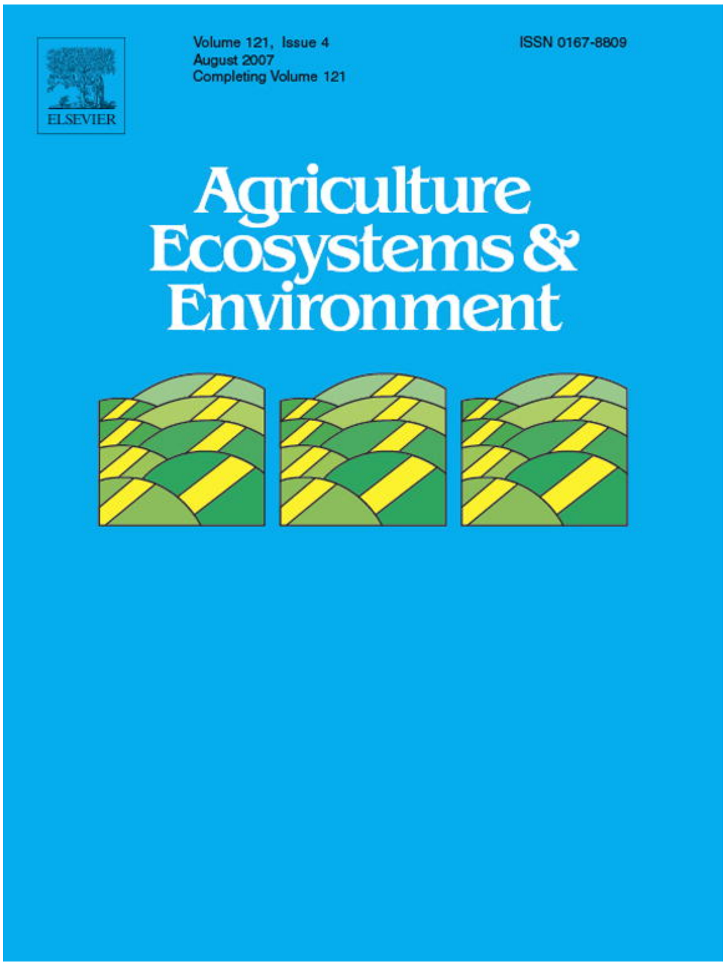
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Carbon sequestration determined using farm scale carbon balance and eddy covariance

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Abstract

Studies using eddy covariance have shown grasslands to be both sinks and sources of carbon dioxide (CO_2). However, such studies do not take into account the exports of carbon (C), such as in meat and milk and imports of C, such as off-farm derived C in cattle feed supplement. By coupling eddy covariance results with farm management data we quantified the farm scale C balance during 2004 for two dairy farms in South West Ireland. The system boundary for inputs and outputs of C is the farm perimeter. Carbon sequestration is determined as the difference between all C inputs and C outputs. Carbon inputs are similar in both farms with net ecosystem exchange (NEE) (2.9 ± 0.5 t C ha^{-1} $year^{-1}$) accounting for 88 and 81% of C inputs in Farms A and B, respectively. Carbon in concentrate feed accounts for 12 and 19% of C inputs in Farms A and B, respectively. Respiration by cattle during the winter housing period, and respiration by cows during milking throughout the grazing season, are the largest C outputs and account for approximately half of C outputs on both farms. The other major sources of C output are milk, CH_4 produced by enteric fermentation and emitted during slurry spreading and dissolved organic carbon (DOC) in streamflow. Carbon in meat and CH_4 emissions from dung (both in the farmyard and fields) and animal slurry in farmyard storage are minor sources of C output. The annual total C inputs are 3.30 and 3.58 t C ha^{-1} and the total C outputs are 1.25 and 1.43 t C ha^{-1} in Farms A and B, respectively. The net difference is 2.05 and 2.15 t C ha^{-1} in Farms A and B, respectively. This suggests that both farms were net C sinks for 2004. Further work on below ground process and soil C turnover is required to determine if this C sink estimate is reflected in changes in soil C stocks. Furthermore, we estimate the global warming potential (GWP) of this grassland to be a sink for ~1 t CO_2 equiv. ha^{-1} $year^{-1}$.

Keywords: Greenhouse gases; Grassland; Carbon cycling; Radiative forcing

1. Introduction

Grasslands are a major land use in Europe, occupying some 62.7 Mha in the EU 25 plus Norway and Switzerland (Janssens et al., 2005). These areas are an important component of the European carbon (C) budget (Janssens et al., 2003) and there is a need to understand their C balance. Furthermore, article 3.4 of the Kyoto protocol makes provision for the use of soil C stock changes in grazing lands to offset greenhouse gas (GHG) emissions and facilitate the achievement of emissions reduction targets. Therefore, there is a need to assess the viability of a range of strategies to reduce greenhouse gas emissions. Such strategies should have a whole farm approach (Oenema et al., 2001) and be capable of reducing or offsetting greenhouse gas emissions or promoting C sequestration. If mitigation strategies are tailored to specific farming systems they are more likely to be accepted by farmers. An essential prerequisite to analysing the effectiveness of GHG reduction strategies is an understanding of the C balance at farm level. The farm scale balance methodology has been used widely and successfully to quantify losses of farm nutrients (Oenema et al., 2003). It is desirable to apply techniques

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successfully used in other areas of research (such as nutrient losses from soils to water, e.g. Tunney et al. (2003)) to help quantify the C source/sink status of complex ecosystems such as grasslands.

The net ecosystem exchange (NEE) in grasslands is determined by the difference between carbon dioxide (CO_2) uptake through photosynthesis and CO_2 loss through respiration (Byrne et al., 2005). The technique most widely applied to measure this at ecosystem level is eddy covariance and over 180 systems are operating globally on a long term and continuous basis (Baldocchi, 2003). By measuring the covariance between the fluctuations in vertical wind velocity and the CO_2 mixing ratio, the EC technique determines the exchange rate of CO_2 across the biosphere/atmosphere interface. The area sampled, called the flux footprint, has longitudinal dimensions varying between hundreds of meters and several kilometers (Schmid, 1994). The EC technique has been applied in a range of ecosystems and numerous studies have shown grasslands to be both sinks and sources of CO_2 (e.g. Flanagan et al., 2002; Hunt et al., 2004; Jaksic et al., 2006; Novick et al., 2004). When deployed in ecosystems where there is no significant lateral C movement into or out of the study site (such as in a forest when no harvesting is occurring) EC measurements on their own provide an estimate of the C sink or source status of the ecosystem. However, EC studies do not adequately represent the farm level C balance given that they do not capture farm outputs such as milk and meat production and C inputs such as concentrate feed. Recent studies by Nieveen et al. (2005) and Lloyd (2006) have combined EC derived NEE measurements with estimates of farm C exports to estimate the sink/source status of soil C. However, these studies do not address all the pathways of C inputs and outputs.

In addition, when considering the contribution of farming systems to GHG emissions there is a need to consider N_2O in addition to CO_2 and CH_4. By considering all biogenic GHGs the net radiative forcing of the system can be assessed. This is done using global warming potential (GWP) (Houghton et al., 2001).

In this paper, we have the following objectives: (1) quantify the farm scale C balance during 2004 for two dairy farms in South West Ireland by combining results of on-site EC studies with farm management data and emission factors derived from published literature; (2) estimate the sink/source status of C as the difference between C inputs and outputs; (3) estimate the uncertainty ranges associated with the major components of the C balance; (4) calculate the net GWP of both farms.

2. Materials and methods

2.1. Site description

This study was located in an area of intensively managed grassland 200 m above sea level in County Cork, southern Ireland (Latitude: 51°59′N, Longitude 8°45′W). The climate is temperate maritime with an average rainfall of 1470 mm $year^{-1}$ and an annual daily mean temperature of 6.2 °C in January and 13.7 °C in July. Photosynthetic photon flux density (PPFD) has a clear seasonal trend with the highest values occurring during the summer months (Fig. 1a). The average air temperature was above 5 °C on 320 days during 2004. Soil temperature at 5 cm depth during 2004 was generally between 4 and 16 °C (Fig. 1b). Frost occurred on less than 10 days during the year. The total rainfall in 2004 was 1340 mm (Fig. 1c) and the average daily mean temperature was 9.5 °C. Soil moisture content was in the range 40–50% during spring, autumn and winter and falls to ~20% during summer (Fig. 1d). Field capacity of this soil was estimated to be approximately 26% and wilting point to be 12%.

The dominant soil type is gleysol (FAO–UNESCO, 1974) with low lying areas having a shallow surface peat layer. The soil organic carbon content (0–10 cm) is 3.9–5.9%. Approximately, 300 kg N ha^{-1} was applied as fertilizer and slurry during 2004.

The dominant grass species is perennial ryegrass (*Lolium perenne* L.) with smaller amounts of Meadow foxtail (*Alopecurus pratensis* L.) and Yorkshire-fog

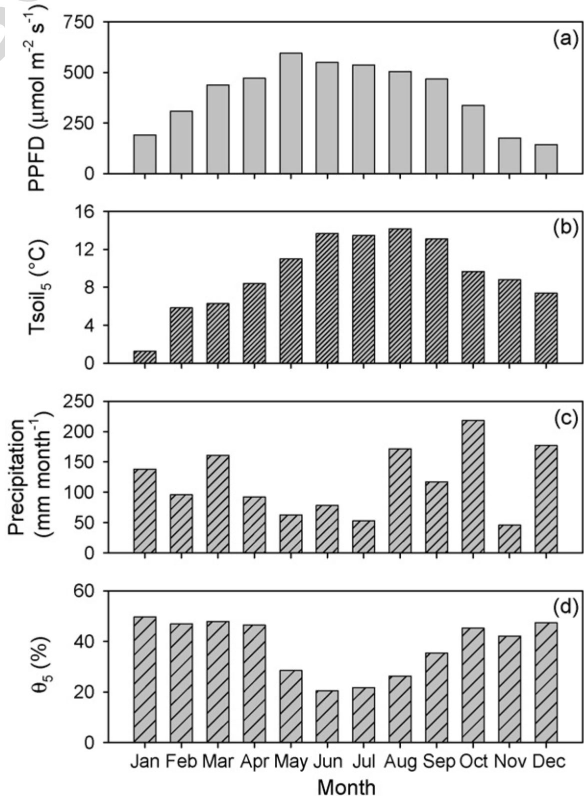

Fig. 1. (a) Average monthly daytime photosynthetic photon flux density (PPFD), (b) average monthly soil temperature at 5 cm depth ($Tsoil_5$), (c) total monthly precipitation and (d) average monthly volumetric soil moisture content at 5 cm depth (θ_5). Field capacity is at θ ~26% and saturation is at θ ~45%. All data were taken from the meteorological station located on site for 2004.

(*Holcus lanatus* L.). Fields vary in size from one to five hectares and are grazed intensively by dairy and beef cattle between April and October each year. Cattle are housed for the remaining 5 months of the year. Approximately 50% of the fields are cut for silage, twice a year, typically in June and September. Grass production rates are in the range 7.6–14 t DM ha^{-1} $year^{-1}$ (Byrne et al., 2005). The grazing season lasts from the end of March to mid-October.

The site was instrumented with two eddy covariance systems on one tower. In the first EC system, CO_2 and H_2O concentrations were measured with an open path infrared gas analyzer (LI-7500, Li-Cor, USA) and the wind speed was measured with a 3-D sonic anemometer (Model 81000, R. M. Young, USA). In the second EC system, N_2O concentrations are measured using a closed path tunable diode laser trace gas analyzer (TGA100, Campbell Scientific, USA). All concentrations and wind speeds were logged at 10 Hz and trace gas flux values were calculated at 30-min intervals. The CO_2 and N_2O sensors were mounted 3 m above the ground. A range of meteorological parameters were also measured, including precipitation, air temperature and relative humidity, soil temperature and moisture content and photosynthetic photon flux density. For a full description of the EC system, data processing and gap filling procedures in relation to CO_2 and N_2O see Jaksic et al. (2006) and Leahy et al. (2004), respectively.

2.2. Farm C balance

For the purposes of this study, we consider the farm gate as being the system boundary. Therefore, the Farm C balance is determined by the difference between all fluxes of C into the farm, 'C inputs' and all C fluxes out of the farm, 'C outputs' (Fig. 2). We assume that the values of NEE measured by the EC tower located on site not only capture the difference between C uptake through photosynthesis and C lost through plant and soil respiration but also respiration by grazing cattle and decomposition by deposits of cattle dung and slurry spread on the fields. All slurry produced is land spread within each farm. Carbon emissions occurring outside the EC footprint (i.e. in the farmyard) are estimated separately. The farm is considered to be the composite of the pasture fields plus the farmyard. The latter is outside the EC footprint.

Carbon emissions associated with on-farm energy consumption (such as electricity and diesel) as well as off-farm activities including N-fertiliser production, transport and application, and production, transport and processing of concentrate animal feed are not included in our C balance.

2.3. Farm data

Two farms were chosen for the case study (Table 1). Both farms (but not the farmyards) were within the footprint of the EC tower during 2004. Given the homogeneous nature of farming practices between both farms we assume that the NEE and N_2O emissions observed by the EC tower are representative of both farms. This is similar to the approach adopted at the same site by Lawton et al. (2006) and Leahy et al. (2004). Management practices are similar in both farms with the dominant activity being dairying. All calves are reared for either replacement cows or beef consumption. Animals reared for beef consumption are sold off-farm at 2 years old.

We adopted the sign convention where C inputs are positive and C outputs are negative. The C inputs and outputs were calculated as follows.

2.4. Carbon inputs

2.4.1. Net ecosystem exchange

Net ecosystem exchange was measured during 2004 using an EC system. The EC system is located on the

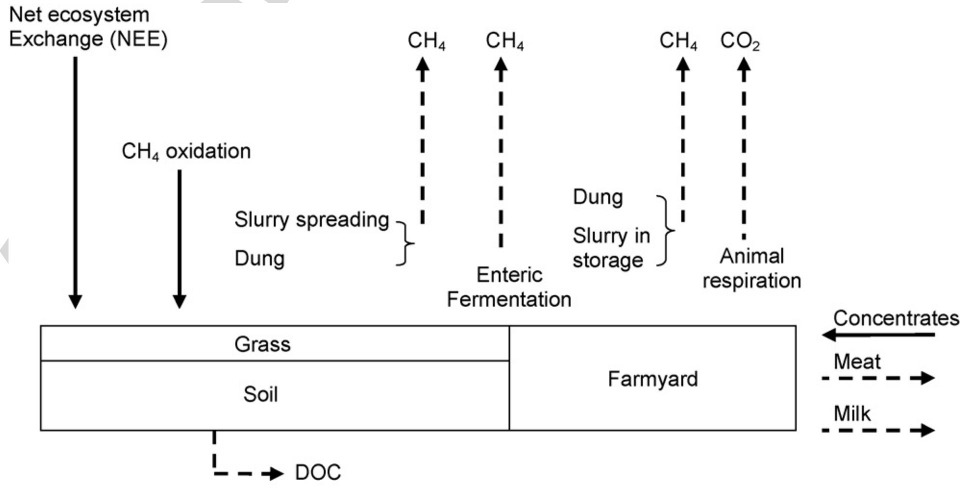

Fig. 2. Schematic representation of the farm scale C balance. Carbon inputs are represented by solid arrows and C outputs by broken arrows.

Table 1
Summary of the two case study farms

Farm	Area (ha)	Livestock numbers				Stocking rate (LU ha^{-1})	Milk production (L cow^{-1})
		Cows	Calves	Bullocks	Heifers		
A	36	35	35	28	–	1.7	5001
B	42.3	47	45	27	7	1.9	6364

field boundary between the two farms. In 2004 the NEE was an uptake of 2.9 ± 0.5 t C ha^{-1} (Jaksic et al., 2006).

2.4.2. Concentrates

Concentrate feed is used for energy supplementation during the winter period when cattle are housed and during the late spring and early summer when grass production is insufficient. In Farm A, cows received 7 kg day^{-1} from calving until turnout and for the first 3 weeks of the grazing season. Bullocks received 4.60 kg day^{-1} for a period of 3 months prior to slaughter and calves received 2.10 kg day^{-1} during the winter housing period. In Farm B, cows received 8.0 kg day^{-1} from calving until turnout and for the first 3 weeks of the grazing season. After this they received 1.0 kg day^{-1} for the remainder of the grazing season. Bullocks received 4.55 kg day^{-1} for a period of 4 months prior to slaughter and calves and heifers received 2.10 kg day^{-1} during the winter housing period. The C content of concentrate feed is 39%. Based on information supplied by the farmers we assume that the concentrate feeding regime is known to within ±15%.

2.4.3. CH_4 oxidation by soils

The CH_4 oxidation capacity of soils is assumed to be 1.5 kg C ha^{-1} year^{-1} (Boeckx and Van Cleemput, 2001).

2.5. Carbon outputs

2.5.1. Milk

The average density of Irish milk is 1.03 kg L^{-1} and it contains on average 3.9% fat and 3.2% protein (McDonagh et al., 1999). The C content of milk fat and protein is 70 and 46%, respectively (Wells, 2001). Based on values reported by the farmers we assume that the milk volume production is known to within ±10%.

2.5.2. Meat

All bullocks and heifers are reared over a 2 year period and slaughtered at approximately 650 and 500 kg, respectively. Based on values reported by the farmers we assume that the final weight is known to within ±10%. After Hammond et al. (1990) gut fill is assumed to be equal to 19% of liveweight and the C content of the carcase live weight is 5.1%.

2.5.3. CH_4 emissions from livestock production

Each cow is assumed to emit 100 kg CH_4 year^{-1} (uncertainty range 85–125) (Houghton et al., 1997) and all other cattle are assumed to emit 50 ± 5 kg CH_4 year^{-1} (EPA, 1998).

2.5.4. CH_4—farmyard emissions from dung

Emissions of CH_4 from dung deposited by cattle in the farmyard before, during and after milking and by all cattle during the winter housing period, were estimated by assuming that cows and bullocks require a floor area of 1.25 m^2, that calves and heifers require an area of 0.62 m^2 and that the emission rate is 4.3×10^{-7} kg m^{-2} h^{-1} (Misselbrook et al., 2001). It is assumed that yard areas are cleaned daily during the winter housing period and weekly during the grazing season with the dung and waste water being collected in storage tanks.

2.5.5. CH_4—field emissions from dung

Each cow was assumed to emit 1.7 g CH_4 day^{-1} (Jarvis et al., 1995). For other cattle it was assumed to be 1.6 g CH_4 day^{-1} (Jarvis et al., 1995).

2.5.6. CH_4 emissions from slurry in storage

The total amount of excreta was assumed to be 0.088 m^3 day^{-1} for dairy cows, 0.012 m^3 day^{-1} for calves, 0.043 m^3 day^{-1} for heifers and 0.053 m^3 day^{-1} for bullocks (DARDNI, 2003). This is produced during the winter period when animals were housed. In addition, cows are assumed to spend 3 h per day in the farmyard for milking during the grazing season (O'Donovan et al., 2000). It was assumed that 75% of slurry was spread by 1st May and the remainder by 1st June (Carton and Magette, 1999). The CH_4 emission factor applied was 5.5 kg CH_4 m^{-3} day^{-1} (Husted, 1994).

2.5.7. CH_4—slurry spreading

The CH_4 emission factor used is 0.0027 kg t^{-1} (uncertainty range 0.0014–0.0042) (Chadwick et al., 2000) and it is combined with the data on excretal volume described above.

2.5.8. Animal respiration

Animal respiration during the grazing season is captured by the EC system. Respiration by animals when they are housed is not captured by the EC system as the farmyard is outside the EC footprint. Therefore, respiration by cows during the winter housing period (and by cows during milking times throughout the grazing season) is assumed to be 6.95 kg CO_2 day^{-1} (±0.25) (Jungbluth et al., 2001). Bullocks are assumed to respire at the same rate as cows. Heifers and calves are assumed to have a respiration of 5.20 (±0.2) and 3.50 kg CO_2 day^{-1} (±0.2), respectively.

2.5.9. Dissolved organic carbon (DOC) in streamwater

The rate of DOC loss in streamwater is 0.10 ± 0.02 t C ha^{-1} $year^{-1}$ (G. Kiely, unpublished data).

2.6. Uncertainty analysis

Using the ranges stated, the uncertainty was noted for those C inputs and outputs that contributed more than 1% to the total carbon input and output, respectively. These are quantified in Table 2.

2.7. N_2O emissions

It was assumed that the nitrogen content of slurry was 5 kg N m^{-3} (Smith and Frost, 2000) and that the N_2O emission rate from slurry in storage was 0.001 kg N_2O–N kg N^{-1} (Houghton et al., 2000). The N_2O emission from the fields was provided by the EC measurements.

3. Results

Carbon inputs are similar in both Farms A and B. This is due to similarity in the management of both farms (Table 1). The EC measurements show that the non-farmyard area of both farms (i.e. fields) are net sinks for atmospheric C with NEE (the difference between gross primary productivity and respiration) being 2.9 ± 0.5 t C ha^{-1}. NEE accounts for 84 and 79% of carbon inputs in Farms A and B, respectively.

Table 2
Carbon balance of Farms A and B in 2004

	Farm A (t C ha^{-1})	Farm B (t C ha^{-1})
Carbon inputs		
NEE	2.9 ± 0.5	2.9 ± 0.5
Concentrates	0.40 ± 0.07	0.68 ± 0.1
CH_4 oxidation	0.0015	0.0015
Sub-total	3.30 ± 0.57	3.58 ± 0.60
Carbon outputs		
Milk	-0.21 ± 0.02	-0.31 ± 0.03
Meat	-0.02 ± 0.002	-0.02 ± 0.003
Enteric fermentation	-0.11 ± 0.02	-0.12 ± 0.03
CH_4—Dung in farmyard	−0.001	−0.001
CH_4—Dung in field	−0.0005	−0.0005
CH_4—Slurry spreading	-0.08 ± 0.04	-0.06 ± 0.03
DOC	-0.10 ± 0.02	-0.10 ± 0.02
CH_4—Slurry in storage	−0.0001	−0.0001
Animal respiration	-0.73 ± 0.03	-0.82 ± 0.06
Sub-total	-1.25 ± 0.12	-1.43 ± 0.18
Net carbon balance	2.05	2.15

Uncertainty estimates are given with C inputs and outputs that contribute more than 1% to total C inputs and outputs, respectively.

Carbon in concentrate feed accounts for 12 and 19% of C inputs in Farms A and B, respectively. Concentrate feed is a larger component of the C inputs in Farm B due the higher feeding regime. This may contribute to the higher milk production in Farm B (Table 1). The C input through CH_4 oxidation represents a very small proportion of C inputs.

The C outputs are derived from a variety of sources. Farm B is more productive than Farm A and this is reflected in the higher C outputs from milk production and animal respiration (Table 2). Respiration by cattle during the grazing season would also be a significant source of C but we assume that it is captured by the EC measurements. Milk is the second largest source of C outputs contributing 16.8 and 21.4% to total C outputs in Farms A and B, respectively. The C output as CH_4 produced by enteric fermentation is the same in both farms although it is a larger proportion of total outputs in Farm A (8.9%) than in Farm B (8.6%). The CH_4 emissions due to slurry spreading are slightly higher in Farm A (6.1%) than in Farm B (4.5%). DOC accounts for 8.0 and 7.0% of C outputs in Farms A and B, respectively. Carbon output as meat is similar in both farms (1.7 and 1.4%, respectively) and CH_4 emissions from dung (both in the farmyard and fields) and slurry in storage are minor sources of C output.

Combining the farm C balance components and EC measurements indicates that both farms are net sinks for ~2 t C ha^{-1} $year^{-1}$ (Table 2).

NEE (through uptake of CO_2) accounts for 88 and 81% of the negative radiative forcing derived from C inputs in Farms A and B, respectively (Table 3). Enteric fermentation is the largest contributor to the positive radiative forcing

Table 3
Net radiative forcing of Farms A and B in 2004

	Farm A (t CO_2 equiv. ha^{-1})	Farm B (t CO_2 equiv. ha^{-1})
Negative radiative forcing		
CO_2—NEE	−10.63	−10.63
CO_2—Concentrates	−1.45	−2.51
CH_4 oxidation	−0.046	−0.046
Sub-total	−12.13	−13.18
Positive radiative forcing		
CO_2—Milk	0.77	1.12
CO_2—Meat	0.08	0.08
CH_4—Enteric fermentation	3.40	3.77
CH_4—Dung in farmyard	0.02	0.02
CH_4—Dung in field	0.01	0.02
CH_4—Slurry spreading	2.33	1.98
DOC	–	–
CH_4—Slurry in storage	0.003	0.003
CO_2—Animal respiration	2.68	3.00
N_2O emissions	1.95	1.95
Sub-total	11.23	11.94
Net radiative forcing	−0.90	−1.25

CH_4 and N_2O emissions were converted into CO_2 equivalents by assuming respective GWPs 23 and 296 times that of CO_2 over a 100 year time horizon (Houghton et al., 2001).

accounting for 30 and 32% in Farms A and B, respectively (Table 3). The other major contributors to positive radiative forcing are animal respiration (during the winter housing period and during milking time for cows), CH_4 emissions from slurry spreading and N_2O emissions.

When the net radiative forcing is considered (Table 3) Farms A and B are shown to have a negative radiative forcing of 0.90 and 1.25 t CO_2 equiv. ha^{-1}, respectively.

4. Discussion

By quantifying the farm level C balance this study suggests that these grass based dairy farms are C sinks. The dominant pathway of C input is photosynthesis and the measured NEE is similar to the value of 3 t C ha^{-1} $year^{-1}$ reported for *L. perenne* grassland in the Netherlands (Schapendonk et al., 1997). NEE is affected by both climate and management and therefore varies between years. The EC measured NEE was 1.9 t C ha^{-1} $year^{-1}$ in 2002 and 2.6 t C ha^{-1} $year^{-1}$ in 2003 (Jaksic et al., 2006). Given that NEE accounts for the largest proportion of C inputs it will have the greatest impact on the annual C balance.

Feeding of concentrates to cattle during wintertime and in the early growing season is a significant route of C inputs (Table 2). However, it is debatable as to whether it should be included in the farm C balance. Firstly, concentrate feed is produced in a location beyond the farm boundary and involves an export of C from the location where it is produced. This will reduce the C sequestration potential of these remote ecosystems. For instance, in a study of the C budget of a maize and soybean rotational system, Hollinger et al. (2005) found that at the local scale maize was a sink for 5.76 t C ha^{-1} $year^{-1}$ and soybean was a sink for 0.33 t C ha^{-1} $year^{-1}$. When considered at regional scale, grain consumption reduced the C sink in maize to 1.84 t C ha^{-1} $year^{-1}$ and converted soybean to a C source of 0.94 t C ha^{-1} $year^{-1}$. Therefore, when considering the farm C balance cognisance should be given to the C balance of ecosystems from which external feed, be that from a national or international source, is derived. Secondly, there are GHG emissions associated with energy consumed in the production and subsequent transport of this feed source. In a study of Irish milk production systems, Casey and Holden (2005a) found that concentrate feed accounted for 13% of greenhouse gas emissions from the average dairy unit.

Respiration by cattle during the winter housing period, and by cows during milking periods, is the largest pathway of C emissions. Measurement of respiration rates for different kinds of livestock would enable this to be estimated more accurately.

While our estimate of DOC output is similar to that reported by Hagedorn et al. (2000) for a grassland in Switzerland, McTiernan et al. (2001) found that export in streamflow from grazed grasslands over 2 months varied from 0.04 to 0.12 t C ha^{-1}. DOC export was positively correlated with nitrogen application and increased dry matter production as a result of fertilization was suggested as an important factor.

The largest outputs of CH_4 are enteric fermentation and slurry spreading. The emission factors for CH_4 produced by enteric fermentation have been used elsewhere (Casey and Holden, 2005a,b) and are considered to be appropriate. CH_4 emissions from slurry spreading have been shown to be affected by the application technique and environmental conditions (Wulf et al., 2002) and therefore the emission factor used here warrants further study.

The approach used here to determine C sequestration has been applied elsewhere in a similar manner. Nieveen et al. (2005) found that grazed pasture on a drained peat soil in New Zealand was a net source of 1.06 ± 0.5 t C ha^{-1} $year^{-1}$. In contrast to this study, Nieveen et al. (2005) does not include farmyard emissions (CO_2 and CH_4) and supplementary feed was not considered. Working at a wetland meadow peat site in the UK, Lloyd (2006) found that when EC measured NEE was combined with harvest and cattle C gains and losses, the site had a loss of soil C of 0.59 t C ha^{-1} $year^{-1}$. However, Lloyd (2006) did not include CH_4 emissions from cattle, which as this study shows is a significant loss of C. Both Nieveen et al. (2005) and Lloyd (2006) show losses of C because peat soils drained for agriculture are known to be sources of C because lowering of the water table increases decomposition of organic matter leading to losses of C. For example, Maljanen et al. (2001) found that grassland on a peat soil in Finland was a net source of 2.04 t C ha^{-1} $year^{-1}$.

Both farms have a negative radiative forcing effect. In a study at the same site, Leahy et al. (2004) found that emissions of N_2O during 2003 accounted for 57% of the cooling effect derived from CO_2 uptake. Leahy et al. (2004) only considered net CO_2 and N_2O emissions within the EC footprint whereas in this study we included net CO_2, CH_4 and N_2O emissions at farms level. Although this leads to a reduced negative radiative forcing effect the farms remain sinks for CO_2 equivalents. However, this sink is likely to be within the error of the EC system and the farms may have neutral radiative forcing. In addition, inclusion of emissions derived from energy production and the production of concentrate feed may lead to positive radiative forcing as found by Casey and Holden (2005a).

It could be argued that no CO_2 emission associated with concentrate feed, meat or milk occurs within the system boundary and therefore these should be excluded from this GWP assessment. The recalculated radiative forcing would be −0.30 and 0.06 t CO_2 equiv. ha^{-1} in Farms A and B, respectively.

Although the results suggest that both our farms are net sinks for C (Table 2) and CO_2 equivalents (Table 3), the manner in which the C sequestered is partitioned between the soil and the vegetation remains unanswered. Based on an assessment of data from studies in France, Soussana et al. (2004) suggest that grassland management may increase soil C stocks by 0.2–0.5 t C ha^{-1} $year^{-1}$ although they estimate the uncertainty at 0.25 t C ha^{-1} $year^{-1}$. This is considerably lower than the value calculated in this study and suggests that the C sink estimated in this study may not reflect changes in soil C but reflect changes in the composite of soil plus vegetation and possibly root biomass.

Given the difficulty of detecting short term changes in soil C stocks using conventional means (e.g. Garten and Wullschleger, 1999) there is a need for studies to follow C flows through the plant-soil-root system and $^{14}CO_2$ pulse labeling techniques (e.g. Kuzyakov et al., 2001) may be one method of investigation. There is also a need for more information about the turnover of the various fractions of soil organic matter and the incorporation of such information into SOM models. In addition, there is a need to track the internal cycling of C at farm level through grass harvesting and manure management.

5. Conclusions

This study finds that grassland in this temperate maritime climate zone with grazing and harvesting of grass is a sink of C to an amount of ~2 t C ha^{-1} $year^{-1}$. This sink was not partitioned between the amounts sequestered in the soil and the vegetation. The approach described here identifies the most significant factors in the Farm C balance and radiative forcing. The estimated C sequestration would need to be verified with soil C measurements on a range of representative soil types before the method could be applied generally. The methodology used to quantify the C sink was a C balance using the farm perimeter as the system boundary. Included in this balance was the NEE measured by an EC system and all the other quantifiable inputs and outputs of C to the farm system. Assessment of radiative forcing finds that this grassland is a sink for ~1 t CO_2 equiv. ha^{-1} $year^{-1}$. Emissions associated with energy consumption and derived from the production and transport of concentrate feed should be included in further studies so that the radiative forcing of the full system can be assessed. The approach described here couples EC data with farm level management data to constrain the farm level C balance. Further work (e.g. soil C measurements) will be required in order to reduce the associated uncertainties.

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