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Methane emissions from sheep pasture, measured with an open-path eddy covariance system

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Abstract

Methane (CH_4) is an important greenhouse gas, contributing 0.4–0.5 W m^{-2} to global warming. Methane emissions originate from several sources, including wetlands, rice paddies, termites and ruminating animals. Previous measurements of methane flux from farm animals have been carried out on animals in unnatural conditions, in laboratory chambers or fitted with cumbersome masks. This study introduces eddy covariance measurements of CH_4, using the newly developed LI-COR LI-7700 open-path methane analyser, to measure field-scale fluxes from sheep grazing freely on pasture. Under summer conditions, fluxes of methane in the morning averaged 30 nmol m^{-2} s^{-1}, whereas those in the afternoon were above 100 nmol m^{-2} s^{-1}, and were roughly two orders of magnitude larger than the small methane emissions from the soil. Methane emissions showed no clear relationship with air temperature or photosynthetically active radiation, but some diurnal pattern was apparent, probably linked to sheep grazing behaviour and metabolism. Over the measurement period (days 60–277, year 2010), cumulative methane fluxes were 0.34 mol CH_4 m^{-2}, equating to 134.3 g CO_2 equivalents m^{-2}. By comparison, a carbon dioxide (CO_2) sink of 819 g CO_2 equivalents m^{-2} was measured over the same period, but it is likely that much of this would be released back to the atmosphere during the winter or as off-site losses (through microbial and animal respiration). By dividing methane fluxes by the number of sheep in the field each day, we calculated CH_4 emissions per head of livestock as 7.4 kg CH_4 $sheep^{-1}$ yr^{-1}, close to the published IPCC emission factor of 8 kg CH_4 $sheep^{-1}$ yr^{-1}.

Keywords: agriculture, carbon sink, closed path, CO_2 flux, global warming potential, grassland, grazing, grazing system, LI-7200, LI-7700

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Introduction

Methane (CH_4) is one of the most important greenhouse gases, contributing 0.48 W m^{-2} to anthropogenic radiative forcing, second only to CO_2 (IPCC, 2007). Many of the present-day global CH_4 emissions are of anthropogenic origin, such as rice paddies, ruminants, release from fossil fuel use and land-fill sites (IPCC, 2007). Natural wetlands are thought to be the biggest individual source, but emissions from ruminants in agricultural systems are of a similar magnitude, according to most large-scale budgets (Wuebbles & Hayhoe, 2002; IPCC, 2007; Levy *et al*., 2007). However, there are many uncertainties in these budgets, as highlighted by recent works (Frankenberg *et al*., 2005; Schulze *et al*., 2009; Bloom *et al*., 2010). At a national level, the estimates of annual methane emissions, required for submission to the United Nations Framework Convention on Climate Change (UNFCC), are generally based on emission factors published by the IPCC (2006). The observational data supporting these tables are sparse, and based on a small number of measurements made on animals in laboratory (or very atypical) conditions, using: tunnel systems (Lockyer & Jarvis, 1995; Lockyer & Champion, 2001; Murray *et al*., 2001); closed or open circuit respiration chambers (Blaxter & Clapperton, 1965); flux gradient technique (Judd *et al*., 1999) or breath sampling (Lassey *et al*., 1997; Leuning *et al*., 1999).

With the development of fast closed-path methane analysers, it has recently become possible to measure CH_4 fluxes over terrestrial surfaces without the logistical problems of running tunable diode lasers in the field (Verma *et al*., 1992; Hendriks *et al*., 2008, 2010; Wille *et al*., 2008; Jackowicz *et al*., 2010; Long *et al*., 2010). Here, we use a new open-path CH_4 sensor to provide continuous measurements of CH_4 fluxes over a grazed agricultural system in central Scotland. This has several advantages, allowing continuous long-term measurements, providing an integrated measure over the whole animal–plant–soil system and being nonintrusive, such

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that the animals behave normally. The data presented here are the first season-long eddy flux measurements of CH_4 from freely grazing sheep.

In the United Kingdom, CH_4 emissions from grazing livestock, mainly cattle and sheep, are a large part of the national budget of greenhouse gas emissions. There is increasing pressure to find ways to reduce emissions so as to meet targets to mitigate climate change (Haydock *et al*., 2008). To do this effectively requires a sound understanding of the magnitude and variability of current emissions, so as to find ways to reduce emissions effectively. In sheep, methane is generated as the result of the complex microbiological fermentation in the rumen and the large intestine, and released via eructation through the mouth and nostrils (Murray *et al*., 1976; Lassey *et al*., 1997). The pattern and magnitude of these emissions may vary with grazing behaviour and diet, and measures to reduce emissions are an active topic of current research (e.g. McAllister & Newbold, 2008; Wood *et al*., 2009). To demonstrate the efficacy of any measures to reduce livestock CH_4 emissions, a method for measuring fluxes in the field over a relatively long term is needed. Here, we aimed to test the ability of eddy covariance (EC) to provide such a method, utilizing new developments in sensor technology.

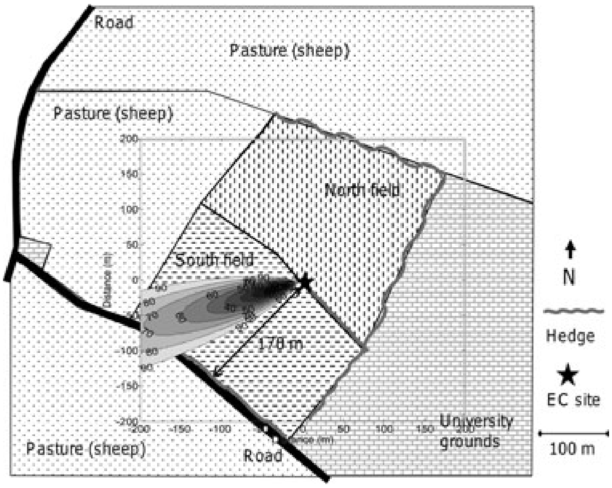

Fig. 1 Map of Easter Bush research site, Bush Estate, Penicuik, UK. Illustrated are the eddy covariance (EC) site, together with the dimensions of the two main fields (South and North field), relevant for the current study as well as the surrounding area. Superimposed are the results of the footprint analysis. It shows that more than 70% of the fluxes originate from the South field with remaining ~30% originating in the neighbouring fields.

Materials and methods

Measurements were carried out at the Easter Bush research site at Bush Estate, Penicuik near Edinburgh (55° 51′ 55.24″ N; 3° 12′ 22.37″ W, 190 m asl.). The site is an intensively managed grassland, dominated by perennial ryegrass (*Lolium perenne* L.), divided into two compartments (South field – 5.424 ha and North field – 5.371 ha, Fig. 1). The fields were stocked with varying numbers of Scottish grey face sheep throughout the 2010 season. These were counted approximately weekly. The grazing system is typical of the British uplands, wherein the pasture is a ley system, being resown every 10 years and fertilized with 180 kg ha^{-1} yr^{-1} of N as ammonium nitrate in three or four fertilizer applications per year. In addition to the continuous EC measurements of the whole system, CH_4 fluxes from the vegetated soil surface were measured using static chambers (38 cm in diameter, 20 cm in height), approximately monthly from 2002 to 2010, using the methodology described in Jones *et al.* (2007).

The EC system was situated in a fenced area between the two fields. It comprised: the LI-7700 CH_4 open-path gas analyser (LI-COR Biosciences, Lincoln, NE, USA), a 3D sonic anemometer (CSAT3; Campbell Scientific, Logan, UT, USA), the LI-COR LI-7200 CO_2/H_2O closed-path gas analyser (LI-COR Biosciences) and associated data loggers. The measuring height was 2.7 m above ground. A high-precision 'cavity ring-down' closed-path methane analyser (G1301; Picarro Inc., Sunnyvale, CA, USA) was also operated at the site, with a sample intake ca. 10 m to the east of the LI-7700. This provided data every 10 s, and was used to compare concentrations, but was not at a high enough frequency to calculate fluxes. Meteorological data, such as solar radiation, precipitation, air and soil temperature were also recorded. Instruments were installed early February 2010, and flux measurements began in mid-February. Snow periodically covered the ground until the beginning of April with a few sheep in the northern field and first lambs appearing in both fields at the end of March. The data presented here cover the period from 1 March to 3 October 2010.

Data processing

Data (20 Hz) were recorded on a field-based laptop and onto a CR3000 datalogger (CR3000; Campbell Scientific). The following processing steps were made in calculating 30 min fluxes from the raw 20 Hz data, using the EdiRe software (Clement, 2004; University of Edinburgh, http://www.geos.ed.ac.uk/abs/research/micromet/EdiRe).

Spike detection was implemented in the EdiRe software, using a standard de-spiking algorithm, whereby wind vector and scalars values outside given limits were removed. We then applied lag correction and tube attenuation relevant to the closed path LI-7200 CO_2/H_2O gas analyser, coordinate rotation using the planar fit method described in Wilczak *et al.* (2001), sonic virtual temperature correction (Schotanus *et al*., 1983; Kaimal & Gaynor, 1991; Campbell Scientific, Inc, 2009), as well as the incorporated frequency response correction derived from Moore (1986) and Massman (2000). The computed cospectra for sensible heat and CH_4 for each half hour using the Fast Fourier Transform were used to verify the magnitude of the frequency response correction, reflecting the ability of the system to measure high frequency transport. We applied the Webb–Pearman–Leuning density correction (WPL; Webb *et al*., 1980) to the data, as well as the LI-7700-specific corrections for spectroscopic effects (LI-COR 2010; McDermitt *et al*., 2011). Fluctuations in temperature and pressure cause variations in the absorption band of methane, and the corrections add extra terms to the WPL correction, with their respective equations being implemented in the EdiRe software.

The LI-7700 has two diagnostic outputs which were used to filter out half-hourly values where the instrument was performing poorly: the received signal strength indicator (RSSI), an indicator of the cleanliness of the mirrors, and a coded value, representing one or more pieces of diagnostic information. For example, a diagnostic code value of 16 384 is an indicator of 'no laser signal detected' which can occur in an event of rain, or a simple obstruction like an insect or leaf flying through the optical path. Low RSSI values do not always lead to outliers or spikes, but need to be combined with diagnostic code values to properly filter instances of instrument malfunction from the data. There are also occasions when the mirrors are clean but the diagnostic value reports malfunctions. Methane and carbon dioxide flux values associated with spikes resulting from signal loss or instrument malfunctioning were removed, as well as short periods when maintenance or cleaning of instruments were carried out or from power failure.

Gaps of up to 2.5 h were filled by applying a simple interpolation and gaps of several hours were filled using the mean diurnal variation (MDV) method (Falge *et al*., 2001), a method where a missing value is replaced by the mean for that time period based on adjacent days. This gap-filling method was considered to be also valid for our CH_4 (atmospheric and soil) fluxes, as there is a daily periodicity in the grazing and behaviour pattern of sheep observed in several studies (Harris & O'Connor, 1980; Champion *et al*., 1994; Lockyer & Champion, 2001), including our own data. Nevertheless, on consecutive rainy days the MDV method was not applicable to methane fluxes and these gaps were not filled. The same applied to gaps longer than 2.5 h (several hours only) when coinciding with rainy periods on one of the neighbouring days.

To investigate the source location of the greenhouse gases measured as part of this study, we applied the analytical

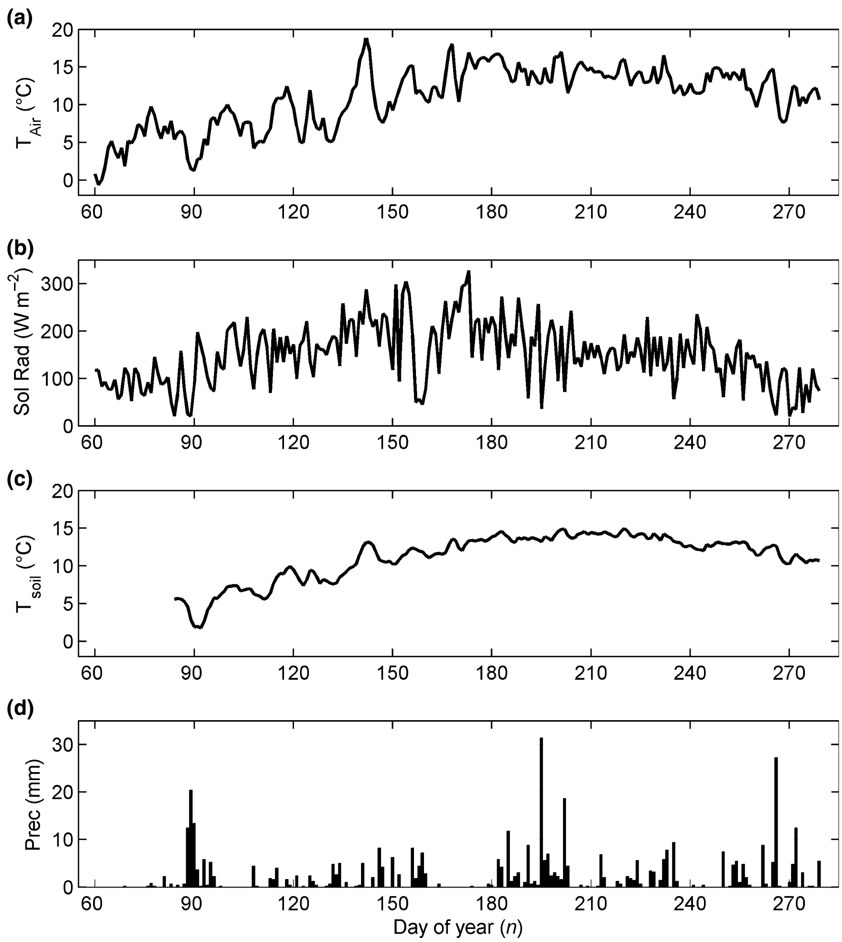

Fig. 2 Meteorological conditions at Easter Bush, Bush Estate, Penicuik, UK (March–October 2010). Daily mean air temperature (T_{Air}) is shown in (a), solar radiation (Sol Rad) in (b) and soil temperature (T_{Soil}) in (c). Figure 2d shows daily total of precipitation (Prec) for the same period of time.

footprint model by Kormann & Meixner (2001), also integrated in EdiRe.

Results

The measurement period was somewhat wet, with 112 of the 217 days recording rain (and snow in March and beginning of April). The minimum and maximum air temperatures recorded at the site were −5.4 and 22.8 °C, respectively (Fig. 2), but the mean daily temperature was always less than 20 °C.

Of a total of 10 416 half hours (217 days), data were not recorded 12.5% of the time (ca. 27 days) because of power failure and maintenance operations. Only 5.8% of the captured data were of low quality, with RSSI values below 10% (Fig. 3a). The remaining data ranged in concentration between 1.7 and 3 ppm, and, once the outliers (because of rain, signal dropouts, instrument malfunction, etc.) had been rejected, agreed well with measurements from the closed-path methane analyser. Occasional signal dropouts (possibly caused by insects) during a half-hour period generally did not affect the mean CH_4 concentration but did negatively affect the flux value. The rain gauge recorded rainfall 8% of the time (809 half-hour values) and these data were excluded. In some cases, it was difficult to identify signal loss due to fog or drizzle, because the tipping bucket rain gauge was not sensitive enough to detect low rates of precipitation. Filtering further using the RSSI and diagnostic code, we ultimately excluded 28.6% of CH_4 flux data.

The flux footprint calculated for average daytime conditions shows that over 70% of the flux originated from the south field (Fig. 1). The source location with maximum contribution to the measured flux (Schuepp *et al.*, 1990; Schmid, 1994) was 41 m from the eddy flux sensor, well within the fields where sheep numbers were monitored. Ninety per cent of the flux came from within 350 m of the eddy flux sensors, and included contributions from the adjacent fields. However, these were under similar management, and although exact sheep numbers were not recorded here, sheep densities appeared to be similar. The influence of occasional traffic on the minor road on CO_2 fluxes was estimated to be very small. Katabatic flow at night-time could result in a loss of methane

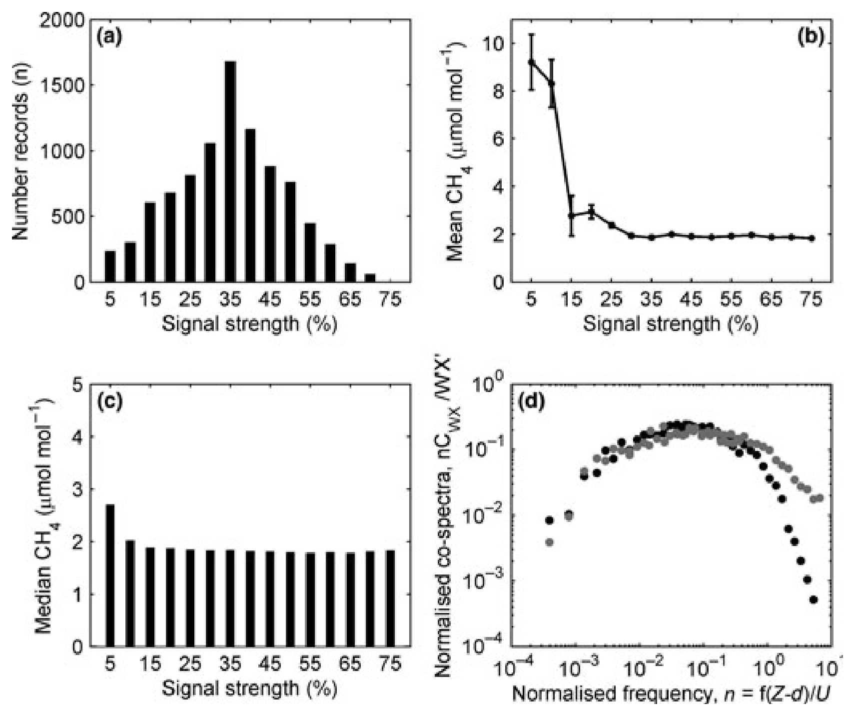

Fig. 3 (a–c) Distribution of the data from the LI-7700 methane analyser by relative signal strength indicator (RSSI). Of a total of 10 416 half hours, 13% were missing data because of power, system failure or corrupt files. Of the remaining 87%, around 6% were rejected when the laser signal strength was below 10 resulting in unreliable CH_4 concentration values. (d) The averaged normalized cospectra of the vertical wind component and methane density (W′CH_4′) in black (full circles) and sensible heat (W′T′) in grey (full circles). The frequency on the *x*-axis has been normalized with $(Z - d)/U$, where Z and d refer to measurement and zero-plane displacement height (m) and U to the mean wind speed (m s^{-1}). The cospectra are based on 50 h of daytime data from July and August with unstable conditions.

from the site, undetected by the system. However, such losses are likely to be small here because the site is windy, relatively flat, and the measurement height is low.

The EC CH_4 fluxes were large compared with CH_4 fluxes from the soil measured by static chambers. The former averaged 18 nmol m^{-2} s^{-1} over the whole measurement period, but typically reached peaks in the morning and afternoon of around 30 and 100 nmol m^{-2} s^{-1}. In contrast, the mean flux from the soil measured by chambers was 0.08 nmol m^{-2} s^{-1}, with minimum and maximum values of −1.3 and 9.6 nmol m^{-2} s^{-1} (Stephanie Jones, unpublished data).

CH_4 fluxes showed a distinct diel pattern, with highest emissions occurring during the day and with afternoon emissions substantially exceeding those of the morning (Fig. 4). Daily mean methane emissions were related to the number of sheep in the field (Fig. 5a); the number of sheep increased over the summer, and the methane emissions increased in parallel (Fig. 5b). The relationship between sheep number and methane flux in the early part of the season was less clear, probably as a result of the varying composition of lambs and sheep in the flock.

Carbon dioxide fluxes show the typical diurnal and seasonal pattern of grasslands and a clear response to photosynthetically active radiation (PAR; Figs 6a and d, 7, 8). Methane fluxes show no response to PAR or temperature, but increases over the course of the season, presumably as the number and mass of grazing sheep in the field increased (Figs 4, 5, 6b and e). There is considerable variability in the CH_4 fluxes, which may come from several sources, including the variation in the number of sheep present in the flux footprint. The net carbon dioxide sink of the field over the measurement period was 819 g CO_2 m^{-2}. Using a global warming potential of 25 for methane (IPCC, 2007), the net sink of greenhouse gases was reduced by 134.3 g CO_2 equivalents m^{-2} (Fig. 8).

Discussion

The summer of 2010 was wetter and warmer than the long-term average for this part of the United Kingdom,

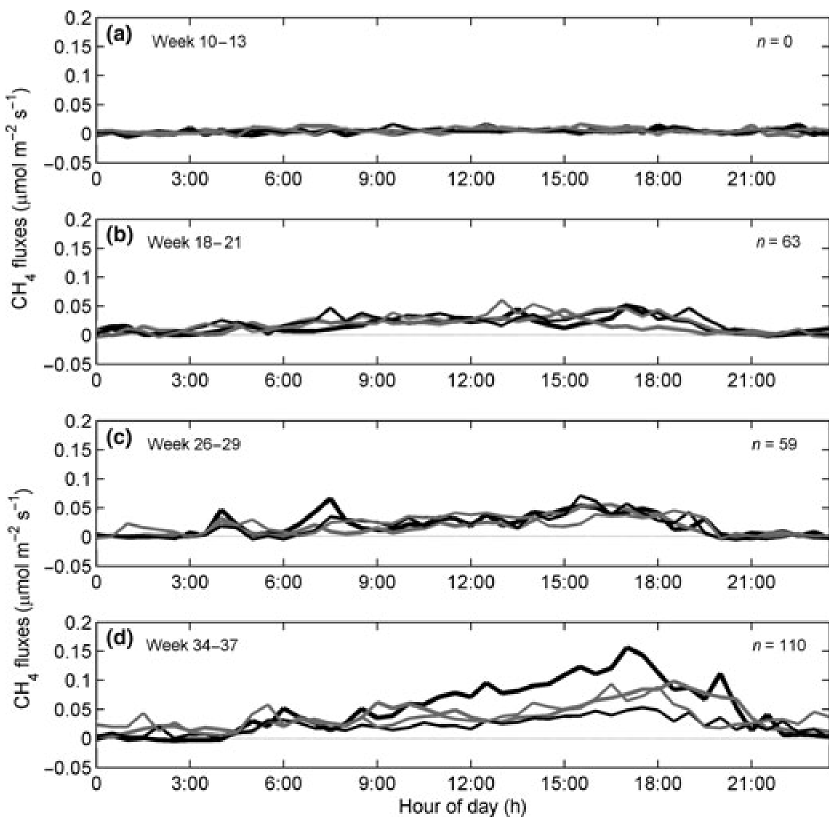

Fig. 4 Fluxes of methane for four periods (a–d) of the year 2010. The separate lines on each graph refer to four successive weeks within the period (first week, thick black; second week, thick grey; third week, thin black; forth week thin grey). The numeral, *n*, in the top right corner refers to the modal number of sheep in the southern field. A diurnal CH_4 emission pattern is visible, with peaks in the afternoon and, to a lesser extent, in the morning. An increase in the flux over the season is also apparent.

the rainfall being 40% higher and the temperature 0.6–0.9 degrees warmer than the 1971–2003 average (National Climate Information Centre (NCIC) (2010). Unusually, precipitation fell as snow in March and beginning of April, and thereafter the rainfall in successive months was periodic. Rather settled weather occurred in the first part of the summer, to be replaced by Atlantic weather systems in the second half (NCIC, 2010), when most of the rainfall fell (Fig. 2). Given the number of days with rain, an open-path system will inevitably produce some erroneous data, because water on the mirrors interrupts the sensor optical path. However, with the ability of the LI-7700 analyser to spin and heat the mirrors, it was possible to minimize the loss of data under dewy, foggy and drizzly conditions. Heavy rain inevitably interrupts measurements, as it also affects the operation of the sonic anemometer, as well as altering the behaviour of sheep (Champion *et al*., 1994), whereby they seek shelter from the hedges at the field margins (Munro, 1962). Further gaps in the flux data were caused by instrument failure in the LI-7200

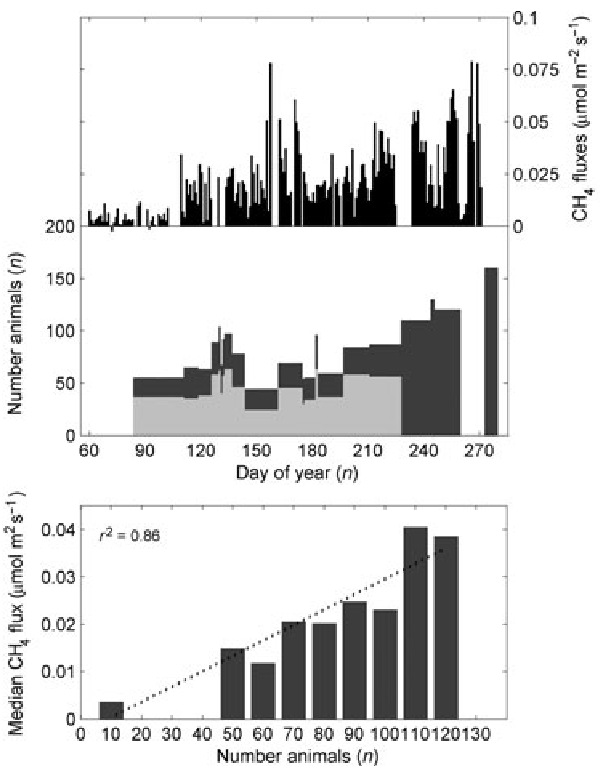

Fig. 5 Comparison of the number of sheep in the South field with mean daily CH_4 flux. Flux data were filtered by wind direction, such that only fluxes from the North and South fields were separated. Each daily flux value from each field was binned according to the number of animals [sheep in dark grey and lambs in light grey (stacked values)] present, and the median CH_4 flux value for each bin calculated.

gas analyser, which provided the water vapour measurements necessary for flux corrections, most often caused by liquid water in the optical path.

The measured net methane fluxes represent the balance between methane production in the sheep rumen and in the soil, and consumption by methanotrophic bacteria in the soil. The comparison with the chamber measurements shows that the soil component is small, and the net flux is dominated by emissions from the sheep. The chamber data show that the soil at the site can act as a net sink for methane on occasions, similar to other pasture sites (Mosier *et al*., 1991; Saggar *et al*., 2007), but this term is an order of magnitude smaller than the animal emissions.

The values measured here by EC are in a similar range to those measured by chambers at peatland sites in the United Kingdom (Macdonald *et al*., 1998), and by EC in the Netherlands (Hendriks *et al*., 2008) and Canada (Long *et al*., 2010). For example, Hendriks *et al*. (2008) reported a mean emission value of around 29 nmol m^{-2} s^{-1} during their 2 week measurement period, close to our mean emission of 26 nmol m^{-2} s^{-1} over the summer season at Easter Bush. The highest half-hourly value reported by Hendriks *et al*. (2008) and Long *et al*. (2010) of 80 nmol m^{-2} s^{-1} was regularly exceeded at Easter Bush.

The measured CH_4 fluxes showed a distinct diel pattern, with a peak in the afternoon, and a smaller one in the morning. There are two likely causes for this: (i) variation in the number of sheep present in the flux footprint in any given half hour, and (ii) variation in feeding and metabolic processes in the sheep rumen. The first of these is potentially a serious bias in the results, if trying to estimate emissions per head of sheep, based on the total number in the field. The EC method was developed for homogeneous vegetated surfaces, and implicitly assumes uniformity in the properties of the upwind surface. Our application pushes the robustness of the method somewhat, by including a number of moving point sources (sheep) on the upwind surface. At one extreme, there will be occasions when no sheep were present in the flux footprint, and only net exchange by soil microbes is recorded. At the other extreme, a number of sheep may be clustered in the field close to the sensor. If sheep movements were approximately random, this would at least add noise to the data. However, studies on farm sheep (Champion *et al*., 1994; Judd *et al*., 1999; Lockyer & Champion, 2001) and freely roaming hill sheep (Harris & O'Connor, 1980) have found a distinct diurnal grazing and resting pattern, and this could add a systematic pattern to the data. Although daily numbers of sheep in each field are known, the time resolution of recording does not allow us to quantify the number of sheep in

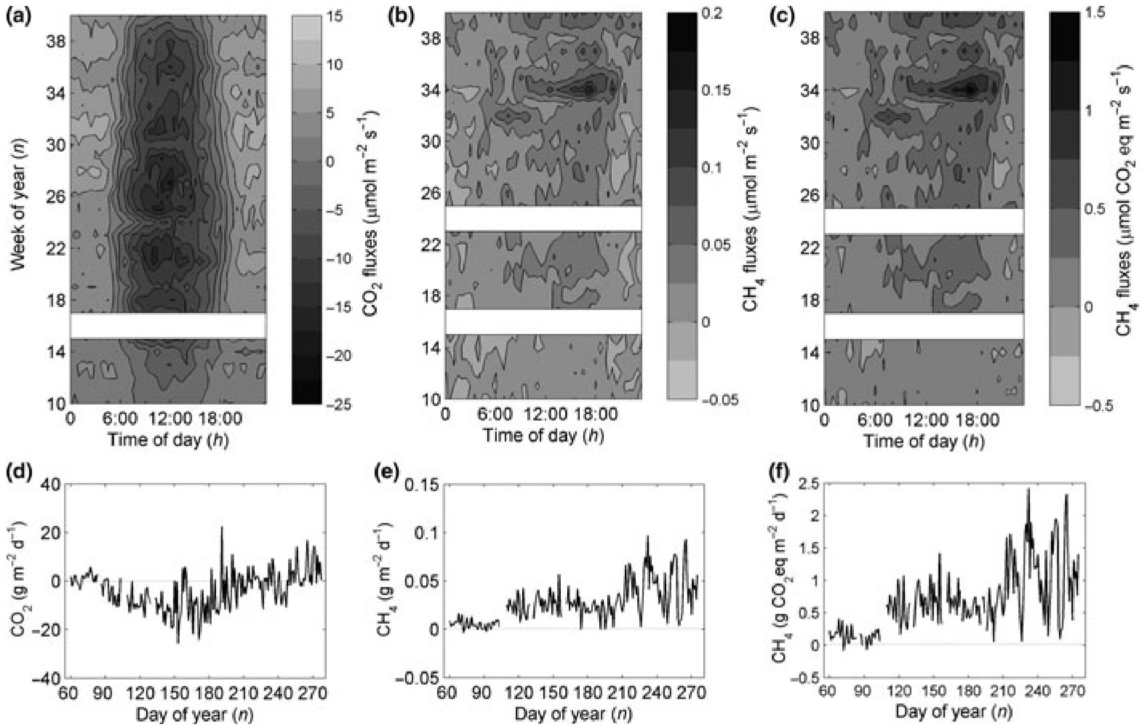

Fig. 6 Weekly mean carbon dioxide (CO_2), methane (CH_4) fluxes and the calculated CH_4 as CO_2 equivalent [global warming potential (GWP), 100 year horizon] (a–c) for Easter Bush during 2010. CO_2 fluxes show a distinctive seasonal pattern with uptake (negative fluxes) during the day and release (positive fluxes) at night. CH_4 fluxes show a reverse pattern with release during the day and occasional uptake at night. The daily total values for CO_2 (in g m^{-2} day^{-1}), CH_4 (in g m^{-2} day^{-1}) and CH_4–CO_2 equivalents (in g m^{-2} day^{-1}), respectively, are illustrated in (d–f).

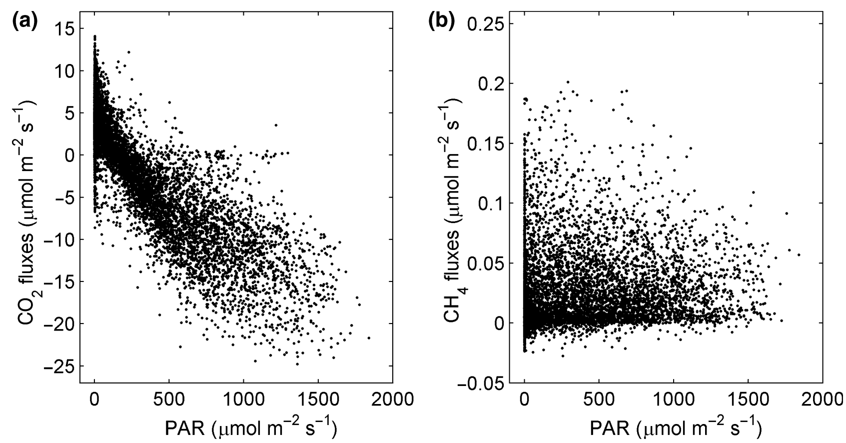

Fig. 7 Response of CO_2 (a) and CH_4 (b) fluxes to photosynthetically active radiation (PAR). CO_2 fluxes show a typical response curve, whereas CH_4 fluxes show no response.

the footprint in any given half hour. An analysis of photographic images from the eddy flux site is on-going to enable further interpretation of the data. We observe for example, that on 4 August, when sheep were especially concentrated within the flux footprint, the measured flux was remarkably high. Thus, we cannot exclude the possibility that the diurnal pattern of methane flux is related to sheep movements within the field.

Feeding patterns and variation in the metabolic processes in the sheep rumen may also cause the observed diel cycle in methane flux. This would not be an artefact of the vagaries of the sampling process, but a real biological pattern. The typical behavioural pattern consists

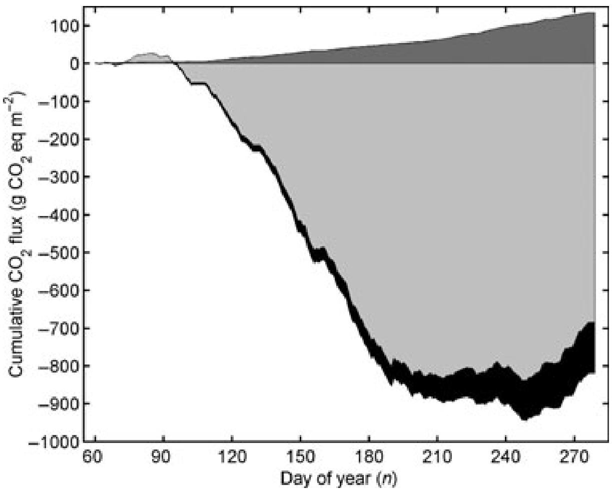

Fig. 8 Cumulative CO_2 flux (g CO_2 equivalents m^{-2}) values over the entire measuring period. CO_2 taken up by the field is marked in black, CH_4 (expressed as CO_2 equivalents) in dark grey, whereas the net sink values are marked in light grey. Positive values denote the loss from the system and negative values denote uptake. At its highest, the field acted as a sink of 945 g C (CO_2 equivalents) m^{-2}.

of grazing during early mornings, followed by a resting period over noon, before another grazing period in the afternoon and evening. Night-time is spent ruminating or idling (Lockyer, 1997). This fits reasonably well with the observed pattern in CH_4 emissions, with a small peak in the morning and a larger peak in the afternoon and early evening, and low values at night. Diurnal emission patterns similar to our observations have been reported in studies using tunnel systems (Lockyer, 1997; Murray *et al*., 2001), flux gradient technique (Judd *et al*., 1999) or nosebands (Lockyer & Champion, 2001). The simplest mechanism underlying this is that the act of feeding displaces gas in the rumen, and promotes eructation, although there may be cycles in the microbial activity in the rumen also. Given that this pattern fits with the measured fluxes and has been seen in other studies, we speculate that the observed diel pattern is a real biological cycle, and not an artefact of the micrometeorological sampling process. This is backed up by the closest comparable study, using the flux gradient method on freely grazing sheep (Judd *et al*., 1999), which observed a similar diel pattern, and also gave similar CH_4 fluxes (morning and afternoon peaks of ca. 30 and 90 nmol m^{-2} s^{-1}, respectively).

The grazing pattern is also affected by the availability of feed, quality of grass and climatic variables, such as temperature, solar radiation, wind and humidity (Munro, 1962; Blackshaw, 1984; Sherwin & Johnson, 1987), so is not entirely predictable. Grass passes through the digestive system more slowly than clover, and so grass-fed sheep are less likely to graze at night (Jensen, 2002). Murray *et al*. (2001) reported that night-time emissions from sheep feeding on clover were much higher than those from sheep feeding on grass. This pattern fits with our data, although we cannot discount the possibility that sheep shelter by the hedge at the field margins, and remain largely outside the footprint area.

Data from the second half of the year (July onwards) show a high correlation between fluxes of CH_4 and the number of sheep in this field with an estimated flux of 20.5 g CH_4 per sheep per day. This value is close to those reported by Crutzen *et al*. (1986) for sheep in developed countries, and used by the IPCC (2006) as an emission factor for annual emissions per head of sheep. Calculated values for the first half (until end June) of the year are lower with 14 g CH_4 per sheep per day because lambs release less CH_4 than sheep (Lockyer, 1997), and very young lambs barely release any CH_4 (Lockyer & Champion, 2001). These values fall well within the margins of daily emissions of sheep measured in other studies, such as by Blaxter & Clapperton (1965), Lockyer & Jarvis (1995), Lassey *et al*. (1997), Lockyer (1997) and Lassey (2007). At the same time, they appear higher than those measured by Leuning *et al*. (1999) and lower than those values measured by Judd *et al*. (1999) and Pelchen & Peters (1998).

Trends in CO_2 fluxes (Figs 6a and 7) show the classical daily variation in carbon dioxide fluxes, with values showing uptake from early morning and photosynthesis continuing later into the afternoon. The effect of longer daylight and higher PAR during the season is also clear (Figs 6a and 7). The net ecosystem exchange values here show similar values as those found by Jaksic *et al*. (2006) in grassland areas and Griffith *et al*. (2002) and Nieveen *et al*. (2005) from pastures with typical maximum rates of -24.7 μmol m^{-2} s^{-1} by day and +14 μmol m^{-2} s^{-1} at night. Daytime minimum values fall well within the values previously recorded under similar grazing conditions at the site in 2002–2005 (Soussana *et al*., 2007). Respiration values appear high at night, but are still within the margin of values observed in other Central European grassland sites (Bahn *et al*., 2008). This respiration arises from sheep and manure as well as the plants and soil.

The net carbon dioxide sink of the field over the measurement period was 819 g CO_2 m^{-2}, reduced by CH_4 emissions by 134.3 g CO_2 equivalents m^{-2} (16%). If the emissions of N_2O are taken into account, the greenhouse-gas balance is much more negative, as annual N_2O emissions are 302 g CO_2 equivalents m^{-2} yr^{-1} (2002–2009 mean; Stephanie Jones, unpublished data). Stephanie Jones (unpublished data) discuss the greenhouse gas balance of the site over the previous 8 years comprehensively, and attempt to quantify all the other losses, including those arising from animal export and leaching, as well as other organic inputs. After accounting for all of these, the site remains an apparent net sink, although this includes all the residual error, and given the uncertainties in estimating many of the terms, the uncertainty is large. Our results show a similar net C sink to that reported by Soussana *et al.* (2007) from several grassland sites and by Byrne *et al.* (2007) at farm scale, with similar grazing and management types. The implication would be that carbon is being accumulated in the soil, and this result needs to be verified by repeated measurements of the soil carbon stock.

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