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Comparison of soil greenhouse gas fluxes from extensive and intensive grazing in a temperate maritime climate

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Abstract

Greenhouse gas (GHG) fluxes from a seminatural, extensively sheep grazed drained moorland and intensively sheep grazed fertilised grassland in SE Scotland were compared over 4 yr (2007–2010). Nitrous oxide and CH_4 fluxes were measured by static chambers, respiration from soil including ground vegetation by a flow through chamber and the net ecosystem exchange of CO_2 by eddy covariance. All GHG fluxes displayed high temporal and interannual variability. Temperature, radiation, water table height and precipitation could explain a significant percentage of seasonal and interannual variations. Greenhouse gas fluxes were dominated by the net ecosystem exchange of CO_2, emissions of N_2O from the grazed grassland (384 $g\,CO_{2eq}\,m^{-2}\,yr^{-1}$) and emissions of CH_4 from ruminant fermentation (147 $g\,CO_{2eq}\,m^{-2}\,yr^{-1}$). Methane emissions from the moorland were small (6.7 $g\,CO_{2eq}\,m^{-2}\,yr^{-1}$). Net ecosystem exchange of CO_2 and respiration were much larger on the productive fertilised grassland (−1624 and +7157 $g\,CO_{2eq}\,m^{-2}\,yr^{-1}$, respectively) than the seminatural moorland (−338 and +2554 $g\,CO_{2eq}\,m^{-2}\,yr^{-1}$, respectively). Large CH_4 and N_2O losses from the grazed grassland counteracted the CO_2 uptake by 35 %, whereas the small N_2O and CH_4 emissions from the moorland did only impact the NEE by 2 %.The 4 yr average GHG budget for the grazed grassland was 1006 $g\,CO_{2eq}\,m^{-2}\,yr^{-1}$ and 331 $g\,CO_{2eq}\,m^{-2}\,yr^{-1}$ for the moorland.

1 Introduction

European governments are required to reduce its GHG emissions by 80 % in 2050. Anthropogenic emissions are recorded annually through UNFCCC and CORINAIR activities, mostly by simple, but crude, IPCC Tier 1 emission factor approaches, which can not accurately reflect regional variability and monitor mitigation. To improve the current reporting structure countries have started to (i) develop and implement more complex Tier 2 reporting systems for some of the emission sectors and (ii) monitor GHG concentrations emissions at the landscape scale together with improving top down modelling. Successful Tier 2 emission factors need to focus on easily measureable or documented variables (i.e. rainfall, temperature) and tower measurements/top down models would benefit from including non anthropogenic emissions. This paper addresses these requirements by comparing 4 yr of GHG flux measurements from nearby intensively grazed grassland and extensively grazed moorland in a temperate maritime climate and assesses the drivers responsible for spatial and temporal variability.

2 Methods

2.1 Site description

Auchencorth Moss (AMo) is a low lying acid moorland dominated by grasses and is approximately 17 km southwest of Edinburgh, Scotland (Table 1). The moorland was drained about 100 yr ago and again in the 1960 to improve the land for extensive grazing and is not fertilised. The peat depth is now mostly 0.5 m, but in places up to 2 m deep. The moss is extensively grazed by sheep at a very low stocking density of 0.2 LSU ha^{-1} (1 LSU ha^{-1} = 10 ewes or 25 lambs).

In contrast two adjacent fields at Easter Bush (EBu), 7 km NW from AMo, have been intensively managed for livestock grazing for over 20 yr. The grass is grown on an imperfectly drained Macmerry soil of the Rowanhill soil association (eutric cambisol, FAO classification) with a pH (in H_2O) of 5.1 and a clay fraction of 20–26 % (Table 1). Although the fields were drained > 50 yr ago, the drainage system does not operate properly any longer. Large puddles of standing water are a regular occurrence during prolonged periods of rain. From 2007 to 2010 the fields were stocked with sheep at an average annual stocking density was 0.77 LSU ha^{-1}. Grazing densities were not constant, animal numbers ranged from 0 to 170 ewes and 0 to 260 lamb. Lambs were only on the field between April and September. To maintain the high stocking densities the grassland received granules of mineral N fertiliser which were applied onto the fields during the growing season. Between spring 2007 and summer 2010 N fertiliser was applied on 16 occasions. The average application rate was 58 (range 35–92) $kg\,N\,ha^{-1}$ and total annual rates were 231, 173, 250,190 $kg\,N\,ha^{-1}\,yr^{-1}$ in 2007, 2008, 2009, 2010, respectively. Mostly ammonium nitrate was applied, but on 3 occasions urea was used and once a NPK compound fertiliser.

Both sites are long term CEH field sites where we have studied carbon and nitrogen fluxes and pools as part of a range of national and European programmes, including Graminae (Sutton et al., 2001), Greengrass (Soussana et al., 2007), Nitroeurope (Skiba et al., 2009) and Carboeurope (Schulze et al., 2010).

2.2 Soil greenhouse gas flux measurements

Methane and N_2O fluxes were measured by static chamber. Chambers were manufactured from opaque polypropylene pipes (0.4 m in diameter) cut to lengths of 0.2 m and fitted with a 0.045 m wide flange at the outward facing end (Clayton et al., 1994). The pipe was inserted into the soil to approx. 0.03–0.07 m depth. The measurement protocol was slightly different at the two sites.

At AMo 9 chambers (approx 17 l volume) were installed within a 25 m radius of each other and within the main fetch of the CO_2 eddy covariance tower. They remained in position over the 4 yr study period and covered the most dominant vegetation types on the Moss: three chambers each on (1) hummocks of *Deschampsia* and/or *Eriopherum* dominated vegetation, (2) hummocks of *Juncus* and (3) hollows dominated by mosses. To measure fluxes a flexible, transparent, dome shaped polyethylene lid was placed onto the chamber for approx. 60 min (MacDonald et al., 1996). Air samples (200 ml) were withdrawn via a 3-way-tap fitted at the side of the chamber, just after chamber closure and then approx. 30 and 60 min later (later referred to as t_0, t_{30}, t_{60}). To mix the chamber air the syringe was flushed three times before collection into 500 ml Tedlar® bags. During summer it was necessary to fit extension collars onto chambers containing *Juncus*, the volume of air enclosed then was approx 30 l. Measuring the volume of a chamber enclosing hummock vegetation was not easy, due to uneven hummock shapes and hidden airspaces within the hummock. Instead of just measuring the chamber height, as done at EBu, we filled the chambers with a know SF_6 concentration (4.75 ppb), stirred the air by fan and collected chamber air after 5 min incubation. The volume was calculated from the magnitude of dilution of SF_6 (Dinsmore, 2008).

At EBu 8 chambers were inserted, 4 within the eddy covariance footprint of prevailing SW wind direction and another 4 in the NW direction (Jones et al., 2011). Chambers were moved every fortnight to allow free grazing. For flux measurements chambers were sealed with aluminium lids fitted with a central port for sample collection. At the beginning of the incubation period ambient air samples were taken from about 0.5 m above the soil surface next to the chambers (t_0). After about 60 min incubation (t_{60}) 200 ml sample were withdrawn from inside the chambers into Tedlar® Bags. Linearity tests, taking samples every 15 min over 2 h, were carried out several times during the study period and demonstrated linearity of up to 120 min with an average $r^2 = 0.96$ for N_2O.

Samples were analysed for N_2O and CH_4 within one week of collection. In the laboratory samples were transferred to glass vials and were analyzed using a Hewlett Packard 5890 series II gas chromatograph (Agilent Technologies, Stockport, UK), fitted with an electron capture detector for N_2O (detection limit $< 0.2\,\mu l\,l^{-1}$) and a flame ionisation detector for CH_4 (detection limit $< 1.3\,\mu l\,l^{-1}$). Fluxes were calculated from the difference of gas concentration from the start (t_0) and average concentration increase at t_{30} and t_{60} for AMo samples and the concentration increase at t_{60} for EBu samples and concentrations multiplied by the chamber volume and divided by the chamber area and time of incubation.

Respiration from soil including the ground covering vegetation (grass at EBU and mosses and small herbs at AMo) were measured close to all static chambers at AMo and EBu using a PP-Systems (Hitchin, UK) SCR-1 respiration chamber (0.1 m

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diameter) attached to an EGM-4 infrared gas analyser (Dinsmore et al., 2009). The chamber was placed onto the ground for 1–2 min periods, during which chamber air was re-circulated between chamber and EGM-4. Fluxes were calculated from the linear increase in concentration, taking into account the soil temperature at the time of measurement. The ground at AMo was too soft to create a proper seal between soil and chamber, therefore during measurements the chamber was attached to small plastic collars inserted 0.05 m into the peat before the 4 yr study period. Measurements were usually made when N_2O and CH_4 fluxes were measured.

The frequency of soil GHG flux measurements was different at the two locations. At EBu outwith fertilisation periods fluxes were measured weekly during the growing period and fortnightly in winter. Intensive measurements scaling down from daily to weekly were operated immediately after N fertiliser applications. Between January 2007 and December 2010, we measured N_2O, CH_4 and respiration on 248, 239 and 222 dates. At AMo fluxes were measured approximately every 2 weeks during the growing season and every 4 weeks in winter, in total on 78 (N_2O and CH_4) and 49 (respiration) dates.

2.3 Net ecosystem exchange of CO_2

The net ecosystem exchange of CO_2 (NEE) was measured by eddy covariance at both locations, using a fast response closed path CO_2 and H_2O analyser (LiCOR 7000 IRGA, LI-COR Lincoln, USA) and a sonic anemometer (Gill Windmaster Pro, Lymington, UK). The sample inlet was fixed just below the sonic anemometer at a height of 3.6 m at AMo and at 2.5 m at EBu. The LI-COR instruments were situated in mains powered research cabins 20 m (AMo) and 10 m (EBu) away from the towers. Sample was drawn into the analysers via 6 mm nonreactive tubing. The three-dimensional wind vector components, sonic temperature, CO_2 and H_2O concentrations were logged at 20 Hz using an in-house LabViewTM data acquisition program. Eddy covariance CO_2 fluxes were calculated following CarboEurope protocols (Reichstein et al., 2005). The protocols prescribed how to deal with block averaging, coordinate rotation, lag time calculation, density corrections and corrections for the systematic high frequency loss.

Data during periods of low turbulence ($< 0.2\,m\,s^{-1}$), unrepresentative wind directions and malfunctions of the analysers were filtered out. Gaps were filled using the online tool developed by M. Reichstein (http://www.bgc-jena.mpg.de/bgc-mdi/html/eddyproc/) and CO_2 fluxes were calculated for 30 min periods.

2.4 Environmental measurements

Both study locations were supersites in the NitroEurope project, which means that fluxes and pools of carbon and nitrogen compounds and meteorological data were measured intensively following a common measurement protocol outlined in Skiba et al. (2009). The measured parameters that caused significant influence on the GHG fluxes discussed in this paper were air temperature, soil temperature, soil heat flux, total solar radiation, photosynthetic active radiation (PAR), net radiation, rainfall, soil moisture, water table height. Average air temperature and cumulative rainfall (using a tipping bucket) were recorded every 30 min from the met stations at both sites. The volumetric soil moisture content at 0.1 m depth was measured using a Theta probe (Delta-T Devices Ltd., Cambridge, UK). In addition water table height was recorded from dip wells (0.04 m diameter) inserted adjacent to each flux chamber at AMo. The moisture and water table measurements were made whenever N_2O and CH_4 fluxes were measured.

2.5 Statistical methods

Minitab version 16 was used to identify significant correlations between greenhouse gases and climate and soil variables.

3 Results

Rainfall and temperature patterns are very similar at both sites and therefore are only shown for EBu in Fig. 1a and b. AMo is on average 1.2 °C colder than EBu and

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precipitations are 17 % larger, although the inter-annual variability is larger than the differences between sites (Table 1). 2009 was the driest year, with monthly rainfall in February, May and October less than 26 mm. In the other years, the same amount of total rainfall was observed between April and September (warm period), January and March and between October and December (cold period). Neither site normally receives more than a few mm of snow covering the ground for a several days rather than weeks; except in 2010, when snow disrupted precipitation measurements from 1 January to the 1 April 2010. Snowfall was estimated from the ratio of precipitation and discharge, recorded at the small burn on AMo not far from the flux measurement site. The warm period average temperatures were almost the same for the 4 years, 11.9 ± 0.24 °C at EBu and 10.5 ± 0.24 °C at AMo. However, cold period temperatures changed, with highest averages in 2007 (6.4 and 5.29 °C in 2007 at EBu and AMo, respectively) and lowest in 2010 (4.3 and 2.9 at EBu and AMo, respectively).

Average annual fluxes of N_2O, CO_2 respiration and NEE fluxes were 507, 4.8 and 2.8 times larger at EBu than at AMo, respectively and CH_4 fluxes were 4.6 times smaller at EBu than at AMo (Table 2). Spatial variability between the 9 flux chambers at AMo and the 8 chambers at EBu was very high. The percentage of standard deviations calculated from the standard deviation on each measurement occasion was 7 %/31 % for respiration, 62 %/121 % for N_2O and 372 %/372 % for CH_4 flux, at AMo/EBu. Note that for CH_4 the same high variability of 372 % was measured at both sites. Temporal variations were also very large and are described in detail for CH_4, N_2O, respiration and NEE below.

3.1 Methane fluxes

At AMo CH_4 fluxes ranged from −38 to 604 $\mu g\,CH_4\,m^{-2}\,h^{-1}$ between January 2007 and December 2010 and the average flux was 37 $\mu g\,CH_4\,m^{-2}\,h^{-1}$ (Fig. 2a). Linear regressions between CH_4 flux (average flux from 9 chambers), water table, rainfall, soil moisture, soil or air temperature were not statistically significant when all 78 measurements were considered. However, trends were observed between CH_4 fluxes and water table

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height and soil temperature. A net uptake of CH_4 (−38 to −0.41 µg CH_4 m^{-2} h^{-1}) was measured when the water table was 250 mm below the peat surface. Large CH_4 emissions (53–604 µg CH_4 m^{-2} h^{-1}) only occurred when the water table was close to the surface (31–118 mm) (Fig. 3). Methane fluxes > 100 µg CH_4 m^{-2} h^{-1} were only measured when the soil temperature at 10 cm depth was at and above 10 °C. Regression analysis demonstrated the significant effect of water table on CH_4 fluxes ($p < 0.05$).

At the grazed grassland EBu, the average CH_4 flux was 4.5 (range −44 to 113) µg m^{-2} h^{-1} (Fig. 2b). On more than 50 % of the measurement dates fluxes were either negative or < 5 µg CH_4 m^{-2} h^{-1}. Larger fluxes occurred sporadically, often only in one of the 8 chambers. Monthly average CH_4 fluxes correlated with the average daily soil heat flux ($p < 0.05$).

3.2 Nitrous oxide

At AMo, the average N_2O flux was −0.22 (range −29 to +36 µg N_2O-N m^{-2} h^{-1}) (Fig. 2a). Correlations between N_2O flux and water table height, air and soil temperature, heat flux or precipitation were not statistically significant. However, N_2O fluxes were influenced by water table height in the same manner as CH_4 (Fig. 3). When the water table was more than 0.15 m below the surface N_2O was absorbed or emitted at very small rates (range −29 to +0.9 µg N_2O-N m^{-2} h^{-1}). Emissions > 1 µg N_2O–N m^{-2} h^{-1} occurred when the water table was close to the surface (< 0.09 m). The period of large N_2O emissions (9 to 36 µg N_2O-N m^{-2} h^{-1}, 19 November 2007 to 5 May 2008) visible in Fig. 2a coincided with a water table close to the surface (above 0.05 m) and soil temperatures at 10 cm depth ranged between 4.7 to 8.1 °C.

Over the four year study period EBu N_2O fluxes ranged from −23 to 1703 µg N_2O-N m^{-2} h^{-1} (mean 146, $n = 248$). Mineral N fertiliser applications stimulated N_2O emissions, and most of the large emission peaks seen in Fig. 2b were measured during the first 2 to 25 days after application. Sometimes the fertiliser

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response was immediate (<1 day in March, May and July 2007, April and May 2008 and June 2009), and on others there was a delay of 5 (June 2008), 9 (August 2008), 14 (March 2008) and 20 days (March 2010). The fertilisation events in March 2009, May 09, May/June 2010 did not stimulate measured N_2O emissions significantly. To further investigate these differences we divided the data set into two groups: (i) average fluxes over the 3 weeks after fertilisation, and (ii) average 3 week fluxes for all other dates. N_2O fluxes averaged over the 3 week period after fertilisation were much larger than fluxes averaged over 3 week periods not affected by fertilisation (period (i): $205 \pm 195\,\mu g\,N_2O\text{-}N\,m^{-2}\,h^{-1}$, range 9.5 to 700, $n = 16$; period (ii): $51 \pm 65\,\mu g\,N_2O\text{-}N\,m^{-2}\,h^{-1}$, range −3.4 to 255, $n = 36$). In fertilisation periods (period (i)) N_2O fluxes correlated with the total rainfall that fell within these 3 weeks. An improved significant correlation ($p < 0.001$) was obtained when the rainfall of the week prior fertilisation was added to the rainfall that fell in period (i) (Fig. 4). Due to different fertiliser application rates (35–92 $kg\,N\,ha^{-1}$) N_2O data in Fig. 4 were expressed as percentage of N applied. In the 3 week fertilisation period (i) N_2O fluxes tended to increase with soil moisture and air temperature, but these trends were not significant. In 3 week periods not affected by fertiliser (period ii) N_2O fluxes did not correlate with the cumulative precipitation or soil moisture, however there was a significant correlation with air temperature ($p < 0.001$).

3.3 Soil and ground cover respiration

Respiration measured at AMo and EBu is the sum of soil respiration and that from short vegetation enclosed by the flux chamber. AMo respiration rates ranged from 81 to 694 (average 285) $mg\,CO_2\,m^{-2}\,h^{-1}$ at AMo, but were around 3 fold larger at EBu (average 1003 $mg\,CO_2\,m^{-2}\,h^{-1}$ (range 97.5 to 3126). At both sites monthly average ground respiration rates correlated significantly ($p > 0.001$) with air temperature, total solar radiation, net radiation, PAR and NEE (Fig. 5) and with soil heat flux ($p < 0.01$). At AMo, respiration also increased significantly ($p < 0.001$) with increasing daily average

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soil temperature measured at 10, 20 and 40 cm depth and decreased significantly ($p < 0.001$) with increasing water table height. At EBu respiration rates tended to decrease with increasing soil moisture, but this correlation was not significant.

3.4 Net ecosystem exchange of CO_2

Net ecosystem exchange of CO_2 followed seasonal cycles (Fig. 2b, c), with CO_2 uptake dominating the flux between April and September. In the cold period (January–March and October to December) CO_2 was absorbed or emitted at small rates (Fig. 6). Annual fluxes ranged from −183 in 2010 to $-592\,g\,CO_2\,m^{-2}\,yr^{-1}$ in 2007 at AMo and from −673 in 2008 to -2264 in $2010\,g\,CO_2\,m^{-2}\,yr^{-1}$ at EBu (Table 2). AMo cumulative fluxes for the 6 months warm period (April to September) steadily decreased between 2007 and 2010. For Easter Bush, there was a very small net uptake CO_2 in the cold periods 2008 ($-5.3\,g\,CO_2\,m^{-2}\,yr^{-1}$) and 2009 ($-17.9\,g\,CO_2\,m^{-2}\,yr^{-1}$), respectively. Warm period NEE uptake rates were 1.6 times larger at EBu than AMo in 2007 and 2008, but 5.6 and 7.4 times larger in 2009 and 2010, respectively. At both sites NEE and respiration fluxes correlated significantly ($p < 0.001$), the slope of the regression line was the same, but AMo fluxes much lower (Fig. 5).

The NEE of CO_2 also correlated significantly ($p < 0.001$) with air temperature, PAR, net radiation and total solar radiation and respiration. At AMo NEE increased with decreasing water table height ($p < 0.01$), but a significant relationship between NEE and volumetric soil moisture content at EBu was not observed.

4 Discussion

The comparison of the intensively grazed grassland (EBu) with the extensively grazed seminatural moorland was done to show the effect of landuse and ecosystem on the seasonal and interannual patterns of GHG fluxes. At both sites GHG fluxes were dominated by CO_2.

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4.1 Methane and N_2O fluxes

Methane fluxes at AMo were small compared to those observed in northern peatlands, due to the shallow peat layer and the old drainage system. For example, a recent analysis of CH_4 flux measurements made across different soil types and landuses in the UK, showed that AMo CH_4 fluxes were at the top end of the range of CH_4 fluxes reported for mineral soils (17–40 $\mu g\,m^{-2}\,h^{-1}$), rather than peatlands (17–1580 $\mu g\,m^{-2}\,h^{-1}$) (Levy et al., 2011). The largest CH_4 fluxes in that analysis were recorded from the deep peats in the flowcountry (Loch More) (peat depth = 4 m), but also from a lowland raised bog, Whim Bog (peat depth = 6 m) (Levy et al., 2011). Whim Bog is located less than 2 km away from AMo, and has same rainfall and temperature rates and patterns. Methane fluxes at Loch More and Whim Bog were at least 50 times larger than those at AMo, and were similar to those measured in Northern Finland (Drewer et al., 2010; Lohila et al., 2010). This can be explained by the differences in peat depth, which is a key determinant of CH_4 fluxes, as discussed by Levy et al. (2011).

An interesting observation is that water table and temperature affected CH_4 and N_2O fluxes in the same manner (Fig. 3). Both gases were absorbed when the water table was below 0.28 m and large CH_4 and small N_2O emissions only occurred when the water table was in the top few cm of the surface (above 0.07 m). Saturated soils provide the anaerobic conditions required for both methanogenesis and denitrification to operate (Dise et al., 1993; Bakken et al., 2012). In a neutral to slightly acid soil, such conditions would facilitate denitrification to proceed to N_2 and one would expect a decline in N_2O production under water logged conditions. This could not be confirmed, as we did not measure denitrification to N_2 at either site. However, in acid soils such as AMo, N_2O tends to be the endproduct of denitrifcation (Bakken et al., 2012).

Soil CH_4 fluxes from the intensively grazed grassland EBu on mineral soil, hovered around zero, with small uptake and small emission rates. The occasional larger emissions observed may be due to sheep dropping providing the carbon source and increased anaerobicity during its decomposition to promote methanogenesis.

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Nitrous oxide fluxes at Easter Bush showed the typical large spatial and temporal variability common to fertilised grazed grasslands (Jones et al., 2007; Klumpp et al., 2011). In addition to the fertiliser-induced emission peaks uneven soil compaction and deposition of excreta/urine increased soil heterogeneity even further. Nitrous oxide fluxes in 2007 and 2008 (Table 2) were similar to those measured from the grazed grass clover field in Ireland (Leahy et al., 2004). However, 2009 and 2010 fluxes were much smaller than the Irish measurements, due to lack of rainfall during the fertilisation period. Fertiliser induced emission rates are not a uniform fraction of the N applied, as assumed by the Tier 1 IPPC methodology (IPCC 2006), they depend on rainfall at the time of fertilisation, rate and type of fertiliser, soil and crop type (Cardenas et al., 2010; Ranucci et al., 2011; Klumpp et al., 2011; Flechard et al., 2007). Easter Bush N_2O, emissions calculated as a fraction of mineral N input, were always larger than the Tier 1 % emission factor (EF); they were 6.5 %, 3.3 %, 1.4 % and 1.4 % in 2007, 2008, 2009, 2010, respectively. Mineral fertiliser induced N_2O emissions are usually short-lived and background conditions tend to be established within 1 to 3 weeks (Fig. 3 and i.e. Bouwman, 1996). The length of the fertiliser induced peaks depends on the precipitation amount and before and during fertilisation. For EBu, cumulative precipitation 1 week before plus 3 weeks after fertilisation correlated with the average N_2O flux during the 3 weeks after fertilisation better ($r^2 = 0.53$, Fig. 4), then when only considering precipitation during the 3 week period after fertilisation ($r^2 = 0.34$). This simple relationship between N_2O flux and precipitation is good news for developing Tier 2 EFs, and should be tested for different soil types, crops and climate zones. Fertiliser induced N_2O emissions are not always larger than the IPCC default value. Emission factors ranging from 0.3 to 0.9 % from fertilised semi-natural grassland in France were reported by Klumpp et al. (2011). In a previous study of GHG fluxes from European grasslands, EF's ranged from 0.01 to 3.56 % (Flechard et al., 2007). Their sites covered several climate zones and grassland management types, and explaining variation at this scale required a multilinear regression equation based on changes in soil temperature, soil moisture and rainfall.

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4.2 CO_2 fluxes: respiration and NEE

Respiration rates reported here are the sum of heterotrophic soil respiration and autotrophic vegetation of short vegetation: mosses and small herbs and grasses at AMo and a continuous grass sward at EBu. At EBu our respiration measurements are synonomous to ecosystem respiration, but at AMo the dominant tall grasses, sedges and heathers are excluded from the respiration measurements. Respiration rates increased with increasing air temperature, as also reported by Raich and Schlesinger (1992), but decreased with water table height at AMo and soil moisture at EBu. Annual cumulative precipitation and average annual air temperature explained 85 % of the interannual variation in respiration rates. The later observation contrasts with Raich and Schlesinger's conclusion that soil respiration rates from locations covering the main global ecosystems increased with precipitation. It appears there is a difference comparing annual soil respiration rates over a wide range of global precipitation rates up to 3000 mm (Raich and Schlesinger, 1992) compared with interannual and seasonal changes within one particular climate zone (AMo and EBu). Fertilisation events did not affect soil respiration rates at EBu and this agrees with Raich and Schlesinger (1992). Schulze et al.'s (2010) synthesis of carbon flux measurements across Europe (CarboEurope IP) included heterotrophic respiration values for the major landcover types. Heterotrophic soil respiration rates from all CarboEurope grasslands were 3 times larger than from their peatlands. We calculated a very similar value, EBu respiration rates were 2.8 times larger than those at AMo. Respiration rates were 3 to 13 times larger than the net ecosystem exchange of CO_2 (Table 2), and are not a trivial component of the carbon balance (Parkin et al., 2005).

NEE and respiration fluxes were almost 3 and 5 times larger, respectively from the fast growing N fertilised grass sward at EBu compared to the slow growing vegetation on the nutrient poor moorland AMo (Table 2). Similarly, in 2003 and 2004 EBu NEE fluxes were 6 times larger than fluxes from grazed seminatural grasslands in France (Laqueuille) and Hungary (Bugac) (Soussanna et al., 2007). The French

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and Hungarian flux rates were of similar magnitude (255 g CO_2 m^{-2} yr^{-1}) to those at AMo (338 g CO_2 m^{-2} yr^{-1}). Easter Bush average annual NEE fluxes in 2007 and 2008 (715 g CO_2 m^{-2} yr^{-1}) were smaller and in 2009 and 2010 (2363 g CO_2 m^{-2} yr^{-1}) larger compared to NEE fluxes measured from a grazed grass clover sward in Ireland (1074 g CO_2 m^{-2} yr^{-1}, Soussana et al., 2007) and a grazed grassland (99 % Lolium) (945 g CO_2 m^{-2} yr^{-1}, Leahy et al., 2004).

The large differences in EBu NEE flux between 2007/2008 and 2009/2010 (Table 2) is striking, and mainly a result of a larger CO_2 sink in 2009/2010 during active growth in the warm period (April–September) (Fig. 6). NEE uptake was 63 % larger in 2009/2010 compared to 2007/2008. This increase coincided with increased soil respiration rates (20 %) and a 4 fold reduction in N_2O emissions. Rainfall amounts was 12 % lower in 2009 and 2010 compared to 2007 and 2008, however the rainfall distribution and number of days with rainfall < 5 mm during the growing period (April to September) did not change. Air temperature pattens did not appear to change either. But, there was a rise in total solar and net radiation (both by 11 %) and PAR (16 %), a 17 fold increase in soil heat flux and a reduction in sheep numbers by 25 %. Change in the above mentioned variables between the 2007/2008 and 2009/2010 periods were relatively small, and it is likely that a combination of increased radiation, drier soils and fewer sheep caused the increase in NEE. It is surprising that NEE fluxes at AMo did not show the same increase in NEE. These differences will be investigated further in a detailed analysis of the NEE fluxes at AMo and EBu in the near future.

4.3 Greenhouse gas budgets

Greenhouse gas budgets were calculated using the 100 yr global warming potential of 25 for CH_4 and 298 for N_2O (IPCC, 2007) (Fig. 7). We only included on field biological production and consumption processes including livestock CH_4 emissions from fermentation. Dengel et al. (2012) measured CH_4 emissions by eddy covariance from the herd at EBu between March and October 2010 and calculated

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a CH_4 EF of 7.4 kg CH_4 sheep^{-1}. This measured EF is very similar to the IPCC default EF of 8 kg CH_4 sheep^{-1}. Using the measured EF, we calculated that sheep contributed a further 147 g CO_{2eq} m^{-2} yr^{-1} to the average annual GHG budget at EBu and < 0.01 g CO_{2eq} m^{-2} yr^{-1} at AMo. NEE of CO_2 provided the largest term in the annual GHG budgets at Auchencorth Moss and Easter Bush (Table 2). At AMo CH_4 and N_2O emissions counteracted the NEE sink strength by 2.0 % and 0.2 %, respectively and the average 4 yr GHG budget thus was 331 g CO_{2eq} m^{-2} yr^{-1}. Interannual variations (Table 2) were mainly caused by variations in NEE during the growing period, April to September (Fig. 6). Contrary, fertiliser use and sheep grazing significantly impacted the NEE sink at EBu. Fertiliser induced N_2O emissions reduced the NEE sink strength by 25 % and ruminant CH_4 emissions by 10 %. The 4 yr average GHG budget was 1006 g CO_{2eq} m^{-2} yr^{-1}, and 3 times larger than at AMo. Interannual variations were mainly influenced by variations in NEE during the growing period and variations in N_2O due to variations in precipitation at times of fertiliser application. In 2007 and 2008 large N_2O emissions, large sheep populations, hence large ruminant CH_4 fluxes, negated the CO_2 uptake. Similar observations were made by Leahy et al. (2005).

5 Conclusions

The GHG budget from a drained acid moorland (Auchencorth Moss) was found to be dominated by net ecosystem exchange of carbon; CH_4 and N_2O fluxes were insignificant by comparison and only occurred when the water table was close to the surface. For intensively grazed fertilised grassland (Easter Bush), CO_2, CH_4 and N_2O contribute significantly to the overall GHG balance. Precipitation before and during fertilisation periods correlated with N_2O emissions. Frequent rainfall events, as commonly experienced in NW Europe together with a high ruminant stocking density can turn a GHG sink into a source, as seen here for 2007 and 2008 at Easter Bush. On the grassland high productivity, facilitated by fertilisation resulted in much larger CO_2 uptake rates during the growing season than on the acid moorland. However this positive effect of CO_2 uptake can be cancelled out by large CH_4 and N_2O emissions when CO_2 uptake rates by the managed grassland are small.

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Table 1. Site characteristics and climate data for Auchencorth Moss and Easter Bush.

Parameter	Easter Bush	Auchencorth Moss
Latitude/Longitude	55°52′ N 03°02′ W	55°47′ N 03°14′ W
Ecosystem type	Managed grazed grassland	Drained peatland
Vegetation	99 % *Lolium perenne*	*Deschampsia flexuosa, Molinia caerulea, Festuca ovina, Eriophorum angustifolium, Eriophorum vaginatum, Juncus effusus, Juncus squarrosus, Calluna vulgaris*; bryophytes are dominated by *Sphagnum* and *Polytrichum* species
Livestock ($LSU\,ha^{-1}$)[1]	0.77	< 0.2
N fertiliser ($kg\,N\,ha^{-1}\,yr^{-1}$)[2]	213 (173, 250)	none
Soil type	Clay loam	Peat ~ 0.5–2 m deep
Cumulative precipitation (mm)		
2007	1026	1135
2008	1053	1203
2009	744	987
2010	927	1072
Air temperature (°C)[3]		
2007	9.1 (−3.8; 16.5)	8.0 (−6.2; 16.5)
2008	8.6 (−3.5; 18.7)	7.3 (−5.3; 17.8)
2009	8.9 (−4.2; 22.1)	7.6 (−5.7; 22.0)
2010	7.7 (−7.2; 18.7)	6.6 (−9.3; 17.9)

[1] 1 livestock unit ha^{-1} = 10 adult sheep or 25 lambs.
[2] 4 yr mean (range).
[3] Annual average (range).

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Table 2. Annual soil greenhouse gas and NEE fluxes ($g\,CO_{2eq}\,m^{-2}\,yr^{-1}$) from the intensively grazed grassland "Easter Bush" and the extensively grazed moorland "Auchencorth Moss".

GHG & year	Easter Bush			Auchencorth Moss		
	Average[1]	Stdev[2]	N[3]	Average[1]	Stdev[2]	N[3]
N_2O						
2007	659.51	563.58	66	0.28	1.27	24
2008	532.36	491.99	83	9.07	17.28	21
2009	208.06	219.18	60	−0.32	12.12	21
2010	137.27	155.43	39	−6.00	16.93	12
CH_4 soil						
2007	1.48	5.15	66	5.15	1.42	24
2008	0.34	3.90	77	3.90	17.03	21
2009	0.97	5.64	57	5.64	9.52	21
2010	2.99	4.92	39	4.92	2.82	12
CH_4 livestock						
2007	174			0.004[4]		
2008	161			0.004		
2009	135			0.004		
2010	119			0.004		
CO_2 respiration[5]						
2007	6432	2099	61	2395	1582	10
2008	7030	2244	72	2660	6909	13
2009	8044	1946	52	2755	11 137	16
2010	7120	2532	37	2404	9335	10
CO_2 net ecosystem exchange						
2007	−757.9		Gap-	−591.7		Gap-
2008	−673.2		filled[6]	−335.9		filled[6]
2009	−2461.8			−241.1		
2010	−2264.2			−183.0		
GHG budgets[7]						
2007	77			−582		
2008	−317			−316		
2009	−2118			−234		
2010	−2005			−189		

[1] Annual fluxes of soil GHG were calculated from monthly averages of 8 chamber measurements at Easter Bush and 9 chamber measurements at Auchencorth Moss.
[2] Standard deviation is the average variation across the chambers.
[3] Number of observations are the total number of measurement dates in each year.
[4] There are no records of actual sheep numbers, we assumed < 1 ewe ha^{-1}.
[5] Respiration from soil plus small vegetation enclosed by the chamber.
[6] Annual fluxes were calculated from gap-filled daily averages of 30 min data.
[7] GHG budgets for EBu included CH_4 emissions from ruminant fermentation.

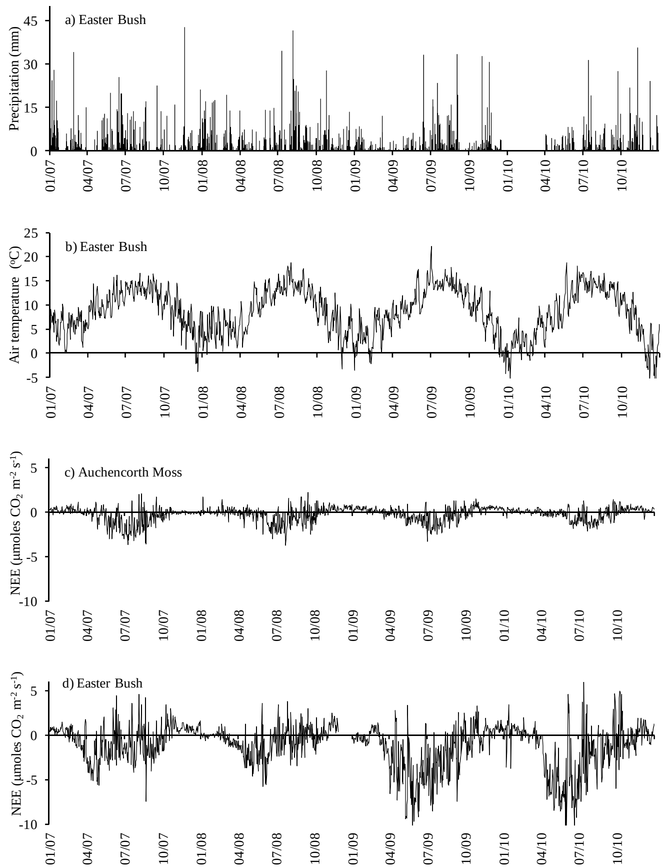

Fig. 1. Daily average air temperature **(a)** and daily cummulative precipitation at Easter Bush **(b)**. The matching data from Auchencorth Moss are not shown as the pattern is almost identical. Daily net ecosystem exchange of CO_2 (NEE) calculated from 30 min averages at Auchencorth Moss **(c)** and Easter Bush **(d)**.

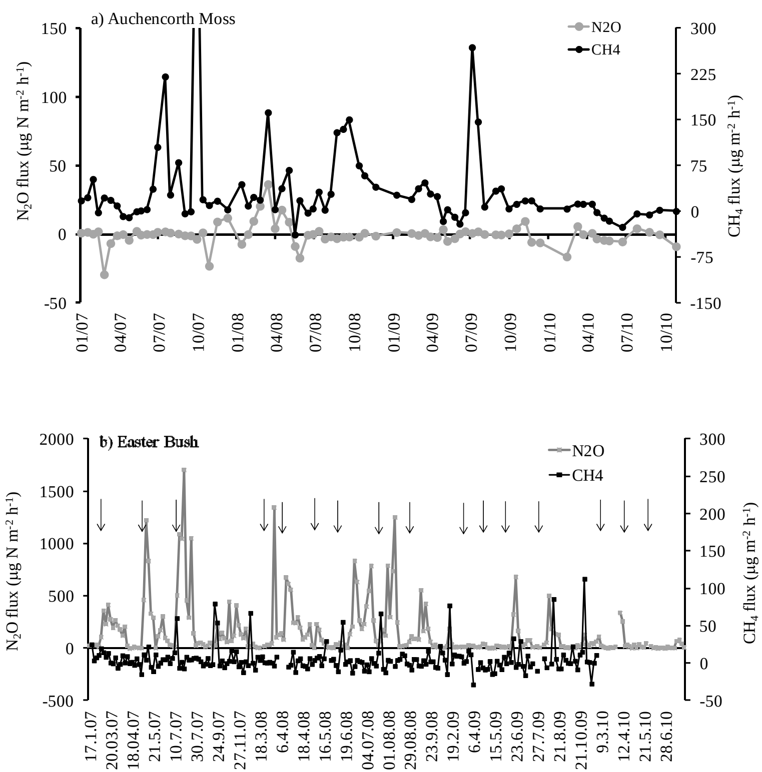

Fig. 2. Variations of CH_4 and N_2O fluxes from the unmanaged, extensively grazed moorland Auchencorth Moss **(a)** and the N fertilised, intensively grazed grassland Easter Bush **(b)**. Data are averages from 9 chamber measurements at Auchencorth Moss and 8 at Easter Bush. Note the different scales for Auchencorth Moss and Easter Bush and for N_2O and CH_4. The x-axis crosses the 0 point of the left hand y-axis (N_2O flux) only. Arrows indicate when N fertiliser was applied. The "off-scale" CH_4 flux in 10 July was 604 µg CH_4 m^{-2} h^{-1}.

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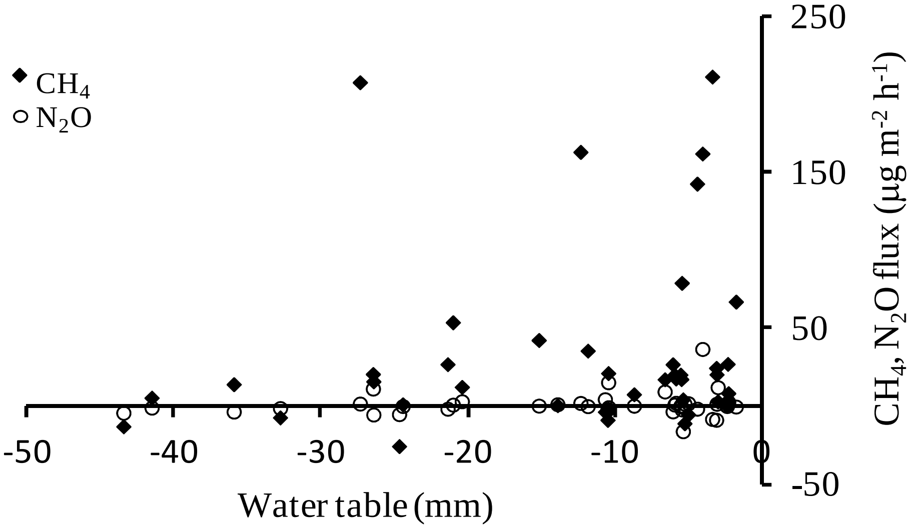

Fig. 3. The influence of water table height on CH_4 and N_2O fluxes at Auchencorth Moss observed during 2007–2010 (data are monthly averages).

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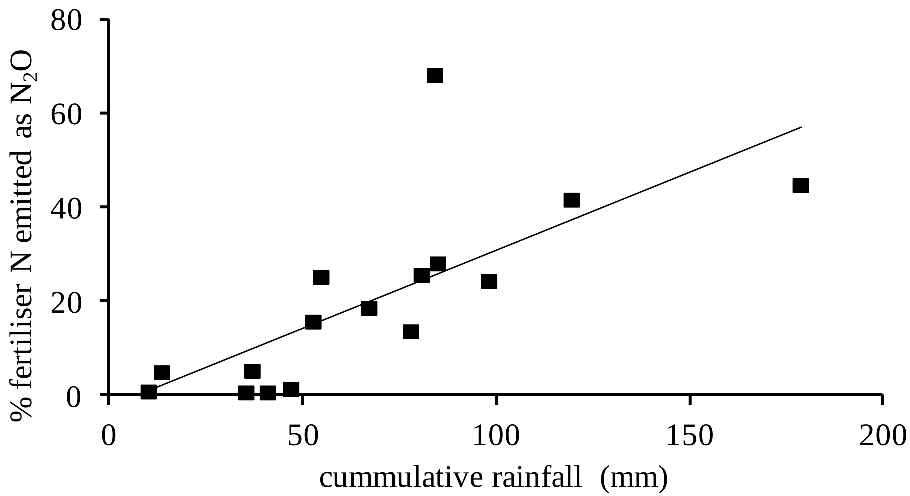

Fig. 4. The role of rainfall in detemining N_2O emission rates after N fertilisation. Data are average N_2O fluxes measured in the 3 weeks after fertilisation (expressed as the % of fertiliser N applied) and the cummulative rainfall in the week before plus 3 weeks after feriliser application. The regession equation is % $N_2O = 0.33 \times$ rainfall (mm) $- 2.52$, $r^2 = 0.53$.

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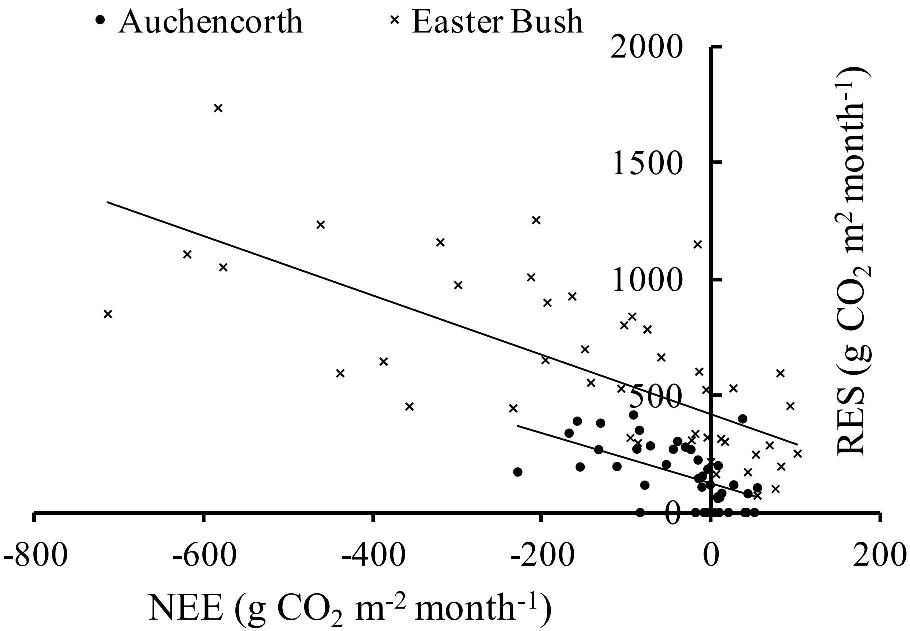

Fig. 5. Relationship betwe CO_2 respiration (RES) measured by chambers enclosing soil and some of the short vegetation and net ecosystem exchange of CO_2 (NEE), measured by eddy covarinace at Easter Bush and Auchencorth Moss. Data are monthly totals for 2007–2010. Regressions equation for Easter Bush is $\text{RES} = -1.2764 \cdot \text{NEE} + 418.93$, $r^2 = 0.48$, $n = 46$, and for Auchencorth Moss $\text{RES} = -1.0792 \cdot \text{NEE} + 125.05$, $r^2 = 0.31$, $n = 46$.

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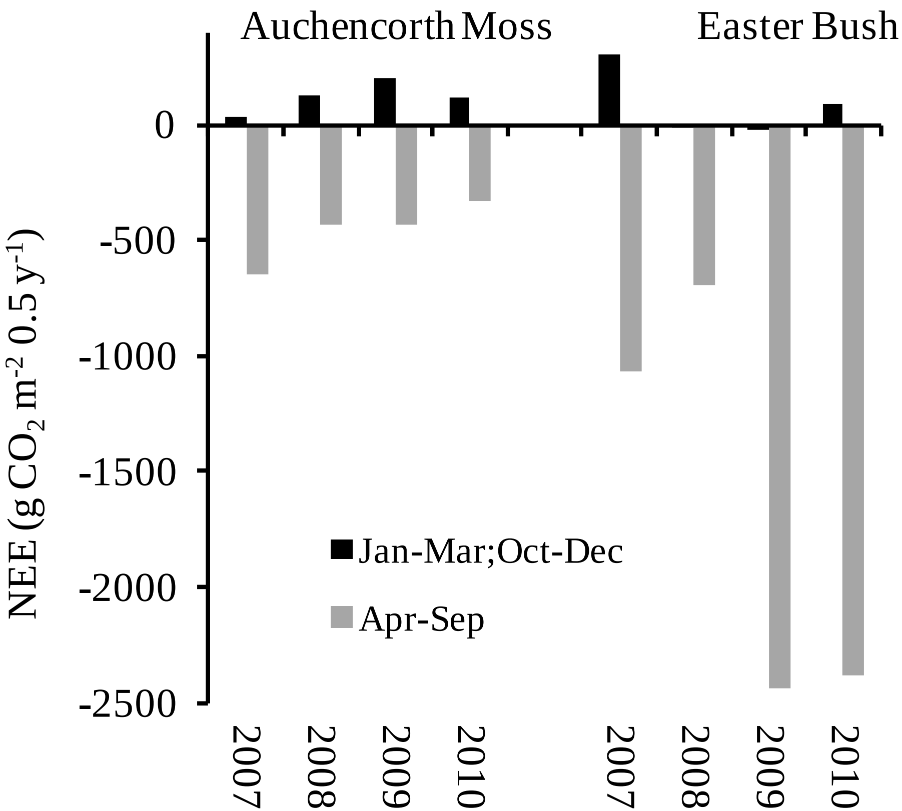

Fig. 6. Cummulative net ecosystem exchange of CO_2 (NEE) fluxes for the cold period (January–March plus October–December) and the warm period (April–September) at Auchencorth Moss and Easter Bush.

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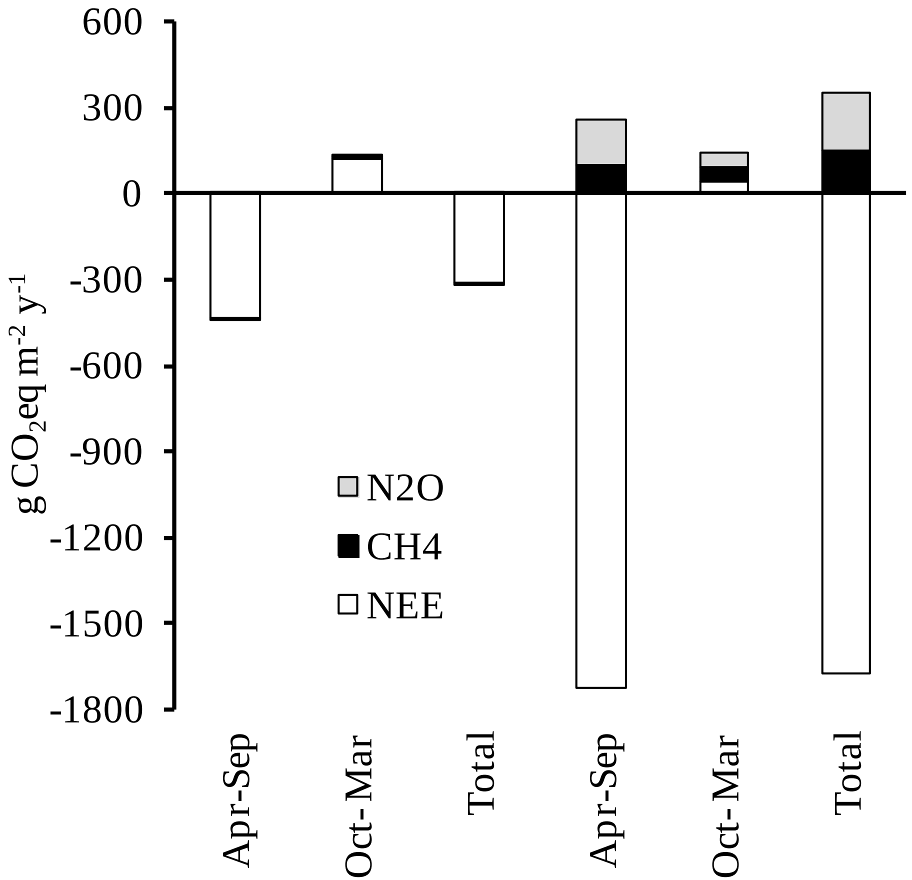

Fig. 7. Greenhouse gas budgets for the grazed seminatural moorland Auchencorth Moss and the intensively grazed grassland Easter Bush. Data are averages over 4 yr (Total) and split into net ecosystem exchange of CO_2 (NEE) uptake period (April–September) and the period when NEE CO_2 was small or positive (January–March plus October–December).

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