EPA STRIVE Programme 2007-2013

Quantification of the components of the carbon budget at farm scale

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End of Project Report

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by

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ACKNOWLEDGEMENTS

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EPA STRIVE PROGRAMME 2007-2013

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Table of Contents

Executive Summary

Grassland is the dominant land use in Ireland. There is a need to understand the carbon (C) sequestration status of these ecosystems in order to support national commitments under the United Nations Framework Convention on Climate Change and it's Kyoto Protocol. This study investigated the farm scale C balance at the Celticflux study site in Co. Cork, Ireland. Carbon dioxide (CO_2) fluxes were compared in new and permanent grassland using a chamber based experiment. Cumulative values of gross primary production (GPP), total respiration (R_{TOT}) and net ecosystem exchange (NEE) in the new grassland were 2.14, -1.98 and 0.15 kg C m^{-2} yr^{-1} respectively. In the permanent grassland cumulative values of GPP, R_{TOT} and NEE were 2.90, -2.52 and 0.38 kg C m_{-2} yr_{-1} respectively. R_{TOT} was partitioned into heterotrophic (R_H) and autotrophic respiration (R_A). During the period from late May until mid-August R_H and R_A both accounted for, on average, 50% of R_{TOT}. During the rest of the year R_H and R_A represented, on average, 62 and 38% of R_{TOT} respectively. The farm scale C balance was quantified by combining results of on-site eddy covariance studies with farm management data and emission factors derived from published literature. This assessment found that grassland is a sink for ~2 t C ha_{-1} yr_{-1}. There is a need for further research to partition this sink between the amounts sequestered in the soil and the vegetation. There is also a need to quantify the major components of the farm C balance and to upscale site level studies to regional and national level.

1 Introduction

Anthropogenic activity is leading to increased levels of greenhouse gases (GHGs) in the atmosphere. This is generally accepted to contribute to global warming (IPCC 2007), which could result in more extreme weather events with severe implications for ecosystems, health, infrastructure, and property. Although estimates of anthropogenic emissions emissions are relatively well understood, less is known about how GHGs are cycled between ecosystems and the atmosphere, and how climate change could perturb these cycles. In addition to this there is a need for scientific tools to account for GHG balances in different land use systems and to support national GHG reporting requirements pursuant to the United Nations Framework Convention on Climate Change and it's Kyoto Protocol.

Grasslands are one of the Earth's most abundant land cover types and account for approximately 40.5% of the terrestrial land area (White et al. 2000). There is a growing body of knowledge about carbon dioxide (CO_2) exchange at field and landscape level (e.g. Flanagan et al. 2002; Novick et al. 2004), which shows that grassland can act as both sources and sinks of CO_2. In addition grasslands are significant sources of nitrous oxide (N_2O) (Scanlon and Kiely 2003). Grassland is estimated to cover 57% of the land area in Ireland (Cruickshank et al. 2000) and is the dominant land cover type. The EPA funded Celticflux project was set up to make eddy covariance based measurements of CO_2 and N_2O at a grassland site at Dripsey, Co. Cork (Jaksic et al. 2006; Lawton et al. 2006; Leahy et al. 2004; Scanlon and Kiely 2003) and a peatland site at Glencar, Co. Kerry (Sottocornola and Kiely 2005).

This study (EPA Post-doctoral Fellowship 2003-CD-LS-FS-13) was established in support of Celticflux and was divided into the following sub-projects:

1. CO_2 fluxes in adjacent new and permanent grasslands (Chapter 2)

2. Partitioning of respiration in an intensively managed grassland (Chapter 3)

3. Carbon sequestration determined using farm carbon balance and eddy covariance (Chapter 4)

Each sub-project is described in the chapter indicated. All three sub-projects were conducted at the Celticflux study site at Dripsey, Co. Cork. For a full description of the site see Byrne et al. (2005)

2 CO_2 fluxes in adjacent new and permanent grasslands

2. 1 Objectives

The objectives of this sub-project were as follows: (1) to measure grass production in recently established and permanent grassland (2) to assess the major biotic and abiotic factors controlling CO_2 dynamics in both grasslands and (3) to use chamber measurements to create statistical response functions for CO_2 exchange in order to reconstruct monthly and annual fluxes of gross primary

production (GPP, kg C m^{-2}), net ecosystem exchange (NEE kg C m^{-2}) and total respiration (R$_{TOT}$, kg C m^{-2}) at the two sites.

2.2 Materials and Methods

2.2.1 Site description

For this sub-project two study sites were selected. Site A was previously grassland and a new pasture was established, following ploughing and cultivation in Autumn 2003. Site B is a permanent 15-year-old pasture. The dominant grass species in both sites is perennial ryegrass (*Lolium perenne* L.) with smaller amounts of Meadow foxtail (*Alopecurus pratensis* L.) and Yorkshire-fog (*Holcus lanatus* L.) The study area is 180 m above sea level and the climate is temperate maritime with an average annual rainfall of 1470 mm. The soil type is gley (Gardiner and Radford 1980) and soil properties are similar in both sites.

2.2.2 Grass growth measurements

In February 2004 eight samples plots were installed in each site (A and B) using stainless steel collars (60 × 60 × 15 cm). Grass production was measured by cutting the grass to a stubble height of 5 cm from two plots of each site every week on a four-week cycle. The dry mass was measured after oven drying at 70 ºC for 48 hours. All plots received an equivalent fertiliser application of 300 kg N ha-1 divided into eight equal applications at intervals of four weeks from 1 March to 13 September. Grass height was measured weekly in all plots from 29 March to 15 November. Weekly, simultaneous measurements of grass height and one-sided leaf area index (LAI) were made in each site throughout the study period. Leaf area index was meausured using an AccuPAR model PAR-80, Ceptometer (Decagon Instruments, WA, USA). Linear regression constrained to pass through the origin was used to develop site-specific relationships between grass height and LAI (Figure 2.1).

2.2.3 CO$_2$ flux measurements

CO$_2$ fluxes were measured from the same stainless steel collars (i.e. eight per site) as used for grass production measurements. Measurements were made one or two times per week from March 2004 to March 2005. CO$_2$ fluxes were measured using a vented and thermostatically controlled, transparent perspex chamber (60 × 60 × 30 cm). The chamber headspace was fitted with a fan to ensure good air mixing. During CO$_2$ measurement the chamber was placed over the stainless steel collar, which has a water channel at the top to allow air sealing. The CO$_2$ concentration in the chamber headspace was measured using a portable infra-red gas analyzer (EGM-4, PP Systems, UK) equipped with a vacuum pump (suction from chamber headspace 100-150 ml air min^{-1}). Analyser readings of CO$_2$ concentration in ppm were recorded at intervals of 15 seconds after closing the chamber. The instantaneous net CO$_2$ exchange was measured with the chamber exposed to ambient illumination for 60-120 seconds. After each measurement the chamber was removed to allow stabilisation of the CO$_2$ concentration. Following this the total respiration rate (R_{TOT}) was measured with the chamber covered with an opaque

canvas cover. For description of the method see Alm et al. (1997) and Tuittila et al. (1999). In order to relate CO_2 fluxes to prevailing environmental conditions, the photosynthetic photon flux density (PPFD) and air temperature inside the chamber were recorded simultaneously with NEE measurements. At the same time, soil temperature at 5 cm depth ($T_{soil,5}$ °C) and volumetric soil moisture content in the top 6 cm (θ_6, m^3 m^{-3}) were measured.
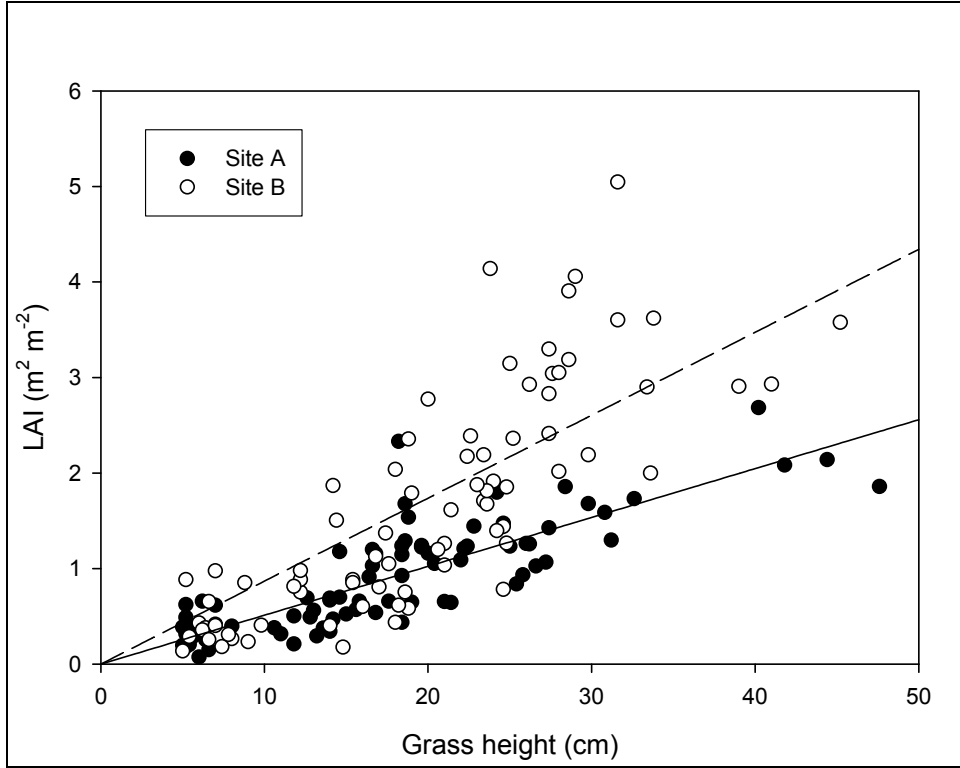
Figure 2.1. Relationships between grass height and leaf area index (LAI) in Sites A and B. For Site A the equation for the fitted (solid) line is LAI$_A$ = 0.015*(h$_A$); R^2 = 0.69; (h$_A$ = grass height in cm); for Site B the equation for the fitted (dashed) line is LAI$_B$ = 0.087*(h$_B$); R^2 = 0.64; (h$_B$ = grass height in cm).

2.2.4 Modeling of CO$_2$ fluxes

Carbon dioxide fluxes were calculated from the linear rate of change in CO_2 concentration inside the chamber headspace. We adopt the sign convention where fluxes from the biosphere to the atmosphere are negative. Gross primary production (GPP) was calculated as the difference between CO_2 fluxes measured in light and dark and it was always positive.

Using the measured CO_2 fluxes and associated values of PPFD, $T_{soil,5}$, θ_6 and LAI statistical response functions for GPP and R_{TOT} were developed separately for each site using the procedure described below.

Gross primary productivity was related to PPFD using the Michaelis-Menten type relationship for the light dependence of the rate of photosynthesis (Stryer 1988). GPP was related to LAI using the Michaelis-Menten type relationship. Both of these relationships were incorporated in a statistical response function of the following form:

$$P_G = a_1 \left(\frac{Q_{PPFD}}{a_2 + Q_{PPFD}} \right) \left(\frac{L}{a_3 + L} \right)$$

(2.1)

Where:

P_G = Gross primary productivity (GPP)

Q_{PPFD} = Photosynthetic photon flux density (PPFD)

L = Leaf area index (LAI)

Site-specific equation parameters for Sites A and B were determined using least squares non-linear regression.

Total respiration was related to $T_{soil,5}$ using an exponential function and to θ_6 using an exponential type equation. Both of these relationships were incorporated in a statistical response function of the following form:

$$R_{TOT} = -a_1 \exp(a_2 T_{soil,5}) \exp\left[-0.5 \left(\frac{\ln\left(\frac{\theta_6}{a_3}\right)}{a_4} \right)^2 \right]$$

(2.2)

Total respiration is limited at low and high values of θ therefore a function to describe the relationship should rise to a maximum value and then decay. The θ response incorporated in Eq. (2.2) has this property. Site-specific equation parameters for Sites A and B (Byrne et al. 2005) were determined using least squares non-linear regression.

GPP and R_{TOT} are influenced simultaneously by the controlling variables in Equations (2.1) and (2.2). The sensitivity of GPP and R_{TOT} to variation in each controlling variable was analysed by adjusting the measured exchange rates so that a single factor was allowed to vary and the other factors were kept constant. These adjusted values of GPP and R_{TOT} allow presentation of the trend in the data related to a single controlling factor (fitted lines in Figures 2.3 and 2.4). Each measured value of GPP and R_{TOT} was partitioned into its predicted and residual components using Equations 2.1 and 2.2 respectively. In this way the component predicted by the model in prevailing conditions was replaced by a value predicted in selected conditions. The set values were LAI = 1.0 m^2 m^{-2}, PPFD = 500 µmol m^{-2} s^{-1}, θ_6 = 20% and Tsoil$_5$ = 15 ºC. Using the same values in both sites allows the response of GPP and R_{TOT} to their respective controlling variables to be compared between Sites.

GPP and R_{TOT} dynamics during 2004 were reconstructed by including the half-hourly environmental data from the meteorological station on-site into the statistical response functions for GPP and R_{TOT} (Eqs. (2.2) and (2.3) respectively).

NEE was calculated half-hourly for each site with the equation:

$$F_c = P_G + R_{TOT}$$

(2.3)

Where:

F_c = Net ecosystem exchange

Net ecosystem exchange and R_{TOT} values were integrated over the study period and monthly and annual totals calculated.

2.3 Results

There was a clear difference in grass production between Sites A and B (Fig. 2.3). This followed the typical trend for Perennial Rye Grass. The cumulative grass production in Sites A and B was 0.38 and 0.70 kg C m^{-2} respectively (Fig.2.2).
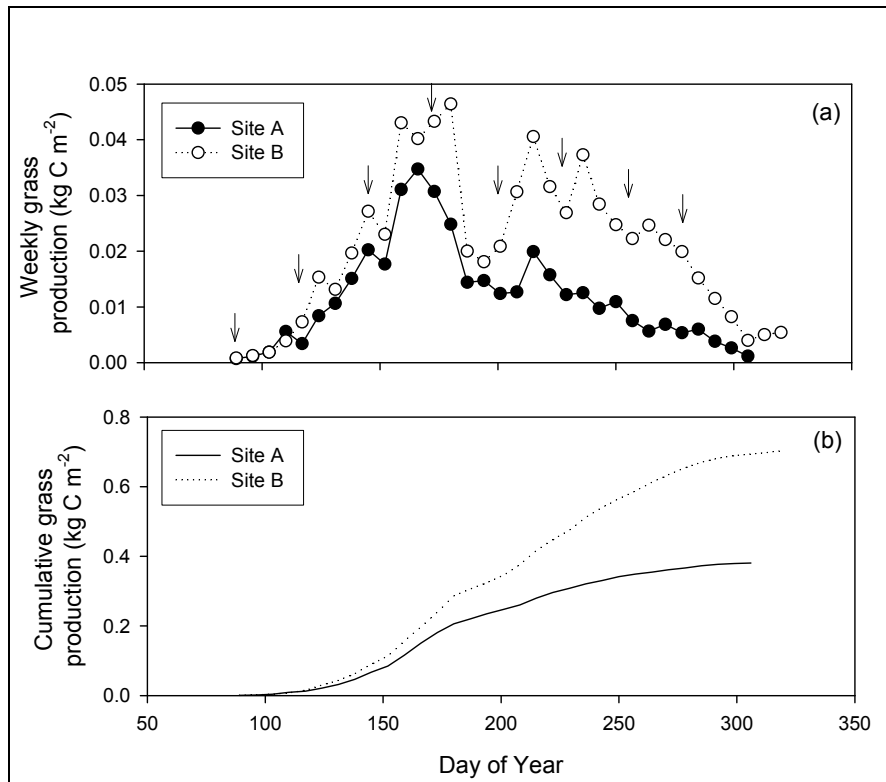
Figure 2.2. (a) Weekly and (b) cumulative grass production in Sites A and B during 2004. The C content of grass is assumed to be 0.5. The arrows indicate the time of fertilizer application.

PPFD and LAI controlled the rate of GPP in both sites. The GPP response to both PPFD and LAI was saturating (Fig. 2.3). Eq. (2.1) explained 78 and 81% of the variation in GPP and Sites A and B

respectively (Byrne et al. 2005). There was good agreement between measured and modelled GPP although Eq. (2.1) may overestimate low GPP values in Site B.

$T_{soil,5}$ and θ_6 controlled the rate of R_{TOT} in both sites (Fig. 2.4). Maximum R_{TOT} occurred when θ_6 was 20.1 and 25.5 % at sites A and B respectively. Eq. (2) explained 86 and 83% of the variation in R_{TOT} in Sites A and B respectively (Byrne et al. 2005). There was good agreement between measured and modelled R_{TOT} (Fig. 7c, d) but Eq. (2.2) overestimates R_{TOT} fluxes below 5 μmol CO_2 m^{-2} s^{-1} in both sites.

In Sites A and B, GPP had a marked seasonality increasing from 0.06 and 0.08 kg C m^{-2} month^{-1} respectively in January to 0.36 and 0.47 kg C m^{-2} month^{-1} respectively in June. Thereafter it declined from June to December. The high rates of GPP between May and August (Table 2.1) coincided with the period of highest grass production (Figure 2.2) and LAI as well as high PPFD and better soil aeration (Byrne et al. 2005). Cumulative GPP for 2004 (Table 2.1) was higher in Site B (2.90 kg C m^{-2}) than in Site A (2.14 kg C m^{-2}) although the difference was not as pronounced as the difference in grass production.
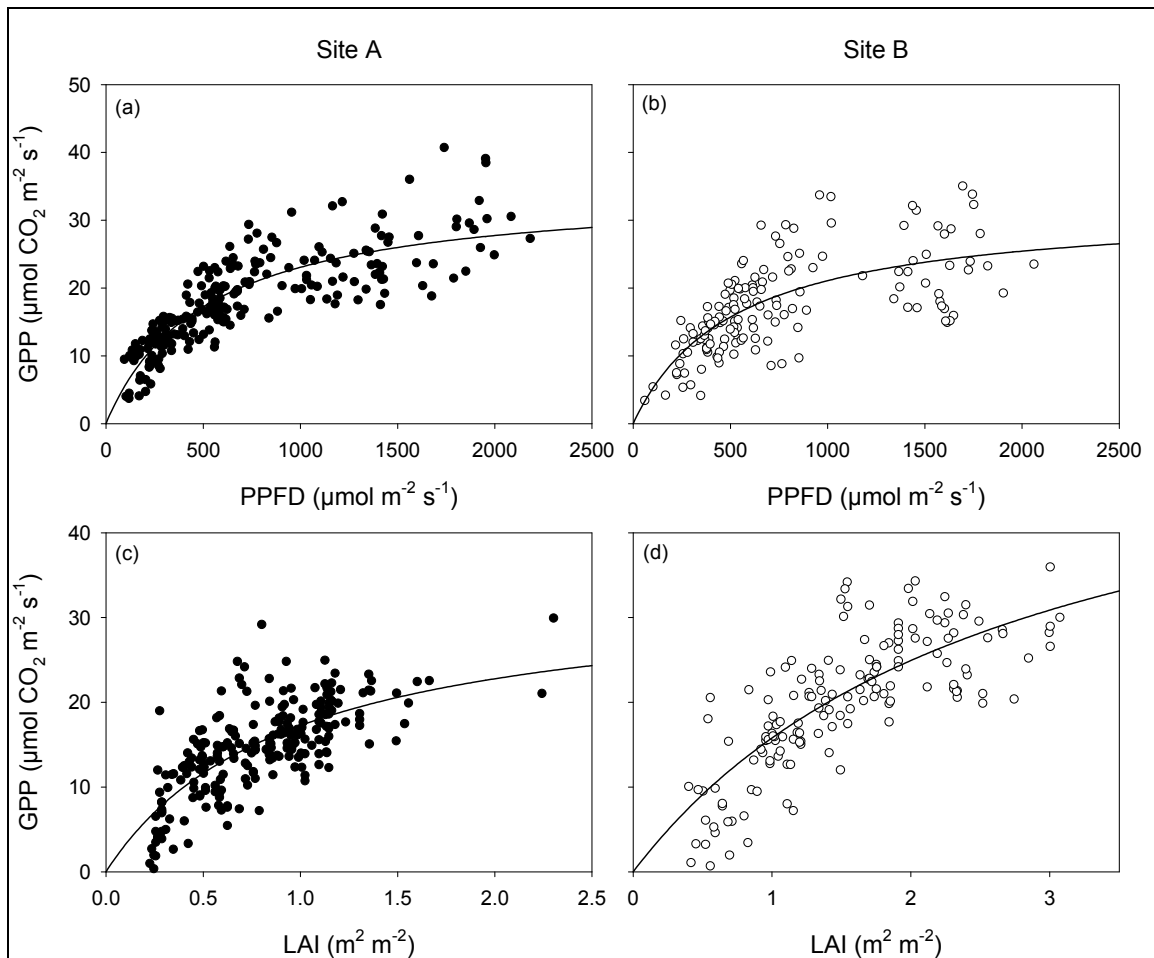
Figure 2.3. (i) Adjusted response of gross primary production (GPP) to photosynthetic photon flux density (PPFD) in (a) Site A and (b) Site B. GPP values were adjusted to LAI = 1.0 m^2 m^{-2} using Equation (1) and the parameter values in Table 1. (ii) Adjusted response of gross primary production (GPP) to leaf area index (LAI) in (c) Site A and (d) Site B. GPP values were adjusted to PPFD = 500 µmol m^{-2} s^{-1} using Equation 1 and the parameter values in Table 1.
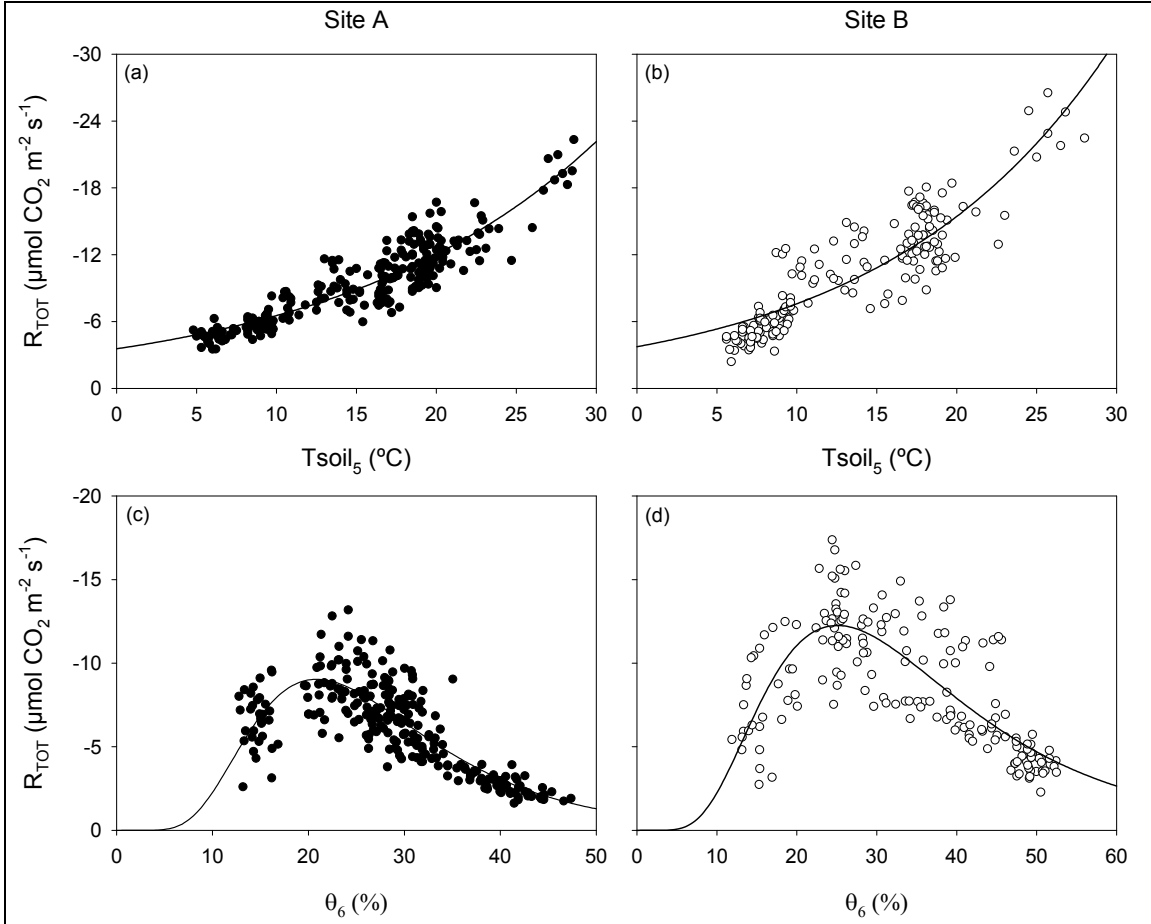
Figure 2.4. (i) Adjusted response of total respiration (R$_{TOT}$) to soil temperature at 5 cm depth (*Tsoil$_5$*) in (a) Site A and (b) Site B. R$_{TOT}$ values were adjusted to soil moisture content in the top 6 cm (θ_6) = 20% using Equation (2) and the parameter values in Table 2. (ii) Adjusted response of R$_{TOT}$ to *Tsoil$_5$* in (c) Site A and (d) Site B. R$_{TOT}$ values were adjusted to *Tsoil$_5$* = 15 ºC using Equation (2) and the parameter values in Table 2.

R$_{TOT}$ varied seasonally in both sites with higher rates occurring in Site B (Table 2.1). The highest R$_{TOT}$ rates occurred during the grass growing season when GPP and consequently R$_{TOT}$ were high. Cumulative R$_{TOT}$ was 1.99 kg C m^{-2} in Site A and 2.52 kg C m^{-2} in Site B (Table 2.1).

NEE was positive (i.e. the site was a net sink for atmospheric CO_2) when GPP exceeded R_{TOT}. In Site A, monthly NEE was positive from March to August (Table 3) and coincided with the period of highest grass growth (Fig. 3). Overall, Site A was estimated to be a sink for 0.15 kg C m^{-2} in 2004 (Table 2.1). NEE was higher in Site B than in Site A and was positive from March to August. Overall Site B was estimated to be a sink for 0.38 kg C m^{-2} in 2004 (Table 2.1).

Table 2.1. Monthly and total values (kg C m^{-2}) of gross primary productivity (GPP), total respiration (R_{TOT}) and net ecosystem exchange (NEE) in Sites A and B during 2004.

	Site A			Site B		
Month	**GPP**	**R_{TOT}**	**NEE**	**GPP**	**R_{TOT}**	**NEE**
January	0.06	-0.09	-0.03	0.08	-0.11	-0.03
February	0.09	-0.10	-0.01	0.12	-0.12	0.00
March	0.14	-0.10	0.04	0.20	-0.13	0.07
April	0.19	-0.12	0.07	0.26	-0.16	0.10
May	0.31	-0.21	0.10	0.38	-0.28	0.10
June	0.36	-0.26	0.10	0.47	-0.29	0.18
July	0.31	-0.26	0.05	0.43	-0.32	0.11
August	0.27	-0.25	0.02	0.38	-0.32	0.06
September	0.18	-0.21	-0.03	0.26	-0.30	-0.03
October	0.12	-0.14	-0.02	0.17	-0.18	-0.01
November	0.05	-0.14	-0.08	0.09	-0.18	-0.10
December	0.05	-0.11	-0.06	0.07	-0.13	-0.07
Total	2.14	-1.99	0.15	2.90	-2.52	0.38

2.4 Discussion

The cumulative grass production in Site B is similar to the typical grass production rate of 0.65-0.75 kg C m^{-2} yr^{-1} in the south west of Ireland (Brereton 1995). However the cumulative grass production in Site A is approximately half of that in Site B. This is surprising given that reseeded *L. perenne* swards have similar grass production rates to permanent swards (Keating et al. 1995). The lower LAI in Site A suggests that this is due to lower tiller density.

The annual NEE values in Sites A and B of 0.15 and 0.38 kg C m^{-2} yr^{-1} respectively are within the range of those reported elsewhere for *L. perenne* grasslands. Working in the Netherlands,

Schapendonk et al. (1997) and Jacobs et al. (2003) found NEE values of 0.30 kg C m^{-2} yr^{-1}.and 0.68 kg C m^{-2} yr^{-1}.

These estimates of NEE assume that the grass was not removed from the sites. However if the cumulative grass production (Fig. 3b) is subtracted from the NEE (Table 2.1) the NEE is reduced to -0.23 and -0.32 kg C m^{-2} a^{-1} in Sites A and B respectively. Under typical grassland management the grass would either be consumed on site by grazing animals or harvested and conserved as winter feed. Some of this C would be returned to the site either in animal excreta or during slurry spreading. Further studies on the farm level C balance and below ground C transfer and soil C cycling are required to ascertain the NEE of such grassland sites.

2.5 Conclusions

This study shows that intensively managed and fertilized temperate grassland has the potential to act as a C sink. Chamber based CO_2 flux measurements found that GPP is strongly related to PPFD and LAI. R_{TOT} is both soil temperature and soil moisture dependent. These measurements provide a basis for developing statistical response functions that can be used to reconstruct seasonal and annual fluxes of GPP and R_{TOT}. The estimated NEE of 0.15 and 0.38 kg C m^{-2} yr^{-1} in Sites A and B respectively is within the range of those reported elsewhere for L. perenne grasslands. Although the results of this study suggest that increased productivity may lead to higher NEE the influence of management factors such as grass cutting and grazing on grassland CO_2 exchange, as well as investigation of the farm level C balance are required to determine the precise NEE.

3 Partitioning of respiration in an intensively managed grassland

3.1 Objectives

Carbon fluxes in terrestrial ecosystems are dominated by two processes: (1) biochemical uptake of CO_2 through photosynthesis and (2) biochemical loss of CO_2 through respiration (R_{TOT}). R_{TOT} is the principal pathway of C loss from the ecosystem to the atmosphere and is a major determinant of the net uptake of C from the atmosphere. R_{TOT} is composed of autotrophic (R_A) and heterotrophic (R_H) respiration. R_A is produced by growth associated processes that require respiration (Hanson et al. 2000; Hogberg et al. 2001). R_H is derived from microbial decomposition of recently produced organic matter (Giardina et al. 2004; Trumbore 2000). Understanding R_{TOT} and its component processes is therefore vital to understanding C cycling and sequestration in soils.

The overall aim of the study is to partition R_{TOT} into R_H and R_A. This is achieved as follows: (1) analyse the effect of air temperature, soil moisture content and leaf area index on R_{TOT} and the influence of soil temperature and soil moisture content on R_H; (2) combine these effects into separate empirical models for R_{TOT} and R_H and; (3) use these models to determine temporal trends in R_{TOT} and R_H and to assess the relative contribution of R_H and R_A to R_{TOT}.

3.2 Materials and methods

3.2.1 Site description

The study was located in Site B as used for the sub-project described in Chapter 2.

3.2.2 Experimental design

This subproject utilized the dataset collected at Site B and as described in Chapter 2 with the following additional measurements being taken. Two additional sample plots were installed in February 2004 and these were kept free of grass by regular clipping. A further three additional plots were installed in January 2005 and also kept free of grass by regular clipping.

3.2.3. *Measurement of CO_2 fluxes*

CO_2 fluxes were measured in these grass free plots one or two times per week during the period March 2004 to March 2005. Measurements were made as descried earlier (Section 2.2.3).

3.2.4 Modelling of CO_2 fluxes

In order to identify the major factors controlling R_{TOT} and R_H and to integrate these fluxes on a daily, seasonal and annual basis the relationships between the flux rate and the controlling factors were determined. For both R_{TOT} and R_H, a subsample of 70% of the flux measurements was randomly selected for regression modelling and the remaining 30% were used for validation of the models.

R_{TOT} was related to T_{air} using an exponential function, to θ_6 using an exponential type equation and to LAI using a linear equation. These relationships were incorporated in a statistical response function of the following form:

$$R_{TOT} = a_1 \exp(a_2 T_{air}) \exp\left[-0.5 \left(\frac{\ln\left(\frac{\theta_6}{a_3}\right)}{a_4} \right)^2 \right] (LAI + a_5)$$ (3.1)

R_H was related to $T_{soil,5}$ using an exponential function and to θ_6 using an exponential type equation. These relationships were incorporated in a statistical response function of the following form:

$$R_H = a_1 \exp(a_2 T_{soil,5}) \exp\left[-0.5 \left(\frac{\ln\left(\frac{\theta_6}{a_3}\right)}{a_4} \right)^2 \right]$$ (3.2)

The parameters (a_i) of the statistical response functions for R_{TOT} and R_H were estimated using the non-linear Levenberg - Marquardt technique. This technique uses an iterative approach to minimise the sum of squares error function, where the initial parameters are adjusted until the most likely parameter values are reached when no further reduction in the sum of squares takes place (Motulsky and Christopoulos 2003). For details of the parameters of Equations 1 and 2 see Byrne and Kiely (2006).

R_{TOT} and R_H dynamics during the 2004 were reconstructed by including the half-hourly environmental data from the meteorological station into the statistical response functions for R_{TOT} and R_H (Equations 1 and 2 respectively). Average daily LAI was included in the R_{TOT} function and was estimated as follows: the average daily grass height was estimated by linear interpolation of the weekly measured grass height. These daily grass heights were converted to daily LAI using the grass height-LAI relationship described in Chapter 2 (Section 2.2.2). Grass height was not measured outside of the grass growing season and therefore LAI was assumed to be 1.0 during this time (Figure 3.4).

R_A (μmol CO_2 m^{-2} s^{-1}) was calculated half-hourly with the equation:

$$R_A = R_{TOT} - R_H$$ (3.3)

R_{TOT}, R_H and R_A values were integrated over the study period and daily and annual totals calculated.

3.3 Results and discussion

R_{TOT} was controlled by T_{air} (Figure 3.1a), θ_6 (Figure 3.2a) and LAI (Figure 3.3). The maximum R_{TOT} occurred when θ_6 was 24.4%. Equation 1 explained 87% of the variation in R_{TOT}. There was good agreement between the measured and modelled R_{TOT} although the R_{TOT} model (Equation 3.1) overestimates R_{TOT} fluxes below 5 μmol CO_2 m^{-2} s^{-1} (Byrne and Kiely 2006). In the 30% independent data set Equation 3.1 explained 91% of the variation in R_{TOT} and there was good agreement between measured and modelled data (Figure 5a).

R_H was related to $T_{soil,5}$ (Figure 3.2b) and θ_6 (Figure 3.3b) and maximum R_H occurred when θ_6 was 27.8%. Equation 2 explained 84% of the variation in R_H and there was good agreement between measured and modeled R_H (Byrne and Kiely 2006). In the 30% independent data set Equation 3.1 explained 87% of the variation in R_H and there was good agreement between measured and modelled data.

There was a marked seasonal variation in R_{TOT} (Figure 3.4) with low values in winter (~4 g C m^{-2} day^{-1}) when the air temperature was lower (Figure 3.4a) and the soil moisture content was higher (Figure 3.4c). R_{TOT} increased during the grass growing season (~10 g C m^{-2} day^{-1}) as the soil became warmer (Figure 3.4a) and drier (Figure 3.4c) and LAI increased (Figure 3.4d). R_H has a similar seasonal trend to R_{TOT} but was consistently lower. Wintertime values of R_H were ~2 g C m^{-2} day^{-1} and increased to (~5 g C m^{-2} day^{-1} in summertime (Figure 3.4e).

The response of respiration to increasing soil moisture content was observed to follow the three phases identified by Reichstein et al. (2003); (1) in dry conditions metabolic activity increases strongly with increasing soil moisture content (Howard and Howard 1993) (2) At near optimum soil moisture content changes in soil moisture have little effect on respiration (Qi and Xu 2001) and (3) when the moisture content exceeds field capacity and the soil begins to saturate respiration is inhibited (Davidson et al. 2000) due to the inhibition of aerobic decomposition by oxygen deficiency (Skopp et al. 1990). Based on the equation developed by Saxton et al. (1986) the soil is at field capacity when the volumetric soil moisture content is 26%. This is very close to the soil moisture content at which maximum R_{TOT} and R_H occurs (Figure 3.2).

The results show that as LAI increased so did the rate of R_{TOT}. Given that a large proportion of R_{TOT} is derived from R_A this suggests that respiration is linked to photosynthesis. Evidence for this is provided by Kuzyakov and Cheng (2001) who found that root–derived CO_2 was sensitive to changes in photosynthesis.
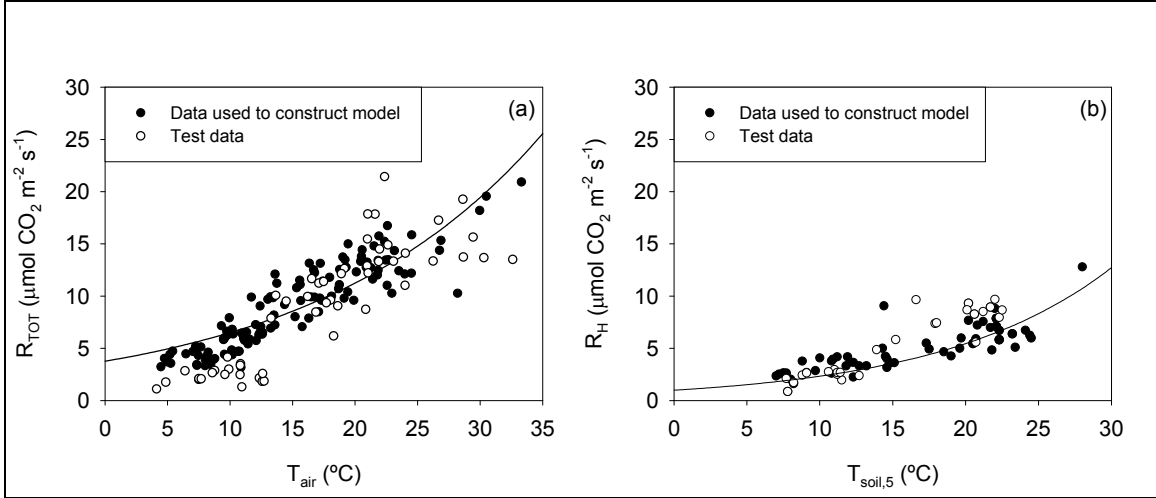
Figure 3.1. (a) Dependence of total respiration (R_{TOT}) on air temperature ($T_{soil,5}$) and (b) dependence of heterotrophic respiration (R_H) on soil temperature at 5 cm depth ($T_{soil,5}$). Using Equation 1 and the parameter values in Table 1, the measured total respiration values were adjusted to soil moisture content in the top 6 cm (θ_6) = 20% and LAI = 1 m^2 m^{-2}. Using Equation 2 and the parameter values in Byrne and Kiely (2006), the measured heterotrophic respiration values were adjusted to soil moisture content in the top 6 cm (θ_6) = 20%.
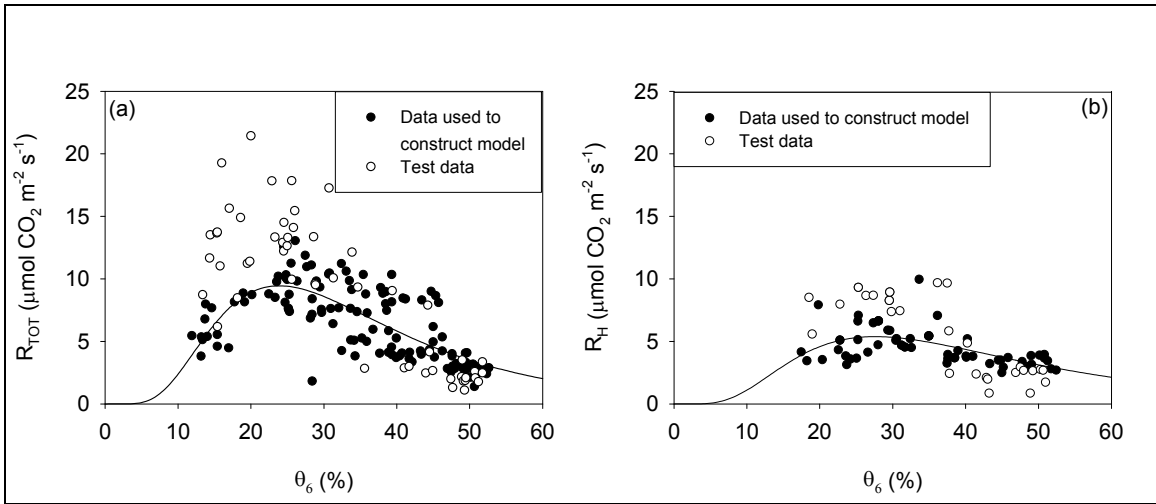
Figure 3.2. Dependence of (a) total respiration (R_{TOT}) on soil moisture content in the top 6 cm (θ_6) and, (b) dependence of heterotrophic respiration (R_H) on soil moisture content in the top 6 cm (θ_6). Using Equation 1 and the parameter values in Byrne and Kiely (2006), the measured total respiration values were adjusted to air temperature (T_{air}) = 15 ºC and LAI = 1 m^2 m^{-2}. Using Equation 2 and the parameter values in Table 1, the measured heterotrophic respiration values were adjusted to soil temperature at 5 cm depth ($T_{soil,5}$) = 15 ºC.

13
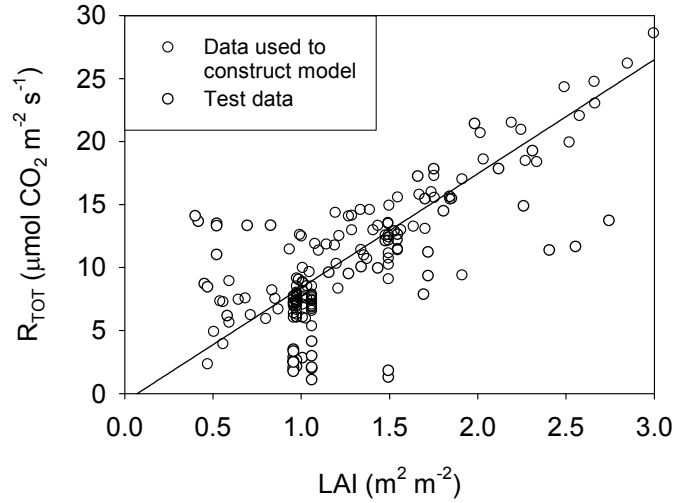
Figure 3.3. Dependence of total respiration (R_{TOT}) on leaf area index (LAI). Using Equation 1 and the parameter values in Table 1, the measured total respiration values were adjusted to air temperature (T_{air}) = 15 ºC and soil moisture content in the top 6 cm (θ_6) = 20%.

The range of values of R_{TOT} (1 to 22 µmol CO_2 m^{-2} s^{-1}) and R_H (1 to 13 µmol CO_2 m^{-2} s^{-1}) observed in this study compare well with other studies in grasslands. Working in a northern temperate grassland, Flanagan and Johnson (2005) measured R_{TOT} values of ~4 to 32 µmol CO_2 m^{-2} s^{-1} while Craine and Wedin (2002) measured fluxes of ~1 to 16 µmol CO_2 m^{-2} s^{-1} in a Minnesota grassland.
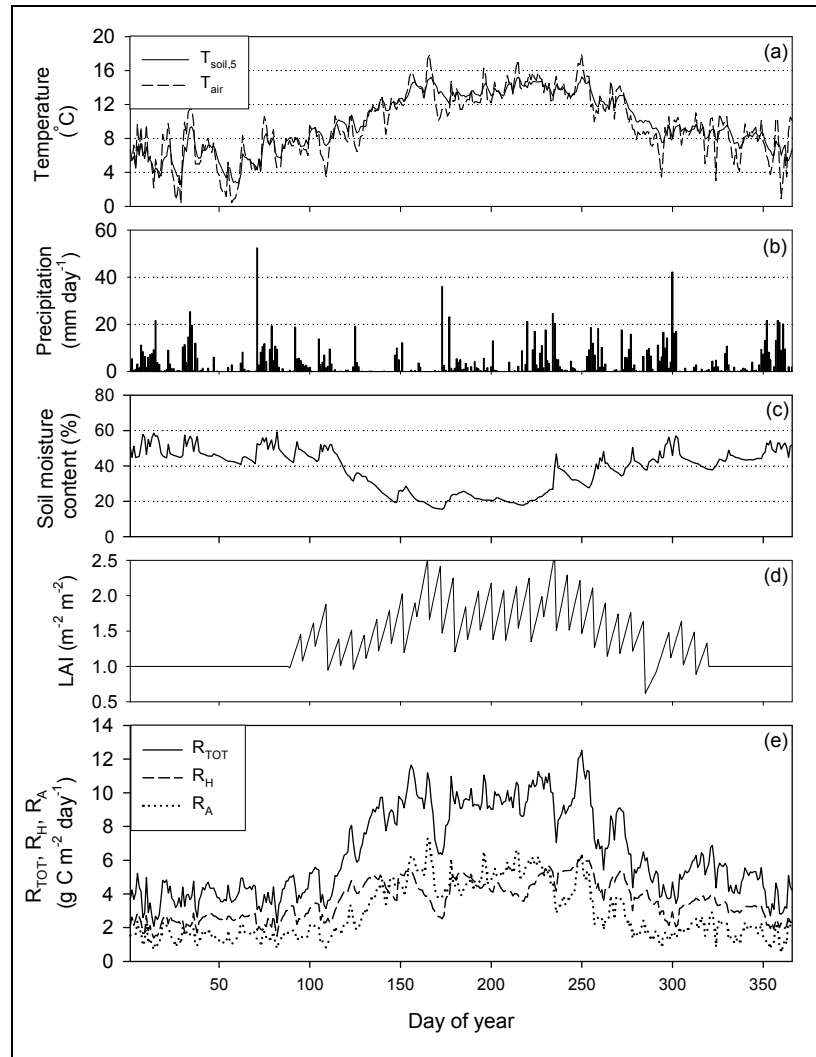
Figure 3.4. (a) Average daily soil temperature at 5 cm depth ($T_{soil,5}$) and air temperature (T_{air}), (b) daily precipitation, (c) average daily volumetric soil moisture content at 5 cm depth (θ_5) and (d) daily leaf area index, (e) average daily total respiration (R_{TOT}), heterotrophic respiration (R_H) and autotrophic respiration (R_A), during 2004.

3.4 Conclusions

In this study we developed empirical regression models of R_{TOT} and R_H in intensively managed grassland. Air temperature, soil moisture content and leaf area index are the most important factors controlling R_{TOT}. The principal factors controlling R_H are soil temperature and soil moisture content. R_A accounted for 50% of R_{TOT} during the summer months and approximately 38% during the rest of the year.

4. Carbon sequestration determined using farm carbon balance and eddy covariance

4.1 Objectives

In this sub-project the objectives are as follows: (1) quantify the farm scale C balance during 2004 for two dairy farms in South West Ireland by combining results of on-site eddy covariance (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.

4.2 Site Description

This study was located at the Celticflux grassland site in Cork, south west Ireland (Jaksic et al. 2006). This is the same site as used for the studies described in Chapter 2 and 3. In addition to the description provided in Chapter 2 the following information is pertinent to this subproject. The dominant grass species is perennial ryegrass (*Lolium perenne* L.) with smaller amounts of Meadow foxtail (*Alopecurus pratensis* L.) and Yorkshire-fog (*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 five 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} yr^{-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 for the measurement of CO_2 and N_2O fluxes. For a full description of the EC systems, 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.

4.3 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' (Figure 2). We assume that the values of net ecosystem exchange (NEE) measured by the EC tower located on site not only captures 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.

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.

Figure 4.1. Schematic representation of the farm scale C balance. Carbon inputs are represented by solid arrows and C outputs by broken arrows.
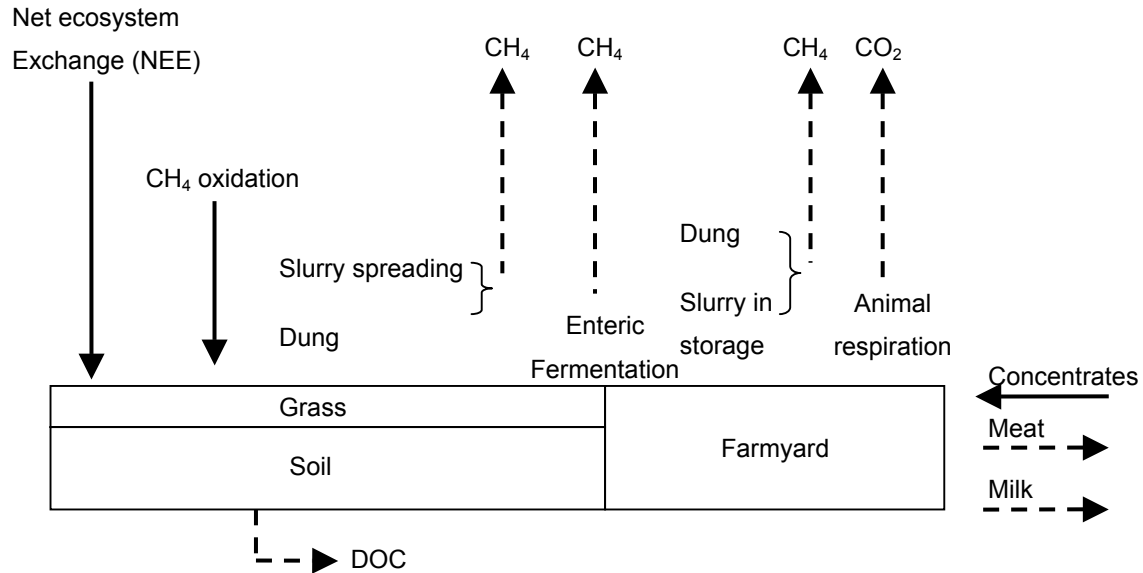
4.4 Farm data

Two farms were chosen for the case study (Table 4.1). 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. A similar approach was adopted at the same site by Lawton et al. (In press) and Leahy et al. (2004). All calves are reared for either replacement cows or beef consumption. Animals reared for beef consumption are sold off farm at two years old. The dominant activity is dairying and management practices are similar in both farms. The sign convention is as follows: C inputs are positive and C outputs are negative. The C inputs and outputs were calculated as follows:

Table 4.1. Summary of the two case study farms. Livestock unit conversion rates (LU) are provided.

Farm	Area (ha)	Cows	Calves	Bullocks	Heifers	Stocking rate (LU ha^{-1})	Milk production (L cow^{-1})
A	36	35	35	28	-	1.7	5001
B	42.3	47	45	27	7	1.9	6364
LU		1.0	0.2	0.7	0.7		

4.5 Carbon inputs

4.4.1 Net ecosystem exchange

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

4.5.2 Concentrates

Concentrate feed is used as additional feed during the winter housing period 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 three weeks of the grazing season. Bullocks received 4.60 kg day^{-1} for a period of three 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 three 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 four 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%.

4.5.3 CH$_4$ oxidation by soils

The CH$_4$ oxidation capacity of soils is assumed to be 1.5 kg C ha^{-1} yr^{-1} (Boeckx and Van Cleemput 2001).

4.6 Carbon outputs

4.6.1 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%.

4.6.2 Meat

All bullocks and heifers are reared over a two 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%. Based on 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%.

4.6.3 CH_4 emissions from livestock production

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

4.6.4 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} hr^{-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.

4.6.5 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).

4.6.6 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). In addition to the winter housing period cows are assumed to spend three hours 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).

4.6.7 CH_4 – slurry spreading

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

4.6.8 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 ($\pm$ 0.25) kg CO_2 day^{-1} (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 ($\pm$ 0.2) and 3.50 ($\pm$ 0.2) kg CO_2 day^{-1} respectively.

4.6.9 Dissolved organic carbon (DOC) in streamwater

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

4.7 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.

4.8 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 kgN^{-1} (Houghton et al. 2000). The N_2O emission from the fields was provided by the EC measurements.

4.9 Results

Carbon inputs are similar in both farms A and B. This is a reflection of the similarity in the management of both farms (Table 4.1). The EC measurements show that the non-farmyard areas of both farms (i.e. fields) are net sinks for atmospheric C with NEE being 2.9 $\pm$ 0.5 t C ha^{-1}. After NEE, carbon in concentrate feed is the most important source of C input in both farms.

Animal respiration during the housing period is the largest output of C, contributing 60% and 57% to total C outputs in Farms A and B respectively (Table 4.2). Although respiration by cattle during the grazing season is probably a significant source of C it is assumed to be captured by the EC measurements. Milk is the second largest source of C outputs contributing 22% and 28% to total C outputs in Farms A and B respectively. CH_4 produced by enteric fermentation in similar in both farms. CH_4 emissions due to slurry spreading are slightly higher in Farm A (5.7%) than in Farm B (4.1%). DOC accounts for 7.5% and 6.4% of C outputs in Farms A and B respectively. Carbon output as meat, CH_4 emissions from dung (both in the farmyard and fields) and slurry in storage are minor sources of C output (Table 4.2).

Combining the farm C balance components and EC measurements indicates that both Farms are net sinks for ~2 t C ha^{-1} yr^{-1} (Table 4.2).

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 4.3). Enteric fermentation is the largest contributor to the positive radiative forcing accounting for 30% and 32% in farms A and B respectively (Table 3). Animal respiration (during the winter housing period and during milking time for cows), CH_4 emissions from slurry spreading and N_2O emissions are also major contributors to positive radiative forcing.

When emissions of CH4 and N2O are considered (Table 4.3) the C sink of farms A and B are is reduced to 0.90 and 1.25 t CO_2 equiv. ha^{-1} respectively.

Table 4.2 Carbon balance of farms A and B in 2004. Uncertainty estimates are given with C inputs and outputs that contribute more than 1 % to total C inputs and outputs respectively.

	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

Table 4.3 Net radiative forcing of farms A and B in 2004. 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).

	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

4.10 Discussion

By quantifying the farm level C balance this study suggests that these grass based dairy farms are C sinks. Photosynthesis is the dominant pathway of C input is and the measured NEE is similar to the value of 3 t C ha^{-1} yr^{-1} reported for *L. perenne* grassland in the Netherlands (Schapendonk et al. 1997). 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 a major source of C inputs (Table 4.2). However a number of reasons may be advanced for not including it in the farm C balance. Firstly, it is often produced in a location beyond the farm boundary and involves an export of C from the location where it is produced. This may impact negatively on the C sequestration potential of these ecosystems. For example, Hollinger et al. (2005) investigated the C budget of a maize and soybean rotational system and found that at a field level maize and soybean were sink for 5.76 t C ha^{-1} yr^{-1} and 0.33 t C ha^{-1} yr^{-1}. However, at regional scale, grain consumption reduced the C sink in maize to 1.84 t C ha^{-1} yr^{-1} and converted soybean to a C source of 0.94 t C ha^{-2} yr^{-1}. This suggests, consideration 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.

Given the importance of respiration by cattle during the winter housing period, there is a need for studies to measure the respiration rates of different kinds of livestock.

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.

Nieveen et al. (2005) using a similar approach to that applied here, found that grazed pasture on a drained peat soil in New Zealand was a net source of 1.06 $\pm$ 0.5 t C ha^{-1} yr^{-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} yr^{-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 (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} yr^{-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. There is a need for further studies to investigate soil C cycling in grassland soils and C cycling of C at farm level through grass harvesting and manure management.

4.11 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} yr^{-1}. Assessment of net GWP finds that this grassland is a sink for ~1 t CO_2 equiv. ha^{-1} yr^{-1}. This sink was not partitioned between the amounts sequestered in the soil and the vegetation. 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.

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