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Net ecosystem exchange of grassland in contrasting wet and dry years

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Abstract

Temperate grasslands represent about 32% of the earth's land area and cover approximately 56% of the area of Ireland; yet their role as sources/sinks of atmospheric CO_2 is not well quantified. We used an eddy covariance (EC) system to measure the net ecosystem exchange (NEE) at a managed grassland site in southern Ireland for 2 years. Rainfall in 2002 and 2003 was 1785 and 1185 mm, respectively, compared to an annual average of 1470 mm. The EC measured NEE was less in the wet year (-193 ± 50 g C m^{-2}, uptake) than in the dry year (-258 ± 50 g C m^{-2}, uptake). Combining NEE measurements with estimates of the components of the farm scale carbon (C) balance we estimated the amount of C fixed to the soil as -24 ± 62 g C m^{-2} for 2002 and -89 ± 62 g C m^{-2} for 2003, indicating that this ecosystem was a small sink for carbon. For the same months in different years, we found that the NEE was similar, although their soil moisture status was very different. This was due to the fact that the soil moisture status in this region, even in dry periods, was always well above the wilting point which resulted in no moisture stress on the vegetation at any time over the 2 years. We concluded that the NEE for this humid grassland ecosystem was not very sensitive to the variation in precipitation over the 2 years. We found that herbage harvesting had a direct effect of reducing the NEE in the month of harvest. We conclude that the interannual variation in NEE of 65 g C m^{-2} is of the order of uncertainty of the EC measurements.

Keywords: NEE; Eddy covariance; Carbon balance; Precipitation

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1. Introduction

The earth's vegetative cover is a key component in the global carbon (C) cycle due to its dynamic response to photosynthetic and respiration processes. Forestry ecosystems have been studied in much detail because of their significant C sink attributes (Falge et al., 2002). Studies of C fluxes in temperate grassland have been overlooked due to the perception that this ecosystem is C neutral (Ham and Knapp, 1998; Hunt et al., 2002). Representing approximately 32% of the earth's natural vegetation, temperate grasslands are now being revisited for C flux studies (Frank and Dugas, 2001; Hunt et al., 2002; Novick et al., 2004; Hsieh et al., 2005; Nieveen et al., 2005; Lawton et al., 2006) and may yet be shown to play a role in the missing global C sink (Ham and Knapp, 1998; Suyker et al., 2003; Goodale and Davidson, 2002). Grassland is the dominant ecosystem in Ireland, representing 90% of agricultural

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land (or 56% of the total land area) (Cruickshank et al., 2000). Several short-term studies have shown that grassland ecosystems can sequester atmospheric CO_2 (e.g. Bruce et al., 1999; Conant et al., 2001) but few multi-annual data sets are available (Frank and Dugas, 2001; Falge et al., 2002; Novick et al., 2004; Verburg et al., 2004). While it is known that most forest ecosystems are sinks for C, the same cannot yet be said for grasslands due to the lack of relevant research. Long-term measurements are essential for examining the seasonal and interannual variability of C fluxes (Goulden et al., 1996; Baldocchi, 2003). The literature (summarised by Novick et al., 2004) shows that the net ecosystem exchange (NEE) of grasslands varies from an uptake of $-800\ \mathrm{g\ C\ m^{-2}}$ to an emission of $+521\ \mathrm{g\ C\ m^{-2}}$ with most grassland ecosystems in the range $\pm 200\ \mathrm{g\ C\ m^{-2}}$. In this paper, we present the eddy covariance measured CO_2 fluxes for 2 years in a humid temperate grassland ecosystem in southern Ireland; these 2 years differ greatly in rainfall amounts but are otherwise similar. In the intensively managed grasslands of Ireland, precipitation patterns play an important role in grassland both in terms of the timing of harvesting of herbage (i.e. grass silage or hay harvesting) and the duration of the livestock grazing season grazing. Hence, precipitation variability has the potential to impact NEE through the meteorological and hydrologic drivers of photosynthesis (e.g. photosynthetically active radiation, vapour pressure deficit) and respiration (e.g. soil moisture) and indirectly through the timing of harvesting, which affects leaf area index dynamics and the amount of biomass removed from the site.

Our aim was to compare the NEE in contrasting dry and wet years. We also aimed to estimate the annual magnitude of C fixed to or lost from the soil by combining NEE measurements with the other components of the farm scale annual C balance (e.g. C lost as methane from cows; C in milk from cows; C lost as dissolved organic C (DOC) in water). The motivation for this is that it is difficult to estimate on short (annual) time steps the amount of C fixed to or lost from the soil.

2. Methods

2.1. Site description

The grassland site, at ~200 m above sea level is located in South West Ireland, 25 km northwest of Cork city (Latitude 51°59′N; Longitude 8°45′W). The climate is temperate (summer average air temperature 15 °C, winter average 5 °C) and humid (mean annual precipitation 1470 mm). The soil is classified as a surface water gley (Gardiner and Radford, 1980) and the topsoil C content is 4% (Byrne et al., 2005). Depth averaged over the top 30 cm, the volumetric soil porosity was 0.49 ($\mathrm{m^3\ m^{-3}}$), the saturation moisture level was 0.45 ($\mathrm{m^3\ m^{-3}}$), the field capacity was 0.32 ($\mathrm{m^3\ m^{-3}}$) and the wilting point was 0.12 ($\mathrm{m^3\ m^{-3}}$). The grassland type is moderately high quality pasture and meadow, with perennial ryegrass (*Lolium perenne* L.) the dominant plant species. Dairying is the dominant farm activity. This means that approximately 40% of the fields are used for grass silage harvesting (for winter feed) while the remainder of the fields are used for cattle grazing. The latter lasts from late March to mid October. Grass productivity is enhanced with the application of $\sim 300\ \mathrm{kg\ N\ ha^{-1}\ yr^{-1}}$ in fertiliser and slurry. In the harvested fields the grass is harvested for silage in the summer (typically a first harvest in June or July and if a second harvest, this is about 8–10 weeks later). The EC footprint covers parts of eight small farms (each farm varying in size from ca. 10 to 40 ha). On those areas that are harvested for grass, each of the eight farmers harvests when it best suits his management plans. As such, there can be several different harvesting events (on different farms) and harvesting over the footprint varies in time (June–September) and in space. Sometimes a harvesting event (normally carried out by external agricultural contractors) is timed to optimise the availability of harvesting machinery and so more than one farm may be harvested during a harvest event. The grass height in the grazing fields varies from 0.1 to 0.2 m. The grass height in the harvested fields reaches a maximum of ~0.45 m prior to harvesting. Typical yields of silage are $6-7\ \mathrm{t\ DM\ ha^{-1}}$ (first harvest) and $4-5\ \mathrm{t\ DM\ ha^{-1}}$ (second harvest). The annual yield of harvested grass (silage) reported for 2002 and 2003 was approximately $7-10\ \mathrm{t\ DM\ ha^{-1}\ yr^{-1}}$. The footprint area of the flux tower (Fig. 1) was conservatively estimated on a fetch to sensor height ratio of 100:1, combined with information from the probability density function of the wind direction (Hsieh et al., 2000). The boundaries of the fields are a mix of post and wire fences and hedges, of heights less than 1 m. The prevailing wind direction is from the south-west (Fig. 1).

2.2. EC Measurements

Precipitation and meteorological measurements were sampled at 1-min intervals and averaged over 30 min. The atmospheric pressure was measured with a PTB101B sensor (Vaisala, Helsinki, Finland) and the air temperature and humidity were measured with a HMP45A sensor (Vaisala, Helsinki, Finland) at a height

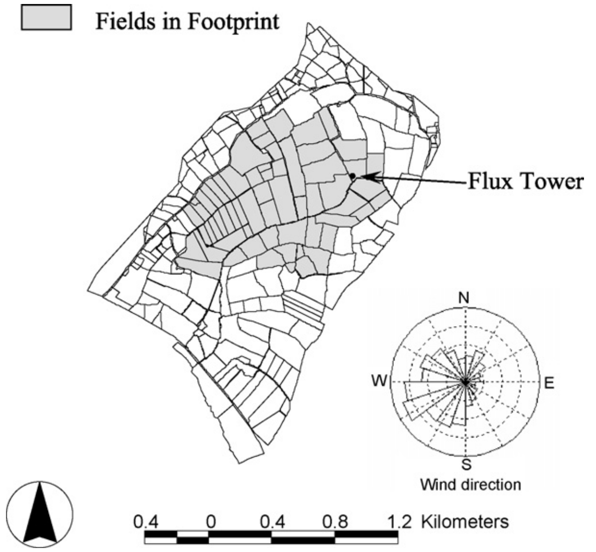

Fig. 1. Map of the grassland catchment with eddy covariance tower location. The field size varies from 1 to 5 ha. The boundaries of the fields are a mix of post and wire fences and hedges, of heights less than 1 m. The prevailing wind direction is from the southwest. The jagged edges of the EC footprint (rather than a smooth curve) represent the perimeter of fields included in the footprint. These fields were used in computing cattle numbers and fertilisation practices.

of 3 m. Soil temperature was measured with three 107 temperature probes (Campbell Scientific (CSI), Logan, Utah, USA), at 2.5, 5 and 7.5 cm deep. The volumetric soil water content was measured at depths of 5, 10, 25, and 50 cm with CS615 time domain reflectometers (CSI) set horizontally in the soil. Two other CS615's were installed vertically, from 0 to 30 cm, and from 30 cm to 60 cm depth. The datalogger was a CR23X (CSI). Net radiation was measured with a CNRI net radiometer (Kipp & Zonen, Delft, The Netherlands) and photosynthetically active radiation was measured with a PAR LITE sensor (Kipp & Zonen). Meteorological data were transferred from site to office by telemetry. The 3D wind velocity and virtual potential temperature were measured at 10 Hz with a model 81000 3D sonic anemometer (RM Young, Traverse City, Michigan, USA) positioned at the top of the 10 m tower. Water vapour and CO_2 densities were measured at 10 Hz with a LI-7500 open path infrared gas analyser (IRGA), (LICOR Inc., Lincoln, Nebraska, USA) placed within 20 cm of the centre of the anemometer air volume. The IRGA was tilted approximately 15° off the vertical to help shed water more rapidly. The 30-min averaged eddy covariance CO_2 fluxes are defined in the following equation:

$$F_{\mathrm{NEE}} \cong -\overline{w'\rho'_{\mathrm{c}}} \qquad (1)$$

where w' is the vertical wind velocity fluctuations ($\mathrm{m\,s^{-1}}$) and ρ'_{c} the CO_2 density fluctuations ($\mu\mathrm{mol\,m^{-3}}$). We adopt the micrometeorological convention in which fluxes from the biosphere to the atmosphere are positive.

2.3. Flux corrections and filtering

F_{NEE} best represents the surface flux for steady-state, planar homogeneous, and well developed turbulent flow (Goulden et al., 1996; Falge et al., 2001). During calm climatic conditions the measured fluxes are underestimated because: (1) as the fluctuations in the vertical wind speed are too small to be resolved by sonic anemometry (Goulden et al., 1996) and (2) for nocturnal and very stable conditions, the flow statistics may be dominated by transient phenomena or even the lack of turbulence (e.g. canopy waves, Cava et al., 2004). Correcting night-time fluxes with runs collected under high friction velocity (u_*), or more precisely for near-neutral to slightly stable conditions, ensures that the turbulent regime is fully developed (and dominated by ramp-like motion). Another reason for using runs with high u_* for night-time flux corrections is that these are associated with a much smaller (and perhaps more realistic) footprint (Novick et al., 2004) which is more similar to day-time footprints.

Uncertainties in night-time fluxes have been examined by many researchers and remain a challenge because a minor underestimation of night-time CO_2 fluxes (respiration) implies overestimation of the annual C uptake (Falge et al., 2001; Baldocchi, 2003). To compare with other long-term studies from different ecosystems, we use u_* to filter transients and weak turbulence conditions (e.g., Goulden et al., 1996; Falge et al., 2001). Specifically, we filtered CO_2 fluxes at night when $u_* < 0.2\ \mathrm{m\,s^{-1}}$ (Baldocchi, 2003).

All the wind data were doubly rotated, so that the mean horizontal wind speed was rotated into the mean wind direction and so that the mean vertical wind velocity was set to zero. The vertical rotation was based on the averaged 30-min angle between the horizontal and vertical axes. The CO_2 fluxes were then corrected for variations in air density due to fluctuation in water vapour and heat fluxes in accordance with Webb et al. (1980).

Filters were then used to remove bad values. Firstly, records collected during wet half hours, and up to 1 h after rain events, were rejected because of the poor performance of the open path gas analyser in wet weather. Secondly, in low wind speed conditions the computation of the vertical angle used for the vertical rotation can give unrealistic outputs and so fluxes that

Table 1
Ranges of CO_2 fluxes (μmol m^{-2} s^{-1}) used as filter limits for day- and night-time fluxes for 2002 and 2003

	Months					
	January–February	March–April	May–June	July–August	September–October	November–December
Day filter	−15 to 5	−25 to 10	−35 to 15	−35 to 15	−25 to 10	−15 to 5
Night filter	0 to 7	0 to 10	0 to 15	0 to 15	0 to 10	0 to 7

Note: If measured values were outside these ranges they were deemed unsuitable for further analysis and were replaced by regression functions.

were rotated for angles $<-2°$ or $>10°$ were rejected. A short-wave incoming radiation threshold of 20 W m^{-2} was used to differentiate night and day. This resulted in 45% of all data being classified as day-time. Thirdly, we filtered fluxes that exceeded predetermined realistic threshold values for the period (see Table 1). For instance, the summer day-time net ecosystem exchange was accepted if $-30 < F_{\mathrm{NEE,day}} < 15$ (μmol m^{-2} s^{-1}).

About 13% of the 2002 data (5.2% from day-time and 7.8% from night-time) and 8% of the 2003 data (3.8% day-time and 4.2% night-time) were rejected due to water drops on the LI-7500 during rainfall and within 1 h after rain. The rest of the non-usable data (33% for 2002 and 34% for 2003) were rejected when found to be out of range (outside the thresholds listed in Table 1) or during periods of low night-time u_* ($u_* < 0.2$ m s^{-1}). After post-processing (e.g. Webb correction) and filtering, 54% of the CO_2 flux data for 2002 and 58% for 2003 were suitable for analysis. The percentage of usable data reported by Falge et al. (2001) was approximately 65%.

2.4. Gap-filling models

The gap filling functions tested were non-linear regressions (see Goulden et al., 1996; Falge et al., 2001; Lai et al., 2002). For night-time data, the ecosystem respiration is linked to the soil temperature (Kirschbaum, 1995) and to a lesser extent to soil moisture. The correlation with different temperatures (air, surface, different soil depths) showed best correlation with soil temperature at 5 cm depth, whereas respiration was less well correlated to soil moisture (consistent with the analysis of Novick et al., 2004, for a warm temperate grassland and with Nieveen et al., 2005). Different soil temperature response functions were tested and parameterised statistically (sum of squares error (SSE), root-square (R^2), adjusted root square (adjusted-R^2), and root mean squared error (RMSE)). A linear relationship, an exponential relationship, the Arrhenius function and a Q_{10} relationship were all considered. The best fit (with highest R^2) regression model (for night-time respiration $F_{\mathrm{RE,night}}$) was that obtained using the van't Hoff (Lloyd and Taylor, 1994) simple empirical exponential fit defined in the following equation:

$$F_{\mathrm{RE,night}} = a\,e^{bT_s} \tag{2}$$

where T_s is the soil temperature at 5 cm depth (°C) and a (μmol of CO_2 m^{-2} s^{-1}) and b (°C) are coefficients. Although the van't Hoff's equation is empirical and has no rational basis, it has been used extensively in biology (Lloyd and Taylor, 1994). In our data set, for 2002 a was found to be 1.476 ± 0.087 μmol of CO_2 m^{-2} s^{-1} and for 2003 it was 1.109 ± 0.072 μmol of CO_2 m^{-2} s^{-1}. The coefficient b for 2002 was estimated as 0.095 ± 0.005 °C^{-1} and for 2003 was 0.122 ± 0.005 °C^{-1}. The R^2 for 2002 was 0.324 and for 2003 was 0.381. The coefficients and statistics are reported in Table 2. Eq. (2) was applied to the data for the full year (separately for 2002 and 2003, Fig. 4). A criticism of the van't Hoff form of the respiration equation (Lloyd and Taylor, 1994) is that it underestimates respiration at low temperatures and overestimates respiration rates at high temperatures. In the temperate climate of this study, the range of daily soil temperature (at 5 cm depth) was 3–16 °C. In this study the van't Hoff form is a reasonable fit to the data, particularly because of the narrow spread of soil temperature on either side of 10 °C.

Table 2
Fitting function and statistics for night-time ecosystem respiration for 2002 and 2003

Year	Equation	Coefficients	SSE	R^2	Adjusted R^2	RMSE
2002	$a\,e^{bT_s}$	$a = 1.476 \pm 0.087$, $b = 0.095 \pm 0.005$	1.254×10^4	0.324	0.324	1.915
2003	$a\,e^{bT_s}$	$a = 1.109 \pm 0.072$, $b = 0.122 \pm 0.005$	1.66×10^4	0.381	0.380	2.071

Note: T_s is the soil temperature at 5 cm depth (°C) and a (μmol of CO_2 m^{-2} s^{-1}) and b (°C) are coefficients. SSE (sum of squared errors), R^2 (root square), adjusted R^2 (adjusted root square) and RSME (root mean squared error).

For day-time, the NEE ($F_{\text{NEE,day}}$ in μmol of CO_2 $m^{-2}\,s^{-1}$) is linked to the photosynthetically active radiation Q (μmol of quantum $m^{-2}\,s^{-1}$), (e.g., Michaelis and Menten, 1913; Smith, 1938; Goulden et al., 1996). The different light response functions evaluated included: a linear relationship, Smith formula (Smith, 1938; Falge et al., 2001), Michaelis–Menten formula (rectangular hyperbola) (Michaelis and Menten, 1913; Falge et al., 2001), Misterlich formula (Falge et al., 2001), and Ruimy formula (Ruimy et al., 1995; Lai et al., 2002). The best fit was achieved with the Misterlich formula defined in the following equation:

$$F_{\text{NEE,day}} = -F_{\text{GPP,opt}}(1 - e^{(-\alpha Q/F_{\text{GPP,opt}})}) + \gamma \quad (3)$$

where Q is the photosynthetic photon flux density (μmol of quantum $m^{-2}\,s^{-1}$); α is ecosystem quantum yield [(μmol of CO_2 $m^{-2}\,s^{-1}$) (μmol of quantum $m^{-2}\,s^{-1})^{-1}$]; and γ is the ecosystem respiration during the day (μmol of CO_2 $m^{-2}\,s^{-1}$). $F_{\text{GPP,opt}}$ is the gross primary productivity at "saturating light" (μmol of CO_2 $m^{-2}\,s^{-1}$), (Smith, 1938; Michaelis and Menten, 1913) and was set at the mean value for this experiment of −24 μmol of CO_2 $m^{-2}\,s^{-1}$. As Q varies seasonally, the regressions are performed on 2-month bins and the values of the coefficients (α and γ) are listed in Table 3.

2.5. Farm scale carbon balance

This flux footprint covers parts of eight small farms (10–40 ha each) with similar land use and management practices. We collected data on management practices, which enabled the annual C budget at the farm scale to be estimated. We used Eq. (4) in a first order estimate of the farm scale C balance:

$$N = \Delta C - C_h - C_m - C_s - C_f \quad (4)$$

where N is the net ecosystem exchange; ΔC the C sequestered in (or lost from) the soil over the annual accounting period; C_h the carbon in methane (CH_4) emissions from animals in the fields within the EC footprint (estimated); C_m the C exported off farm in milk; C_s the C exported as dissolved organic C (DOC) in a stream within the study area and C_f the farmyard emissions in excess of what we measure (i.e. the respiring cattle housed in the farmyard for ~5 winter months of the year). The farmyard is outside the EC footprint boundary. We collected data for each of the parameters in Eq. (4) except ΔC. We exclude C imported in concentrates (cattle food supplements, nuts, etc). For the different components in Eq. (4), we have a stocking density of 2.2 LU ha^{-1} (LU = livestock unit = one 550 kg cow):

- To estimate the loss of methane we use the emission rate of 100 kg CH_4 $LU^{-1}\,yr^{-1}$ (Houghton et al., 1997). Hence this emission as C is

$$C_h = \frac{2.2 \times 100 \times 12}{16} = 165\,\text{kg C ha}^{-1} = 16.5\,\text{g C m}^{-2}\,\text{yr}^{-1}$$

- For C in milk exported, the milk export is 5000 L per cow (=5000 kg) and the amount of C in milk is assumed to be 4%. Thus

$$C_m = 2.2 \times 5000 \times 0.04 = 440\,\text{kg C ha}^{-1} = 44\,\text{g C m}^{-2}\,\text{yr}^{-1}$$

- During 2004 and 2005, we measured dissolved organic carbon (DOC) in the stream and the mean annual concentration was ca. 5 mg C L^{-1}. With an average annual rainfall of 1470 mm and an evapotranspiration of ~400 mm, the export of carbon in the

Table 3
Values of day fitting regression parameters and statistics for use with the Misterlich equation (3)

Year	Months	Coefficients	SSE × 10^4	R^2	Adjusted R^2	RMSE
2002	January–February	$\alpha = 0.017 \pm 0.002$, $\gamma = 0.217 \pm 0.54$	0.3	0.508	0.507	2.625
2002	March–April	$\alpha = 0.031 \pm 0.004$, $\gamma = 2.525 \pm 0.95$	2.2	0.553	0.552	4.782
2002	May–June	$\alpha = 0.030 \pm 0.004$, $\gamma = 3.703 \pm 0.54$	3.1	0.554	0.554	4.972
2002	July–August	$\alpha = 0.018 \pm 0.001$, $\gamma = 3.501 \pm 0.55$	2.3	0.525	0.521	4.156
2002	September–October	$\alpha = 0.029 \pm 0.003$, $\gamma = 3.24 \pm 0.717$	1.5	0.661	0.605	3.896
2002	November–December	$\alpha = 0.019 \pm 0.002$, $\gamma = 1.212 \pm 0.514$	0.2	0.519	0.518	2.359
2003	January–February	$\alpha = 0.017 \pm 0.002$, $\gamma = 0.809 \pm 0.431$	0.3	0.515	0.514	2.349
2003	March–April	$\alpha = 0.030 \pm 0.004$, $\gamma = 2.088 \pm 0.93$	2.4	0.578	0.578	4.794
2003	May–June	$\alpha = 0.033 \pm 0.005$, $\gamma = 5.243 \pm 1.19$	4.3	0.494	0.493	5.965
2003	July–August	$\alpha = 0.032 \pm 0.004$, $\gamma = 6.039 \pm 0.827$	2.6	0.579	0.579	4.383
2003	September–October	$\alpha = 0.030 \pm 0.003$, $\gamma = 2.788 \pm 0.736$	1.7	0.594	0.593	4.029
2003	November–December	$\alpha = 0.015 \pm 0.002$, $\gamma = 0.544 \pm 0.334$	0.2	0.514	0.513	2.044

stream is

$$C_s = 50\,\mathrm{kg\,C\,ha^{-1}} = 5\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$$

This is of the order of stream C export found by Hope et al. (1997).

- For the farmyard emission, C_f (for 150 days when cattle are housed indoors), a LU consumes 10 kg of dry matter per day, which is equivalent to 4.5 kg C. A LU respires an amount of CO_2 that is approximately 70% of the C consumed as food. The remaining 30% of C goes into meat and milk and as dung and urine. Hence the farmyard CO_2 emission as C is estimated as:

$$C_f = 2.2 \times 0.7 \times 4.5 \times 150 = 1039\,\mathrm{kg\,C\,ha^{-1}}$$
$$= 103.9\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$$

It is relevant to note that the grass harvested (silage) is fed to the animals during the winter. From the harvested fields (approximately 40% of the footprint) an estimated 8500 kg of dry matter $\mathrm{ha^{-1}\,yr^{-1}}$ was produced. The dry matter of silage has a 45% C content. Thus, silage = 0.4 × 8500 × 0.45 = 1530 kg C $\mathrm{ha^{-1}}$ = 153 g C $\mathrm{m^{-2}}$. Approximately 70% of this silage feed is equivalent to C_f.

3. Results and discussion

3.1. Climate and annual NEE

In 2002 the annual precipitation was 1785 mm and in 2003 it was 1185 mm (Fig. 2a). The monthly average vapour pressure deficit VPD in kPa is shown in Fig. 2b. The monthly average evapotranspiration (ET) in mm and monthly average potential evapotranspiration (PET) in mm are shown in Fig. 2c and d, respectively. The environmental variables are shown in Fig. 3: daily average photosynthetically active radiation Q in μmol of quantum $\mathrm{m^2\,s^{-1}}$ (Fig. 3a); daily average air temperature T_a (Fig. 3b); daily average soil temperature T_s (Fig. 3c) and daily average volumetric soil moisture content, from 0 to 30 cm depth $\theta_{0\text{–}30}$ (Fig. 3d). The night-time fluxes for 2002, $F_{\mathrm{RE,night}}$ versus T_s, are shown in Fig. 4a with an exponential fit. The night-time fluxes for 2003 are shown in Fig. 4b with a different exponential fit. In Fig. 5a we show the day-time fluxes in June 2002 and June 2003, $F_{\mathrm{NEE,day}}$ versus Q, with different Misterlich formula fits. In Fig. 5b we show the day-time fluxes in August 2002 and August 2003 with similar Misterlich formula fits. In Fig. 6 we show the monthly NEE and in Fig. 7 we show the cumulative NEE for each of the 2 years.

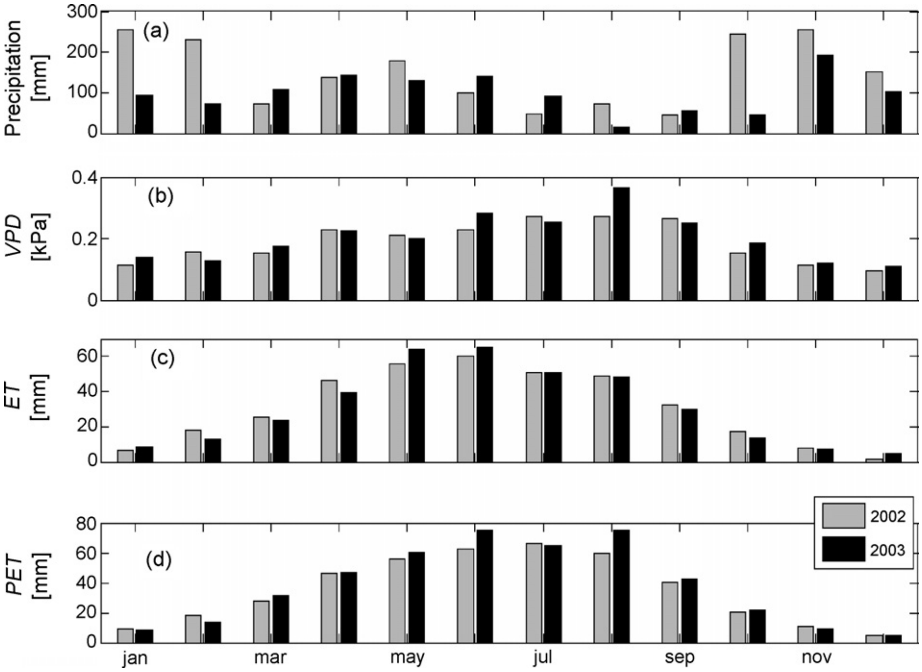

Fig. 2. (a) Monthly precipitation (mm) for 2002 (grey) and 2003 (black); (b) monthly vapour pressure deficit (VPD in kPa); (c) monthly (actual) evapotranspiration (ET in mm) for 2002 and 2003; (d) monthly potential evapotranspiration (PET in mm) calculated using the Penman–Monteith equation.

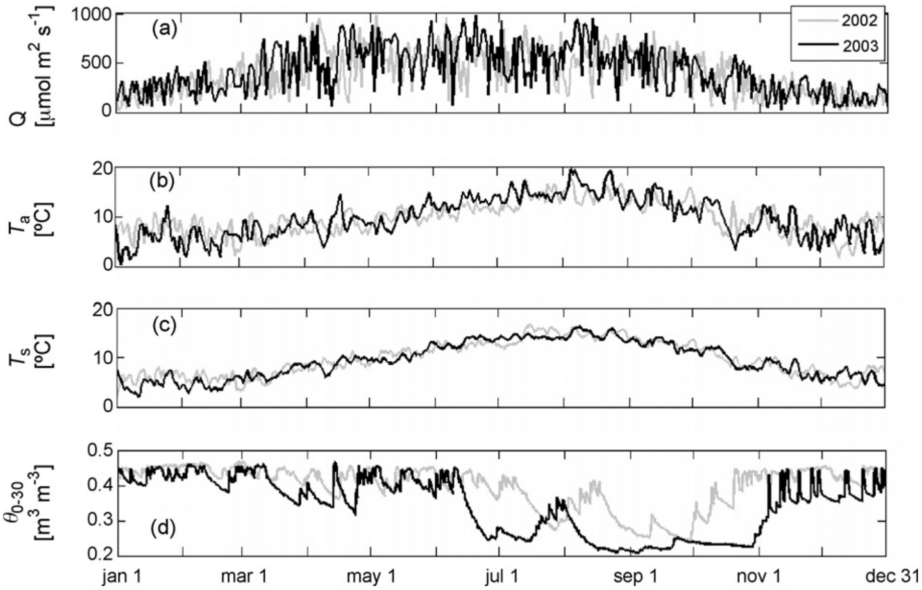

Fig. 3. (a) Daily photosynthetic active radiation (Q, μmol m^{-2} s^{-1}) for 2002 and 2003; (b) daily averaged air temperature (T_a in °C) for 2002 and 2003; (c) daily averaged soil temperature (T_s in °C) at a depth of 5 cm for 2002 and 2003; (d) near surface soil moisture (θ in m^3 m^{-3}) at 30 min interval over a depth of 0–30 cm for 2002 and 2003.

This grassland had an EC measured net ecosystem uptake of C in both years: −193 g C m^{-2} in 2002 and −258 g C m^{-2} in 2003 (Fig. 7). These NEE magnitudes are similar to those reviewed in Novick et al. (2004). We extrapolated the night-time respiration functions to estimate the 24-h respiration and summed to get the total annual ecosystem respiration R_E of +1480 g C m^{-2} for 2002 and +1460 g C m^{-2} for 2003. We further estimated the gross primary production, GPP = R_E − NEE, to be −1673 g C m^{-2} for 2002 and −1718 g C m^{-2} for 2003. The difference in the NEE between the 2 years of 65 g C m^{-2} is only 4% of GPP.

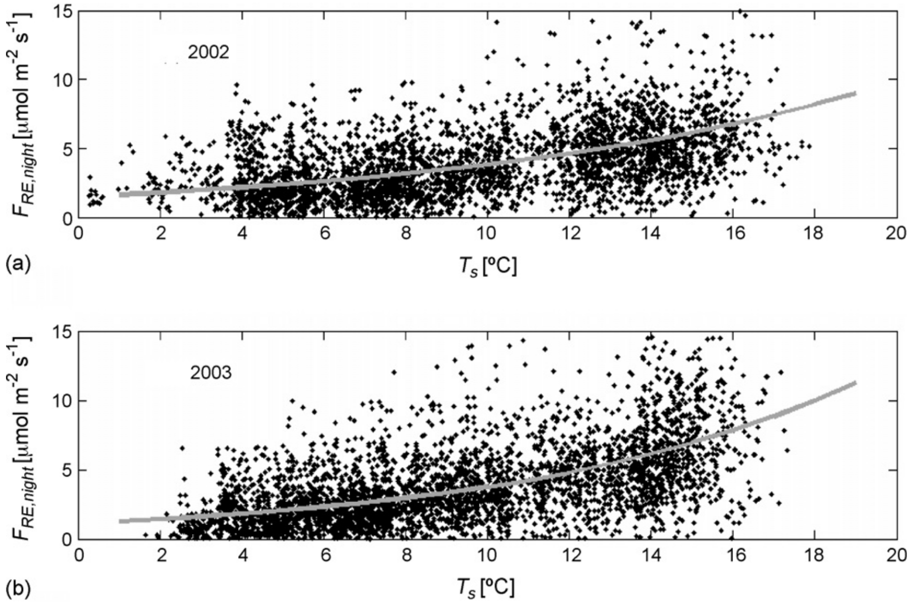

Fig. 4. Measured 30 min averages of night-time net ecosystem CO$_2$ exchange ($F_{\mathrm{RE,night}}$) vs. 5 cm soil temperature (T_s) where $u_* > 0.2$ m s^{-1}. Using the van't Hoff (see Lloyd and Taylor, 1994) empirical exponential model of form $F_{\mathrm{RE,night}} = a\,e^{bT_s}$, where $F_{\mathrm{RE,night}}$ is the night-time respiration. (a) 2002 data fitted with a = 1.476 and b = 0.095 (R^2 = 0.324); (b) 2003 data fitted with a = 1.109 and b = 0.122 (R^2 = 0.381).

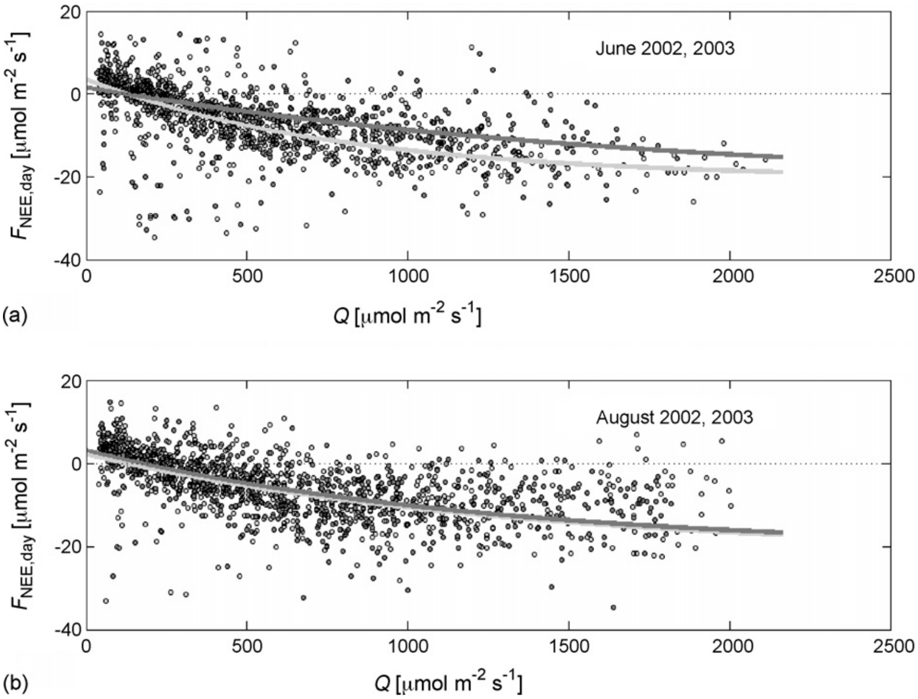

Fig. 5. Day-time 30 min averages of the net ecosystem CO_2 exchange ($F_{\mathrm{NEE,day}}$ or NEE) as a function of photosynthetic photon flux density (Q). (a) June 2002 and June 2003. June 2002 (black line) was wet and no harvesting took place. June 2003 (grey line) was dry and harvesting took place on part of the EC footprint on 15 June. $F_{\mathrm{NEE,day}}$ was higher during the non-harvested June (2002, black line) than the harvested June (2003). The effect of harvesting is to reduce the monthly NEE; (b) August 2002 (wet) and August 2003 (dry) show no difference in the monthly NEE.

3.2. Differences in interannual NEE

We firstly examined the environmental variables in an attempt to explain the NEE differences between the 2 years. The high humidity and low potential for evaporation of the region is evidenced by the low and similar VPD in both years (Fig. 2b) with a maximum of 0.36 kPa in August 2003. Thus, the stomatal conductance (i.e. rate of passage of CO_2 and water vapour through plant pores) was similar in both years. Fig. 3a shows that Q in 2002 was similar to Q in 2003. The annual integrated Q in 2002 was 6293 mol of quantum m^{-2} and in 2003 was 6604 mol of quantum m^{-2}, suggesting that Q was unlikely to play a major role in explaining the interannual NEE difference. In fact, Hsieh et al. (2005) found that increases in Q are

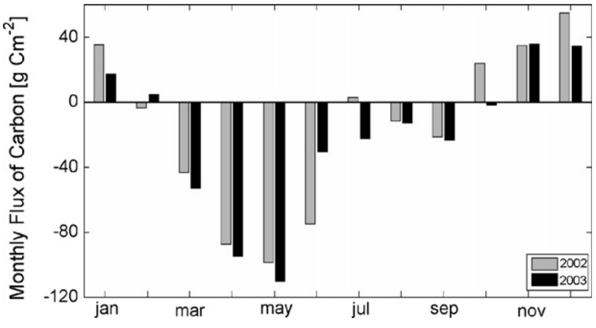

Fig. 6. Monthly C flux (g C m^{-2}) for 2002 (grey) and 2003 (black).

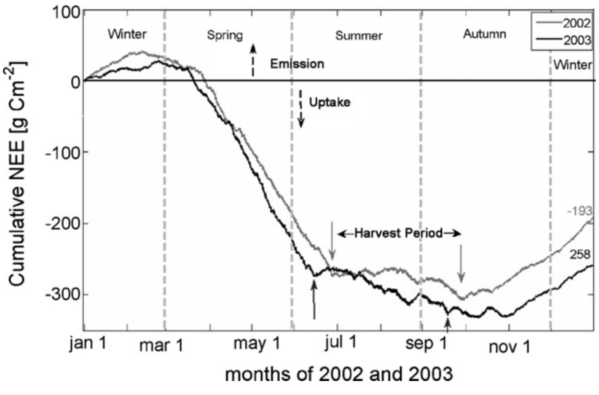

Fig. 7. Cumulative uptake of C for 2002 (grey) and 2003 (black). The NEE for 2002 was −193 g C m^{-2} and for 2003 was −258 g C m^{-2}. The grey solid arrows show the first harvest date (1 July) and the last harvest date (25 September) in 2002. Between these dates there were two additional smaller harvests on 25 July and 28 August, as shown by the concave parts to the curve at these dates. The black solid arrows show the first harvest date (15 June) and the last harvest date (18 September) in 2003. Between these dates there was one additional smaller harvest on 20 August, as shown by the concave part to the curve at this date.

correlated with decreases in VPD at this site and their combined effect on photosynthesis cancels out. The daily air temperature (Fig. 3b) had a small range during the year: from a maximum of 21 °C (in August) to a minimum of 0 °C (January). The summer average was 15 °C and the winter average was 5 °C. The soil temperature (at 5 cm depth, Fig. 3c) tracks the air temperature and rarely fell below 4 °C. Hence, neither (summer nor winter) temperature extremes could have limited the stomatal conductance or leaf photosynthesis.

Precipitation leaves a signature in the volumetric soil moisture $\theta_{0\text{–}30}$ (depth averaged over 0–30 cm). In Fig. 3d we show that $\theta_{0\text{–}30}$ in both years varies from highs of 0.45 $m^3\ m^{-3}$ to lows of 0.22 $m^3\ m^{-3}$ (saturation is ~0.45 $m^3\ m^{-3}$, field capacity is ~0.32 $m^3\ m^{-3}$ and wilting point is ~0.12 $m^3\ m^{-3}$ (Jaksic, 2004)). Examining Fig. 3d we note that the soil moisture was much lower in 2003 particularly during the summer months of June–September, but was always higher than the wilting point in both years. To assess how important these soil moisture differences are for stomatal conductance (and hence photosynthesis), we compared the actual and potential evapotranspiration for these 2 years. The annual evapotranspiration (ET) measured by the EC system (Fig. 2c) was 372 and 368 mm for 2002 and 2003, respectively, with little difference in the monthly ET between the 2 years. The corresponding potential evapotranspiration (PET) estimated using Penman–Monteith was 422 and 455 mm for 2002 and 2003, respectively (Fig. 2d). This suggests that both atmospheric water vapour demand (PET) and actual water vapour fluxes (ET) to the atmosphere were similar for these 2 years. The fact that the ratio of actual to potential evapotranspiration for these 2 years (88% for 2002 and 81% for 2003) was not very sensitive to soil moisture indicates that soil moisture could not have limited the stomatal conductance. This analysis suggests that any differences in annual NEE was not likely to be attributed to stomatal conductance limitations.

Fig. 5b shows a comparison of NEE (day-time) for August 2002 and August 2003. The soil moisture content in August 2003 was higher than in August 2003, but the NEE (day-time) relationship with Q was similar in both months resulting in similar monthly NEE (Fig. 6). This suggests that the soil moisture difference had no significant effect on NEE (day-time). This may be due to the fact that in the studied grassland, the soil moisture status was predominantly wet, and neither year experienced soil moisture below 0.22 $m^3\ m^{-3}$. This is >0.1 $m^3\ m^{-3}$ above the wilting point for this soil. In the dry periods (e.g. August 2003), there was more than adequate soil moisture to maintain the grassland ecosystem without water stress.

In Fig. 7 we show that the NEE for 2002 was -193 g C m^{-2} and for 2003 was -258 g C m^{-2}. The grey solid arrows show the first harvest date (1 July) and the last harvest date (25 September) in 2002. Between these dates there were two additional smaller harvests on 25 July and 28 August, as shown by the concave parts to the curve at these dates. The black solid arrows show the first harvest date (15 June) and the last harvest date (18 September) in 2003. Between these dates there was one additional smaller harvest on 20 August, as shown by the concave part to the curve at this date. Fig. 7 shows that there are multiple harvesting events between June and September, each covering a part of the EC footprint.

We examined harvesting dates to see if this might be responsible for the NEE difference (Figs. 5b and 6). In each year there was net uptake (C sink) in the 7 months, March–September (except July 2002) and net respiration (C source) in the months, October–January. In February in both years the ecosystem is C neutral. The net uptake in May 2002 of -99 g C m^{-2} is similar to -110 g C m^{-2} in May 2003. The net uptake in June 2002 of -75 g C m^{-2} was more than double the -31 g C m^{-2} uptake of June 2003. The net uptake in July, 2002 of $+2$ g C m^{-2} and in July 2003 was -23 g C m^{-2} (Fig. 6).

In Fig. 5a we show the relationship of NEE (day-time) with Q in the months of June 2002 and June 2003. June 2002 was wet and so no harvesting was carried out. By contrast harvesting was carried out in mid June 2003. In Fig. 5a it is clear that the relationship between NEE (day-time) and Q results in a higher uptake in June 2002 (non-harvested) than in June 2003 (harvested). This suggests that the effect of harvesting is to reduce the NEE in the month of harvesting (or more likely in the few weeks immediately after the harvest event). The reduced NEE in the month of harvest (June 2003) is also clear from Figs. 6 and 7. Immediately after harvesting (when the grass was harvested to within 5 cm of the bare soil), there is a period of approximately 2 weeks during which there is net emission. After this 2-week period the effect then changes from net daily emission to net uptake. The cumulative NEE over the summer months was approximately the same in both years. This suggests that even though there were different dates to harvesting events that the effect of harvesting balanced out over the two summer periods. It must be noted that the harvest effect on radiation use efficiency is short lived at about 2 weeks after which

Table 4
Components of farm C balance (g C m^{-2} yr^{-1}) used in Eq. (5)

	Parameter					
	N	C_h	C_m	C_s	C_f	ΔC
2002	−193 ± 50	16 ± 0	44 ± 0	5 ± 2	104 ± 10	−24 ± 62
2003	−258 ± 50	16 ± 0	44 ± 0	5 ± 2	104 ± 10	−89 ± 62

N, the net ecosystem exchange; ΔC, the carbon sequestered in (or lost from) the soil over the annual accounting period; C_h, carbon in methane (CH_4) emissions from animals in the fields within the EC footprint (not measured); C_m, the carbon exported off farm in milk; C_s, the carbon exported as dissolved organic carbon (DOC) in a stream within the farm; C_f, farmyard emissions in excess of what was measured, (i.e. from respiring cattle housed in the farmyard for ~5 winter months of the year).

productivity is restored. Over the 3- or 4-month summer harvest season, a loss in radiation use efficiency due to harvesting in 1 month at one part of the footprint is similar to the loss in another part of the footprint in another month. We suggest that if the full footprint were all harvested at one time, then the reduced radiation use efficiency would be much more obvious. However in this land management set up, with multiple farmers, with different practices of harvesting, a clear harvest signal in radiation use efficiency is not to be expected.

The sum of the NEE for the 7-month growing season (March–September) was similar in both years: -340 g C m^{-2} for 2002 and -345 g C m^{-2} for 2003 (Fig. 6). From the above we conclude that there is practically no difference in NEE over the growing season. This is despite the large differences in growing season precipitation; the monthly differences in NEE due to different harvesting dates; and differences in monthly soil moisture status.

3.3. Farm scale carbon balance

In addition to the eddy covariance analysis we also estimated the annual carbon budget at the farm scale from data collected from the farmers (Table 4). We rewrite Eq. (4) as Eq. (5):

$$\Delta C = \mathrm{NEE} + C_h + C_m + C_s + C_f \qquad (5)$$

The estimated values for these variables are given in Table 3. With this approach, ΔC is estimated to be an uptake (sink) of -24 ± 62 g C m^{-2} for 2002 and -89 ± 62 g C m^{-2} for 2003. The soils on this site have a C content of approximately 4%. If -89 g C m^{-2} were fixed in any 1 year this is an additional 0.012% C per year, suggesting that at this rate of C fixation it would take ~80 years to increase the C content by 1%. Thus, this fixation rate is not detectable by conventional soil sampling methods.

3.4. Uncertainty

Uncertainty in the form of random errors and systematic errors complicate analysis of C exchange. Random errors due to sampling and gapfilling techniques tend to decrease with increasing length of record (Falge et al., 2001). Averaging numerous flux density measurements to construct monthly and annual sums reduces random sampling errors to within ±5% (Baldocchi, 2003). Baldocchi (2003), notes that the error bound on the net annual exchange of CO_2 is likely to be less than ±50 g C m^{-2}. As with Nieveen et al. (2005) we adopt an indicative ‘confidence range’ for annual summed NEE of ±50 g C m^{-2}. Thus we have an NEE of -193 ± 50 g C m^{-2} for 2002 and an NEE of -258 ± 50 g C m^{-2} for 2003.

The rate of CH_4 emissions from the grazing animals is similar in many countries (Nieveen et al., 2005; Houghton et al., 1997), suggesting that there is unlikely to be any serious error in this component of the C balance. The estimate of C export in milk was based on long-term farm records (locally and nationally) and is therefore assumed to also have negligible error. The estimate of C emissions as respiration from the cattle while housed in the farmyard are based on the farm management practice of housing animals for 5 winter months per year and records of their food consumption. A standard Irish cow (550 kg) requires dry matter containing 4.5 kg C d^{-1} with 70% of the carbon consumed being respired as CO_2 (O’Loughlin et al., 2001). Animal faeces and urine from winter housing is spread on land where it decomposes and respires, and is measured as part of the NEE by the EC system along with soil, grass and grazing animal respiration. Therefore our estimate of C emissions from the farmyard is 103.9 ± 10 g C m^{-2}.

The error in the C export in the stream is low. The error in the streamflow measurement over the year is less than ±10% as the water balance for this small catchment closes to within ±10% and the DOC concentrations are assumed to be within ±20%. As such the export of C as DOC was estimated for both years to be 5 ± 2 g C m^{-2}.

4. Conclusions

Our study shows that intensively managed and fertilised grassland in a humid temperate climate has the potential to fix carbon to the soil. Eddy covariance (EC) measurements over contrasting wet and dry years resulted in annual NEE sums (uptake) of -193 ± 50 g C m^{-2} for the wet year and -258 ± 50 g C m^{-2} for the dry year. Although there were large differences in soil moisture status between the 2 years, this was not responsible for the interannual difference in NEE of -65 g C m^{-2} because the soil moisture status was well above wilting point at all times during the 2 years ensuring that the vegetation did not experience any water stress. We conclude that this humid grassland was not very sensitive to the precipitation variability for the wet year (with 21% above average annual rainfall) or for the dry year (with 24% below average annual rainfall). Harvesting was shown to reduce NEE in the month of harvesting. However, integrated over the summer harvest period, the effect of harvesting was similar in both years. We concluded that the interannual variation in NEE of 65 g C m^{-2} is of the order of uncertainty of the EC measurements. By combining the EC measurements with estimates of the key components of the farm scale C balance we found that the site was a small sink, -24 ± 62 g C m^{-2} yr^{-1} in 2002 and -89 ± 62 g C m^{-2} yr^{-1}in 2003, for carbon during the study period.

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