of −54.9 g C-CO_2 m^{-2}, similar to a Scottish blanket bog (−41 g C-CO_2 m^{-2} $year^{-1}$; Beverland et al., 1996), the Mer Bleue Canadian boreal raised bog (average of −58.8 g C-CO_2 m^{-2}; Lafleur et al., 2007) and a sedge fen in Southern Finland (−51.3 g C-CO_2 m^{-2}; Aurela et al., 2007). A lower annual NEE was estimated for a boreal fen in Russia (−88 g C-CO_2 m^{-2} $year^{-1}$; Friborg et al., 2003) while generally higher values were measured in a temperate raised bog in southern Sweden (−21.4 g C-CO_2 m^{-2}; Lund et al., 2007) and in the Kaamanen subarctic fen in Finland (average of −21.5 g C-CO_2 m^{-2}; Aurela et al., 2004). Peatlands are known to be less productive than other ecosystems so that the NEE in Glencar was between 8% and 32% of that in forest ecosystems (Aubinet et al., 2002; Barr et al., 2007; Saigusa et al., 2005) and about 22% of that in a grassland in Southern Ireland (Jaksic et al., 2006; Lawton et al., 2006).

The annual averages of ER and GEP in Glencar were approximately 60% of those in the Mer Bleue boreal raised bog (Lafleur et al., 2001; Moore et al., 2002) and between 25% and 35% of those in forest ecosystems (Barr et al., 2007; Saigusa et al., 2005). The GEP in Glencar was low due to low aboveground biomass (Sottocornola et al., 2009): the bryophytes cover only 25% of the ground area compared with the full bog moss cover in Mer Bleue (Moore et al., 2002), while the leaf area index (thus the vascular plants cover) peaked at only 0.6 m^2 m^{-2} compared to 1.3 m^2 m^{-2} in Mer Bleue (Lafleur et al., 2001). On the other hand, the ER in Glencar seemed to be restricted by both the low temperature and the persistently high water table level (Table 5).

Our study found a large inter-annual variation in NEE with the highest annual CO_2 uptake being almost 6 times the lowest (−96.5 ± 23.2 and −16.5 ± 5.1 g C-CO_2 m^{-2} $year^{-1}$, respectively). Slightly higher IAV in NEE were observed in the Mer Bleue boreal raised bog (from −2 to −136 g C-CO_2 m^{-2} $year^{-1}$; Lafleur et al., 2007) and in the Kaamanen subarctic Finnish fen (from −4 to −53 g C-CO_2 m^{-2} $year^{-1}$; Aurela et al., 2004), while similar or lower IAV were observed in forest and grassland ecosystems (Aubinet et al., 2002; Barr et al., 2007; Jaksic et al., 2006).

4.2. Hydro-meteorological controls over the CO_2 fluxes

The correlation coefficient analysis indicates the intensity of the association between two variables, so that it can be used as a first statistical investigation of possible links between the variation of

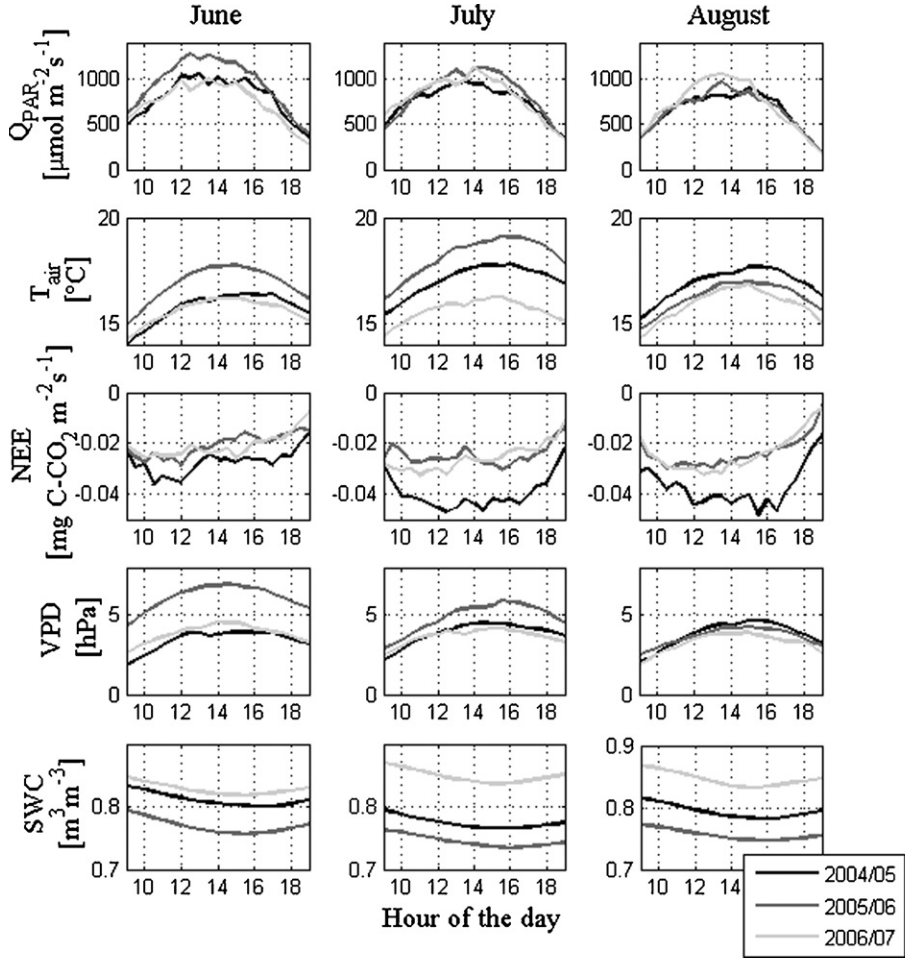

Fig. 6. Diurnal averages of photosynthetically active radiation (Q_{PAR}), air temperature (T_{air}), net ecosystem exchange (NEE), vapour pressure deficit (VPD) and soil water content (SWC) in the months of June, July and August 2004/05, 2005/06 and 2006/07.

CO_2 fluxes and measured environmental parameters (e.g. Aubinet et al., 2002; Aurela et al., 2004; Barr et al., 2007; Carrara et al., 2003; Wohlfahrt et al., 2008b). This type of analysis searches for simple linear correlations, but may fail with more complex relationships. Moreover, the success of such analysis depends on the size of the population and on the extent of the variation of the measured variables. Five years of data are a limited dataset, but the large inter-annual variation offers some insights in the CO_2 flux mechanisms of our study site.

The IAV of NEE in Glencar was not just associated with the summer variation of NEE, as found in the Mer Bleue boreal raised bog (Moore et al., 2006), in the Kaamanen Finnish subarctic fen (Aurela et al., 2004) and in a boreal aspen forest (Barr et al., 2007), but also with the variation in spring NEE (Table 2), as partly observed in a Canadian subarctic fen (Griffis et al., 2000). The inter-annual variation in summer NEE was clearly determined by GEP (Table 3), while in spring it showed no correlation. This difference between summer and spring NEE was probably due to the fact that GEP overshadowed the influence of ER over the NEE during the summer, but not in the spring when the vascular plants had not fully developed yet. The lack of any correlation of NEE in the spring was therefore probably caused by the fact that in this season it emerged strongly the opposite influence that ER and GEP have on NEE (Reichstein et al., 2007). NEE had the highest CO_2 uptake in the summer with intermediate precipitation and WTL as observed in the Mer Bleue raised bog (Lafleur et al., 2007; Roulet et al., 2007), but also with the highest air humidity and lowest Q_{PAR} (Fig. 1 and Table 1). The smallest CO_2 uptakes were measured in the two summers with extreme weather conditions (warm and dry with low WTL and low precipitation in 2005/06; cool and wet with high WTL and precipitation in 2006/07) (Figs. 1 and 3). The ER had a lower summer IAV than GEP (Figs. 4 and 5) as the poor fen part of a boreal peatland complex (Bubier et al., 2003) and a lower impact on NEE IAV during the growing season. The ER was partly driven by temperature, as generally found in raised bogs (Blodau et al., 2007; Lafleur et al., 2005; Roehm and Roulet, 2003), and as expected since it was gap-filled based on T_{soil}, but also by wet conditions, i.e. WTL, as found in mineral poor fens (Bubier et al., 2003). Thus, despite having lower GEP and ER fluxes, the Glencar Atlantic blanket bog seems to have some similar CO_2 flux mechanisms to sedge dominated poor fens, possibly because of the comparable vegetation structure, relatively rich in herbaceous plants and brown mosses and poor in shrubs and *Sphagnum* mosses (Sottocornola et al., 2009). The NEE variation was associated to ER variation in autumn, when both ER and GEP were reduced by high rain frequency and higher temperature (Table 5). This last relationship contradicts the correlation in winter but is explained by the September $T_{soil\_5\ cm}$, which is positively correlated, and thus triggered the end of the growing season (Table 4).

On the other hand, an earlier onset of the growing season led to both lower annual NEE (thus higher CO_2 uptake) as found in the Kaamanen subarctic fen (Aurela et al., 2004) and in temperate forests (Aubinet et al., 2002; Hui et al., 2003), and to higher annual GEP as in a boreal aspen forest (Barr et al., 2007). The OGS was dependent on the soil temperature average in winter and not in spring (Table 4) and on the maximum number of days with no rain in February. This is explained by the fact that in Glencar the first leaves emerge already in February and indicates the importance of the winter conditions in a temperate region not prone to frosts, as boreal regions, where the OGS is correlated with snow melt and spring temperature (Black et al., 2000; Moore et al., 2006). Nevertheless, despite large climatic differences, the start of the vascular plants growing season in Glencar occurred in May at the earliest, as in peatlands of boreal regions (Arneth et al., 2002; Aurela et al., 2004, 2007; Friborg et al., 2003; Lund et al., 2007; Roulet et al., 2007; Valentini et al., 2000).

The peatland started acting as a sink of CO_2 (Fig. 4a) well before the full emergence of the vascular plant leaves and photosynthesis was measured also in autumn and winter (Fig. 2). In these seasons, GEP correlated positively with ER (Table 3), indicating evergreen shrub and bryophyte activity with suitable weather conditions (cooler and dryer in autumn, warmer in winter, Table 5). NEE in the summer showed a higher CO_2 uptake with intermediate more than extreme environmental conditions, in terms of T_{air}, SWC, Q_{PAR} (Fig. 6). This pattern, together with the low values of VPD, is probably explained by the moss activity, which might have a key role in the CO_2 uptake in Glencar, as was observed in raised bogs (Lafleur et al., 2007). High values of T_{air}, Q_{PAR}, VPD and low of SWC might cause desiccation of the moss layer, which would stop contributing to the ecosystem CO_2 sequestration. The occurrence of moss desiccation episodes is also suggested by the negative correlation between the annual GEP and VPD and by the low GEP in the warm, dry and bright 2005/06 summer, when vascular plants were not found water limited (Sottocornola, 2007; Sottocornola and Kiely, submitted). Since it correlated positively with GEP at an annual and spring basis (Table 5), the evapotranspiration might be an indicator of photosynthetic activity of an entire ecosystem in some types of peatland.

5. Conclusions

This work indicated that in the Glencar Atlantic blanket bog both the annual net ecosystem exchange and the gross ecosystem production showed a higher uptake of CO_2 in years with an earlier onset of the growing season. The annual NEE was also driven by the spring and summer NEE, the latter being controlled by the summer GEP. While the inter-annual variation in the summer NEE appeared complicated by the influence of divergent processes, so that the CO_2 uptake was favoured by intermediate weather conditions, simple linear relationships explained the CO_2 balances in the other seasons. Wet conditions favoured the CO_2 uptake in autumn and in winter, and the annual GEP, while they decreased the annual and spring ecosystem respiration. Both ER and GEP were reduced by warmer and dryer weather in autumn while enhanced in winter.

Consequently, the CO_2 sequestration in Irish blanket bogs is likely to be particularly affected by climate change because this ecosystem appears extremely sensitive to hydro-meteorological variations, especially due to the variations in spring and summer GEP and in spring and autumn ER. The climate change scenarios for Ireland predict a warmer climate (all year round) with precipitation amount and frequency decreasing in summer and increasing in winter (Dunne et al., 2008; Fealy and Sweeney, 2007). More extreme conditions are likely to increase the NEE since higher summer CO_2 sequestration was measured in intermediate weather. A warmer and dryer summer climate is expected to reduce the GEP, while higher temperatures might increase the winter ER, with a consequent reduction in CO_2 sequestration. Some compensation mechanisms might alleviate the impact of climate change: wetter conditions could lower the ER in spring and autumn, while higher autumn rain frequency and winter water table level might decrease NEE (i.e. higher CO_2 uptake). Moreover a warmer winter might increase the GEP and trigger an earlier start of the emergence of the vascular plants with benefits to both the annual NEE and GEP, while a warmer September might delay the vascular plant senescence.

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References

Admiral, S.W., Lafleur, P.M., Roulet, N.T., 2006. Controls on latent heat flux and energy partitioning at a peat bog in eastern Canada. Agricultural and Forest Meteorology 140 (1–4), 308–321.

Arneth, A., Kurbatova, J., Kolle, O., Shibistova, O.B., Lloyd, J., Vygodskaya, N.N., Schulze, E.-D., 2002. Comparative ecosystem–atmosphere exchange of energy and mass in a European Russian and a central Siberian bog. II. Interseasonal and interannual variability of CO_2 fluxes. Tellus 54B, 514–530.

Aubinet, M., Heinesch, B., Longdoz, B., 2002. Estimation of the carbon sequestration by a heterogeneous forest: night flux corrections, heterogeneity of the site and inter-annual variability. Global Change Biology 8, 1053–1071.

Aurela, M., Laurila, T., Tuovinen, J.-P., 2002. Annual CO_2 balance of a subarctic fen in northern Europe: importance of the wintertime efflux. Journal of Geophysical Research 107 (D21), 4607, doi:10.1029/2002JD002055.

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

Aurela, M., Riutta, T., Laurila, T., Tuovinen, J.-P., Vesala, T., Tuittila, E.-S., Rinne, J., Haapanalen, S., Laine, J., 2007. CO_2 exchange of a sedge fen in southern Finland—the impact of a drought period. TellusB 59 (5), 826–837, doi:10.1111/j.1600-0889.2007.00309.x.

Aurela, M., Tuovinen, J.-P., Laurila, T., 1998. Carbon dioxide exchange in a subarctic peatland ecosystem in northern Europe measured by the eddy covariance technique. Journal of Geophysical Research 103 (D10), 11289–11301.

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

Barr, A.G., Black, T.A., Hogg, E.H., Griffis, T.J., Morgenstern, K., Kljun, N., Theede, A., Nesic, Z., 2007. Climatic controls on the carbon and water balances of a boreal aspen forest, 1994–2003. Global Change Biology 13, 561–576, doi:10.1111/j.1365-2486.2006.01220.x.

Beverland, I.J., Moncrieff, J.B., Oneill, D.H., Hargreaves, K.J., Milne, R., 1996. Measurement of methane and carbon dioxide fluxes from peatland ecosystems by the conditional-sampling technique. Quarterly Journal of the Royal Meteorological Society 122 (532), 819–838.

Black, T.A., Chen, W.J., Barr, A.G., Arain, M.A., Chen, Z., Nesic, Z., Hogg, E.H., Neumann, H.H., Yang, P.C., 2000. Increased carbon sequestration by a boreal deciduous forest in years with a warm spring. Geophysical Research Letters 27 (9), 1271–1274.

Blodau, C., Roulet, N.T., Heitmann, T., Stewart, H., Beer, J., Lafleur, P.M., Moore, T.R., 2007. Belowground carbon turnover in a temperate ombrotrophic bog. Global Biogeochemical Cycles 21, GB1021, doi:10.1029/2005GB002659.

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

Burba, G.G., McDermitt, D.K., Grelle, A., Anderson, D.J., Liukang, X.U., 2008. Addressing the influence of instrument surface heat exchange on the measurements of CO_2 flux from open-path gas analyzers. Global Change Biology 14 (8), 1854–1876.

Carrara, A., Kowalski, A.S., Neirynck, J., Janssens, I.A., Yuste, J.C., Ceulemans, R., 2003. Net ecosystem CO_2 exchange of mixed forest in Belgium over 5 years. Agricultural and Forest Meteorology 119 (3–4), 209–227.

Dunn, A.L., Barford, C.C., Wofsy, S.C., Goulden, M.L., Daube, B.C., 2007. A long-term record of carbon exchange in a boreal black spruce forest: means, responses to interannual variability, and decadal trends. Global Change Biology 13, 577–590, doi:10.1111/j.1365-2486.2006.01221.x.

Dunne, S., Hanafin, J., Lynch, P., McGrath, R., Nishimura, E., Nolan, P., Ratnam, J.V., Semmler, T., Sweeney, C., Varghese, S., Wang, S., 2008. Ireland in a warmer world. Scientific predictions of the Irish climate, 109 pp.

Eaton, J.M., McGoff, N.M., Byrne, K.A., Leahy, P., Kiely, G., 2008. Land cover change and soil organic carbon stocks in the Republic of Ireland 1851–2000. Climatic Change 91, 317–334, doi:10.1007/s10584-008-9412-2.

Falge, E., Baldocchi, D.D., Olson, R., Anthoni, P., Aubinet, M., Bernhofer, C., Burba, G., Ceulemans, R., Clement, R., Dolman, H., Granier, A., Gross, P., Grünwald, T., Hollinger, D., Jensen, N.-O., Katul, G., Keronen, P., Kowalski, A., Ta Lai, C., Law, B.E., Meyers, T., Moncrieff, J., Moors, E., Munger, J.W., Pilegaard, K., Rannik, Ü., Rebmann, C., Suyker, A., Tenhunen, J., Tu, K., Verma, S., Vesala, T., Wilson, K., Wofsy, S., 2001. Gap filling strategies for defensible annual sums of net ecosystem exchange. Agricultural and Forest Meteorology 107, 43–69.

Fealy, R., Sweeney, J., 2007. Statistical downscaling of precipitation for a selection of sites in Ireland employing a generalised linear modelling approach. International Journal of Climatology 27 (15), 2083–2094.

Foss, P.J., O'Connell, C.A., Crushell, P.H., 2001. Bogs & Fens of Ireland. Conservation Plan 2005. Irish Peatland Conservation Council, Dublin, 144 pp.

Friborg, T., Soegaard, H., Christensen, T.R., Lloyd, C.R., Panikov, N.S., 2003. Siberian wetlands: Where a sink is a source. Geophysical Research Letters 30 (21), 2129, doi:10.1029/2003GL017797.

Frolking, S.E., Bubier, J.L., Moore, T.R., Ball, T., Bellisario, L.M., Bhardwaj, A., Carrol, P., Crill, P.M., Lafleur, P.M., McCaughey, J.H., Roulet, N.T., Suyker, A.E., Verma, S.B., Waddington, M.J., Whiting, G.J., 1998. Relationship between ecosystem productivity and photosynthetically active radiation for northern peatlands. Global Biogeochemical Cycles 12 (1), 115–126.

Garrigues, S., Shabanov, N.V., Swanson, K., Morisette, J.T., Baret, F., Myneni, R.B., 2008. Intercomparison and sensitivity analysis of Leaf Area Index retrievals from LAI-2000, AccuPAR, and digital hemispherical photography over croplands. Agricultural and Forest Meteorology 148 (8–9), 1193–1209.

Gorham, E., 1991. Northern peatlands: role in the carbon cycle and probable responses to climate warming. Ecological Applications 1 (2), 182–195.

Griffis, T.J., Rouse, W.R., Waddington, M.J., 2000. Interannual variability of net ecosystem CO_2 exchange at a subarctic fen. Global Biogeochemical Cycles 14 (4), 1109–1121.

Grünwald, T., Bernhofer, C., 2007. A decade of carbon, water and energy flux measurements of an old spruce forest at the Anchor Station Tharandt. Tellus 59B, 387–396, doi:10.1111/j.1600-0889.2007.00259.x.

Higuchi, K., Shashkov, A., Chan, D., Saigusa, N., Murayama, S., Yamamoto, S., Kondo, H., Chen, J., Liu, J., Chen, B., 2005. Simulations of seasonal and inter-annual variability of gross primary productivity at Takayama with BEPS ecosystem model. Agricultural and Forest Meteorology 134 (1–4), 143–150.

Hsieh, C.-I., Katul, G., Chi, T.-w., 2000. An approximate analytical model for footprint estimation of scalar fluxes in thermally stratified atmospheric flows. Advances in Water Resources 23 (7), 765–772.

Hui, D., Luo, Y., Katul, G., 2003. Partitioning interannual variability in net ecosystem exchange between climatic variability and functional change. Tree Physiology 23, 433–442.

Ito, A., Saigusa, N., Murayama, S., Yamamoto, S., 2005. Modeling of gross and net carbon dioxide exchange over a cool-temperate deciduous broad-leaved forest in Japan: Analysis of seasonal and interannual change. Agricultural and Forest Meteorology 134 (1–4), 122–134.

Jaksic, V., Kiely, G., Albertson, J., Oren, R., Katul, G., Leahy, P., Byrne, K.A., 2006. Net ecosystem exchange of grassland in contrasting wet and dry years. Agricultural and Forest Meteorology 139, 323–334.

Kiely, G., McGoff, N.M., Eaton, J., Leahy, P., 2008. SoilC – Measurement and Modelling of Soil Carbon Stocks and Stock Changes in Irish Soils. EPA, Wexford, Ireland.

Krishnan, P., Black, T.A., Barr, A.G., Grant, N.J., Gaumont-Guay, D., Nesic, Z., 2008. Factors controlling the interannual variability in the carbon balance of a southern boreal black spruce forest. Journal of Geophysical Research 113, D09109, doi:10.1029/2007JD008965.

Lafleur, P.M., Humphreys, E.R., 2008. Spring warming and carbon dioxide exchange over low Arctic tundra in central Canada. Global Change Biology 14 (4), 740–756.

Lafleur, P.M., Moore, T.R., Roulet, N.T., Frolking, S., 2005. Ecosystem respiration in a cool temperate bog depends on peat temperature but not water table. Ecosystems 8, 619–629, doi:10.1007/s10021-003-0131-2.

Lafleur, P.M., Roulet, N.T., Admiral, S.W., 2001. Annual cycle of CO_2 exchange at a bog peatland. Journal of Geophysical Research 106 (3), 3071–3081.

Lafleur, P.M., Roulet, N.T., Bubier, J.L., Frolking, S., Moore, T.R., 2003. Interannual variability in the peatland-atmosphere carbon dioxide exchange at an ombrotrophic bog. Global Biogeochemical Cycles 17 (2), 1036, doi:10.1029/2002GB001983.

Lafleur, P.M., Roulet, N.T., Moore, T.R., Humphreys, E.R., Richard, P.J.H., 2007. 8 Years of NEE measurement at the Mer Bleue Bog: what is normal? In: Presentation at the Annual General Meeting of Fluxnet Canada, Ottawa (Canada), March 9–11, http://www.trentu.ca/academic/bluelab/FCRN.AGM07.Lafleur.v3.ppt.

Laine, A., Byrne, K.A., Kiely, G., Tuittila, E.-S., 2007. Patterns in vegetation and CO_2 dynamics along a water level gradient in a lowland blanket bog. Ecosystems 10, 890–905, doi:10.1007/s10021-007-9067-2.

Laine, A., Sottocornola, M., Kiely, G., Byrne, K.A., Wilson, D., Tuittila, E.-S., 2006. Estimating net ecosystem exchange in a patterned ecosystem: example from blanket bog. Agricultural and Forest Meteorology 138, 231–243, doi:10.1016/j.agrformet.2006.05.005.

Lawton, D., Leahy, P., Kiely, G., Byrne, K.A., Calanca, P., 2006. Modeling of net ecosystem exchange and its components for a humid grassland ecosystem. Journal of Geophysical Research 111, G04013, doi:10.1029/2006JG000160.

Lloyd, J., Taylor, J.A., 1994. On the temperature-dependence of soil respiration. Functional Ecology 8 (3), 315–323.

Lund, M., Lindroth, A., Christensen, T.R., Strom, L., 2007. Annual CO_2 balance of a temperate bog. Tellus 59B (5), 804–811, doi:10.1111/j.1600-0889.2007.00303.x.

Moore, T.R., Bubier, J.L., Frolking, S.E., Lafleur, P.M., Roulet, N.T., 2002. Plant biomass and production and CO_2 exchange in an ombrotrophic bog. Journal of Ecology 90, 25–36.

Moore, T.R., Lafleur, P.M., Poon, D.M.I., Heumann, B.W., Seaquist, J.W., Roulet, N.T., 2006. Spring photosynthesis in a cool temperate bog. Global Change Biology 12, 2323–2335, doi:10.1111/j.1365-2486.2006.01247.x.

Moureaux, C., Debacq, A., Hoyaux, J., Suleau, M., Tourneur, D., Vancutsem, F., Bodson, B., Aubinet, M., 2008. Carbon balance assessment of a Belgian winter wheat crop *Triticum aestivum* L. Global Change Biology 14 (6), 1353–1366, doi:10.1111/j.1365-2486.2008.01560.x.

Oechel, W.C., Vourlitis, G.L., Hastings, S.J., Zulueta, R.C., Hinzman, L., Kane, D., 2000. Acclimation of ecosystem CO_2 exchange in the Alaskan Arctic in response to decadal climate warming. Nature 406, 978–981.

Piñeiro, G., Perelman, S., Guerschman, J.P., Paruelo, J.M., 2008. How to evaluate models: Observed vs. predicted or predicted vs. observed? Ecological Modelling 216 (3–4), 316–322.

Proctor, M.C.F., 1992. Regional and local variation in the chemical composition of ombrogeneous mire waters in Britain and Ireland. Journal of Ecology 80 (4), 719–736.

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grunwald, T., Havrankova, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J.-M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., Valentini, R., 2005. On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. Global Change Biology 11 (9), 1424–1439, doi:10.1111/j.1365-2486.2005.001002.x.

Reichstein, M., Papale, D., Valentini, R., Aubinet, M., Bernhofer, C., Knohl, A., Laurila, T., Lindroth, A., Moors, E., Pilegaard, K., Seufert, G., 2007. Determinants of terrestrial ecosystem carbon balance inferred from European eddy covariance flux sites. Geophysical Research Letters 34 (L01402), doi:10.1029/2006GL027880.

Richardson, A.D., Hollinger, D.Y., Aber, J.D., Ollinger, S.V., Braswell, B.H., 2007. Environmental variation is directly responsible for short- but not long-term variation in forest-atmosphere carbon exchange. Global Change Biology 13 (4), 788–803, doi:10.1111/j.1365-2486.2007.01330.x.

Roehm, C.L., Roulet, N.T., 2003. Seasonal contribution of CO_2 fluxes in the annual C budget of a northern bog. Global Biogeochemical Cycles 17 (1), 1029.

Roulet, N.T., Lafleur, P.M., Richard, P.J.H., Moore, T.R., Humphreys, E.R., Bubier, J., 2007. Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland. Global Change Biology 13, 397–411, doi:10.1111/j.1365-2486.2006.01292.x.

Roulet, N.T., Moore, T., Bubier, J.L., Lafleur, P.M., 1992. Northern fens: methane flux and climatic change. Tellus 44B (2), 100–105.

Saigusa, N., Yamamoto, S., Murayama, S., Kondo, H., 2005. Inter-annual variability of carbon budget components in an AsiaFlux forest site estimated by long-term flux measurements. Agricultural and Forest Meteorology 134 (1–4), 4–16.

Sottocornola, M., 2007. Four years of observations of carbon dioxide fluxes, water and energy budgets, and vegetation patterns in an Irish Atlantic blanket bog. Ph.D. Thesis, University College Cork, Cork, Ireland. http://www.ucc.ie/hydromet/files/Sottocornola.2007.pdf.

Sottocornola, M., Kiely, G., 2005. An Atlantic blanket bog is a modest CO_2 sink. Geophysical Research Letters 32 (L23804), doi:10.1029/2005GL024731.

Sottocornola, M., Kiely, G. Energy fluxes and evaporation mechanisms in an Atlantic blanket bog in South-western Ireland, submitted to Water Resources Research.

Sottocornola, M., Laine, A., Kiely, G., Byrne, K.A., Tuittila, E.-S., 2009. Vegetation and environmental variation in an Atlantic blanket bog in South-western Ireland. Plant Ecology 203 (1), 69–81, doi:10.1007/s11258-008-9510-2.

St-Hilaire, F., Wu, J., Roulet, N.T., Frolking, S., Lafleur, P.M., Humphreys, E.R., Arora, V., 2008. McGill Wetland Model: evaluation of a peatland carbon simulator developed for global assessments. Biogeosciences Discussions 5 (2), 1689–1725.

Tedeschi, L.O., 2006. Assessment of the adequacy of mathematical models. Agricultural Systems 89 (2–3), 225–247.

Urbanski, S.P., Barford, C.C., Wofsy, S., Kucharik, C., Pyle, E., Budney, J., McKain, K., Fitzjarrald, D.R., Czikowsky, M., Munger, J.W., 2007. Factors controlling CO_2 exchange on timescales from hourly to decadal at Harvard Forest. Journal of Geophysical Research 112 (G02020), doi:10.1029/2006JG000293.

Valentini, R., Dore, S., Marchi, G., Mollicone, D., Panfyorov, M., Rebmann, C., Kolle, O., Schulze, E.-D., 2000. Carbon and water exchanges of two contrasting central Siberia landscape types: regenerating forest and bog. Functional Ecology 14, 87–96.

Webb, E.K., Pearman, G.I., Leuning, R., 1980. Correction of flux measurements for density effects due to heat and water vapour transfer. Quarterly Journal of the Royal Meteorological Society 106, 85–100.

Weltzin, J.F., Bridgham, S.D., Pastor, J., Chen, J., Harth, C., 2003. Potential effects of warming and drying on peatland plant community composition. Global Change Biology 9 (2), 141–151.

Wohlfahrt, G., Fenstermaker, L.F., Arnone, I., John, A., 2008a. Large annual net ecosystem CO_2 uptake of a Mojave Desert ecosystem. Global Change Biology 14 (7), 1475–1487.

Wohlfahrt, G., Hammerle, A., Haslwanter, A., Bahn, M., Tappeiner, U., Cernusca, A., 2008b. Seasonal and inter-annual variability of the net ecosystem CO_2 exchange of a temperate mountain grassland: effects of weather and management. Journal of Geophysical Research 113 (D08110), doi:10.1029/2007JD009286.