epa Research
Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Report No. **227**

GHG Fluxes from Terrestrial Ecosystems in Ireland

Authors: Gerard Kiely, Paul Leahy, Ciaran Lewis, Matteo Sottocornola, Anna Laine and Ann-Kristin Koehler

Roinn Cumarsáide, Gníomhaithe ar son na hAeráide & Comhshaoil
Department of Communications, Climate Action & Environment

www.epa.ie

ENVIRONMENTAL PROTECTION AGENCY

The Environmental Protection Agency (EPA) is responsible for protecting and improving the environment as a valuable asset for the people of Ireland. We are committed to protecting people and the environment from the harmful effects of radiation and pollution.

The work of the EPA can be divided into three main areas:

Regulation: *We implement effective regulation and environmental compliance systems to deliver good environmental outcomes and target those who don't comply.*

Knowledge: *We provide high quality, targeted and timely environmental data, information and assessment to inform decision making at all levels.*

Advocacy: *We work with others to advocate for a clean, productive and well protected environment and for sustainable environmental behaviour.*

Our Responsibilities

Licensing

We regulate the following activities so that they do not endanger human health or harm the environment:

- waste facilities *(e.g. landfills, incinerators, waste transfer stations)*;
- large scale industrial activities (*e.g. pharmaceutical, cement manufacturing, power plants)*;
- intensive agriculture *(e.g. pigs, poultry)*;
- the contained use and controlled release of Genetically Modified Organisms *(GMOs)*;
- sources of ionising radiation *(e.g. x-ray and radiotherapy equipment, industrial sources)*;
- large petrol storage facilities;
- waste water discharges;
- dumping at sea activities.

National Environmental Enforcement

- Conducting an annual programme of audits and inspections of EPA licensed facilities.
- Overseeing local authorities' environmental protection responsibilities.
- Supervising the supply of drinking water by public water suppliers.
- Working with local authorities and other agencies to tackle environmental crime by co-ordinating a national enforcement network, targeting offenders and overseeing remediation.
- Enforcing Regulations such as Waste Electrical and Electronic Equipment (WEEE), Restriction of Hazardous Substances (RoHS) and substances that deplete the ozone layer.
- Prosecuting those who flout environmental law and damage the environment.

Water Management

- Monitoring and reporting on the quality of rivers, lakes, transitional and coastal waters of Ireland and groundwaters; measuring water levels and river flows.
- National coordination and oversight of the Water Framework Directive.
- Monitoring and reporting on Bathing Water Quality.

Monitoring, Analysing and Reporting on the Environment

- Monitoring air quality and implementing the EU Clean Air for Europe (CAFÉ) Directive.
- Independent reporting to inform decision making by national and local government *(e.g. periodic reporting on the State of Ireland's Environment and Indicator Reports)*.

Regulating Ireland's Greenhouse Gas Emissions

- Preparing Ireland's greenhouse gas inventories and projections.
- Implementing the Emissions Trading Directive, for over 100 of the largest producers of carbon dioxide in Ireland.

Environmental Research and Development

- Funding environmental research to identify pressures, inform policy and provide solutions in the areas of climate, water and sustainability.

Strategic Environmental Assessment

- Assessing the impact of proposed plans and programmes on the Irish environment *(e.g. major development plans)*.

Radiological Protection

- Monitoring radiation levels, assessing exposure of people in Ireland to ionising radiation.
- Assisting in developing national plans for emergencies arising from nuclear accidents.
- Monitoring developments abroad relating to nuclear installations and radiological safety.
- Providing, or overseeing the provision of, specialist radiation protection services.

Guidance, Accessible Information and Education

- Providing advice and guidance to industry and the public on environmental and radiological protection topics.
- Providing timely and easily accessible environmental information to encourage public participation in environmental decision-making *(e.g. My Local Environment, Radon Maps)*.
- Advising Government on matters relating to radiological safety and emergency response.
- Developing a National Hazardous Waste Management Plan to prevent and manage hazardous waste.

Awareness Raising and Behavioural Change

- Generating greater environmental awareness and influencing positive behavioural change by supporting businesses, communities and householders to become more resource efficient.
- Promoting radon testing in homes and workplaces and encouraging remediation where necessary.

Management and structure of the EPA

The EPA is managed by a full time Board, consisting of a Director General and five Directors. The work is carried out across five Offices:

- Office of Environmental Sustainability
- Office of Environmental Enforcement
- Office of Evidence and Assessment
- Office of Radiation Protection and Environmental Monitoring
- Office of Communications and Corporate Services

The EPA is assisted by an Advisory Committee of twelve members who meet regularly to discuss issues of concern and provide advice to the Board.

EPA RESEARCH PROGRAMME 2014–2020

GHG Fluxes from Terrestrial Ecosystems in Ireland

(CCRP08Proj-1.1A)

EPA Research Report

Prepared for the Environmental Protection Agency

by

University College Cork and Waterford Institute of Technology

Authors:

Gerard Kiely, Paul Leahy, Ciaran Lewis, Matteo Sottocornola, Anna Laine and Ann-Kristin Koehler

ENVIRONMENTAL PROTECTION AGENCY
An Ghníomhaireacht um Chaomhnú Comhshaoil
PO Box 3000, Johnstown Castle, Co. Wexford, Ireland

Telephone: +353 53 916 0600 Fax: +353 53 9160699
Email: info@epa.ie Website: www.epa.ie

ACKNOWLEDGEMENTS

This report is published as part of the EPA Research Programme 2014–2020. The programme is financed by the Irish Government. It is administered on behalf of the Department of Communications, Climate Action and Environment by the EPA, which has the statutory function of co-ordinating and promoting environmental research.

We would like to thank Mr Philip O'Brien and Dr Frank McGovern of the EPA for their continuous support throughout the project. Information contained in this report has drawn extensively, and in some cases verbatim, from theses and papers published by the Hydromet Research Group over the past decade.

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

EPA RESEARCH PROGRAMME 2014–2020

Published by the Environmental Protection Agency, Ireland

ISBN: 978-1-84095-742-6 January 2018

Price: Free Online version

Project Partners

Professor Gerard Kiely
The Hydromet Research Group
The Centre for Hydrology, Micrometeorology and Climate Change
Department of Civil and Environmental Engineering
University College Cork
College Road
Cork
Ireland
Tel: +353 21 490 2965
Email: g.kiely@ucc.ie

Dr Paul Leahy
The Hydromet Research Group
The Centre for Hydrology, Micrometeorology and Climate Change
Department of Civil and Environmental Engineering
University College Cork
College Road
Cork
Ireland
Tel: +353 21 490 2017
Email: paul.leahy@ucc.ie

Dr Matteo Sottocornola
Forestry Department
School of Science and Computing
Waterford Institute of Technology
Waterford
Ireland
Tel: +353 87 175 7192
Email: msottocornola@wit.ie

Contents

List of Figures

List of Tables

Executive Summary

Ireland's land cover and land use is very different from that of most other European countries. The split is approximately 60% grassland; 20% peatland; 10% forests and 10% cropland. Ireland has one of the highest grassland and one of the lowest forest covers of all European countries. Furthermore, Ireland has a unique Atlantic maritime temperate climate – without extremes of heat, cold or precipitation. Ireland also has unique soils with a preponderance of high soil organic carbon (SOC) type soils. These unique combinations enable Ireland to be one of the most productive countries in the world, as measured by gross primary productivity (GPP), in grassland or forest covers.

The Environmental Protection Agency (EPA) funded the establishment of three greenhouse gas (GHG)-flux eddy covariance (EC) stations in 2002: one at the Dripsey grassland site; one at the Glencar blanket peatland site; and one at the Wexford grassland site. As of 2017, none of these three sites is currently operational. In 2006 with funding from the EPA and Coford, we established an EC station at the recently planted Dripsey forest site, which is adjacent to the Dripsey grassland site. In this report we detail the recent carbon flux results from three sites: the Dripsey grassland site, the Dripsey forest site and the Glencar peatland site.

The Dripsey grassland site is typical of the grasslands found in the southern half of Ireland, with a mix of fields for grazing and silage harvesting. The livestock density on site has ranged from approximately 1.5 to 2.5 livestock units (LU) over the past decade with a mix of dairy and beef cattle. Nitrogen (N) fertiliser application has decreased in recent years from approximately 350 kg N ha^{-1} yr^{-1} to 150 kg N ha^{-1} yr^{-1}. Using the EC method, we measured the carbon dioxide (CO_2) net ecosystem exchange (NEE) between the ecosystem and the atmosphere. For the years 2003 to 2011, the mean of CO_2 flux was a sink of –2.2 t C ha^{-1} yr^{-1} and the annual range was –0.71 to –3.19 t C ha^{-1} yr^{-1}. The meterological conditions during these years varied from wet years in which the annual rainfall exceeded 1600 mm to relatively dry years in which the annual rainfall was less than 900 mm. This study shows that intensively managed and fertilised grassland in the Irish humid temperate climate sequesters carbon to the soil. Although there were large differences in soil moisture status between the different years, this was not responsible for the interannual difference in NEE because the soil moisture status exceeded wilting point at all times during the years studied, ensuring that the vegetation did not experience any water stress. We conclude that this humid grassland was not very sensitive to the precipitation variability. Harvesting reduces NEE in the month of harvesting. However, integrated over the summer harvest period, the effect of harvesting was similar in all years. We conclude that the interannual variation in NEE is of the order of uncertainty of the EC measurements.

Glencar, County Kerry, is the site of a pristine Atlantic blanket bog. In the summer of 2002, the Hydromet Research Group from University College Cork (UCC) set up the EC flux tower for the purpose of measuring the fluxes of CO_2, methane (CH_4) and dissolved organic carbon (DOC). We report on 10 years of measurements. For the 10 years, 2003 to 2012, the annual flux of CO_2, known as the NEE, ranged from –0.32 to –0.79 t C-CO_2 ha^{-1} yr^{-1} with an annual mean of –0.5 t C-CO_2 ha^{-1} yr^{-1} (i.e. uptake or sink). For the 6 years, 2003 to 2008, the annual flux of CH_4 ranged from +0.036 to +0.046 t C-CH_4 ha^{-1} yr^{-1} with an annual mean of +0.041 t C-CH_4 ha^{-1} yr^{-1} (i.e. a source). For the 6 years, 2003 to 2008, the annual flux of DOC ranged from +0.131 to +0.165 t DOC ha^{-1} yr^{-1} with a mean annual of +0.140 t C ha^{-1} yr^{-1} (i.e. a source). Adding the three components of the carbon budget over the 6 years, we found that for 4 of the 6 years, the site was a sink for carbon in the range of –0.241 to –0.656 t C ha^{-1} yr^{-1} and in the two source years the magnitude was +0.028 and +0.086 t C ha^{-1} yr^{-1}. The 6-year average annual carbon uptake at Glencar was –0.297 t C ha^{-1} yr^{-1}, which is similar to reported uptake rates from other high latitude peatland sites, e.g. –0.215 t C ha^{-1} yr^{-1} at Mer Bleue (Canada) and –0.271 t C ha^{-1} yr^{-1} at Degerö Stormyr (Sweden).

Relative to other ecosystems, this blanket bog has a NEE of approximately –0.5 t C-CO_2 ha^{-1} yr^{-1} in comparison with a NEE in Irish grasslands of

~−3 t C-CO_2 ha^{-1} yr^{-1} and a NEE in Irish forestry of ~−10 t C-CO_2 ha^{-1} yr^{-1}. To enable the protection of pristine blanket bog peatlands, a deeper understanding is required of the dynamics of the components of the carbon budget, with a view to modelling future climate change impacts.

The forest site in Dripsey was established in February 2005. It has 20% black alder and 80% ash and saplings of 0.5 m in height. Growth was slow in the first few years with heights achieved of approximately 2 m in 2010 and approximately 3 m in 2011. We report annual EC CO_2 fluxes for 2 years – 2010 and 2011. The mean of 2 years was –1.3 t C ha^{-1} yr^{-1} and the range was –0.46 to –2.12 t C ha^{-1} yr^{-1}. In the first year (2010) of measurements the forest was a small sink for CO_2 and a bigger sink for CO_2 in the second year (2011). As the forest height had reached approximately 5 m by 2015, we expected the CO_2 fluxes to have increased significantly from the –2.12 t C ha^{-1} yr^{-1} achieved in 2011.

A long growing season combined with a plentiful supply of precipitation throughout all seasons and reasonable amounts of sunshine make Ireland one of the most productive eco-regions of the world. In grasslands, the Irish growing season can be as long as 10 months of the year, enabling a grassland management practice of outdoor grazing for almost the full year in the milder southern parts the country. The carbon fluxes in the three ecosystems examined in this study all report sinks in the annual NEE. The Dripsey grassland averaged a NEE in excess of –2.0 t C ha^{-1} yr^{-1}, while the Glencar blanket bog peatland averaged an annual NEE in excess of –0.5 t C ha^{-1} yr^{-1}. The study of the Dripsey afforested grassland site is too short to draw conclusions on its annual NEE, but the second year of the study had a NEE in excess of –2.0 t C ha^{-1} yr^{-1}, with a likelihood that, as the forest matured, the NEE would be increased significantly.

Ireland, through the funding support of the EPA, initiated a GHG flux monitoring programme in 2002. This funding established EC and chamber flux sites on the key ecosystems across Ireland. With this support Ireland was a significant contributor to and beneficiary of two large-scale EU projects, CarboEurope and NitroEurope, that followed in 2005 and 2008. This Irish work has continued for almost a decade through EPA support and has provided input to GHG policy for Ireland. In 2012 the international project Integrated Carbon Observation System (ICOS) was established to bring the monitoring of GHG fluxes of different ecosystems to the next level. This is where instrumentation is being standardised and all data are being fed in real time into central databases across the EU. The EPA represents Ireland at ICOS. However, Ireland has been unable to continue funding flux studies and is now a bystander at ICOS conventions and remains outside the active science progress being made in Europe and across the world. It is now time for Ireland to step up and re-energise GHG flux research, without which it will be difficult to make the case for Ireland at international GHG policy conventions.

1 Introduction

1.1 Aims and Objectives

The aims of this work are:

1. To review the literature on carbon and nitrogen fluxes [carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and dissolved organic carbon (DOC)] in:
   (a) agricultural grasslands;
   (b) blanket peatlands; and
   (c) forestry.
2. To quantify the carbon fluxes (CO_2, CH_4 and DOC) at the University College Cork (UCC)-managed Irish greenhouse gas (GHG) flux sites in:
   (a) an agricultural grassland;
   (b) a blanket peatland; and
   (c) an afforested grassland.
3. To discuss the relevance of these measured/modelled fluxes to Irish GHG emissions/sinks of agricultural ecosystems and to make recommendations on the future direction of research for Irish agricultural lands in the context of the international project: the Integrated Carbon Observation System (ICOS).

1.2 Layout of Report

The EcoGHG project aimed to add value to a number of carbon flux studies previously carried out at the Dripsey, County Cork, grassland; the Glencar pristine blanket bog, County Kerry; and the Dripsey afforested grassland, County Cork. It also aimed to summarise these studies into one report. Chapter 1 includes a literature review of the carbon fluxes of each of these land cover types. Chapter 2 describes the sites at Dripsey and Glencar, the field instrumentation for flux studies and the data processing involved. Chapter 3 presents the results and discussion of fluxes of CO_2, CH_4, and DOC fluxes at each of the sites. A summary discussion of these fluxes and the total carbon budget is presented in Chapter 4. Conclusions and recommendations are detailed in Chapter 5, which is followed by a bibliography of international literature.

1.3 Grasslands – CO_2 and CH_4 Fluxes

Grasslands cover approximately 19% of the lands of the EU-27. Ireland, with a land area of 6.9 million ha, has 4.2 million ha under agriculture with 3.36 million ha devoted to grass (silage, hay and pasture), 0.46 million ha for rough grazing and 0.38 million ha allocated to crop production. Thus grassland in permanent or temporary management accounts for close to 60% of Irish land cover.

In this report, we consider carbon and nitrogen trace gas fluxes of CO_2 and CH_4. Grasslands (as an ecosystem) exchange carbon as CO_2 between the soil/grass ecosystem and the atmosphere through photosynthesis and respiration. Furthermore, grazing animals produce emissions of both CH_4 and CO_2 from digestion of grass/fodder. N_2O is emitted from grassland soils mainly as a result of the application of artificial nitrogen fertilisers and slurry and of urine deposition from grazing animals. Therefore, there are two budgets that we are interested in: the first is the carbon (C) budget (CO_2 and CH_4); and the second is the GHG budget (CO_2, CH_4 and N_2O). The net ecosystem exchange (NEE) of CO_2, or the carbon flux, is simply the exchange of CO_2 between the soil/grass ecosystem and the atmosphere (through photosynthesis and respiration) and for a *natural* grassland (as opposed to managed) is written as:

$$NEE = R_h - NPP + R_{animal} \qquad (1.1)$$

Typically, NEE is presented in units of $g\,C\,m^{-2}\,yr^{-1}$, that is, in terms of the amount of elemental carbon and not CO_2. R_h is heterotrophic respiration, *NPP* is net primary productivity, and R_{animal} is the respiration from grazing animals. The last is typically of the order of 5% and is often ignored in the literature (Chang *et al*., 2015a,b). Note that the sign convention for NEE is minus (or negative) where the flux of carbon is towards the surface (photosynthesis) and plus (or positive) where the flux is away from the surface (respiration). So a negative NEE is a sink and a source is positive. This is consistent with meteorological sign conventions. We typically measure these entities in $g\,C\text{-}CO_2\,m^{-2}\,yr^{-1}$ [1] or $t\,C\text{-}CO_2\,m^{-2}\,yr^{-1}$ (g being grams and t being tonnes). NEE (without animals) and $NEE–R_{animal}$ (with animals) can be directly measured using the field methodologies of eddy covariance (EC) or with greater uncertainty using chamber methods. The carbon budget (at farm level for managed grassland) is also termed the net biome productivity (NBP), again in units of carbon and not of CO_2, and includes the imports and exports of organic carbon and losses of methane and is defined as:

$$NBP = -NEE + F_{input} - F_{silage} - F_{milk/meat} - F_{CH_4} - F_{DOC} \quad (1.2)$$

where the F_{input} term is for carbon flux input (from outside the farm or ecosystem) to the grassland as manure, slurry or animal food concentrates; F_{silage} is the carbon removal (lost) from the farm/ecosystem as silage/harvest; $F_{milk/meat}$ is the carbon removed/lost from the farm/ecosystem as milk or animal meat; F_{CH_4} is the carbon lost as CH_4 emissions from the grazing animal; and F_{DOC} is the carbon lost as DOC (in streams/rivers). NBP is the total rate of accumulation of carbon to the grassland ecosystem, where a sink has a positive value and an emission has a negative value.

The GHG budget is the combination of carbon (in CO_2 and CH_4) and nitrogen (as N_2O). While we can make a budget of carbon (in CO_2 and CH_4), we cannot simply add carbon and nitrogen directly. We write the net GHG exchange (NGHGE) in terms of the global warming potential (GWP) of each gas for a 100-year time horizon (IPCC, 2013). The flux of CH_4 and N_2O is generally away from the surface and, therefore, is a source and is positive. The NGHGE is negative if a sink and positive if a source. We consider the NGHGE of the grassland ecosystem only (similar to equation 1.1) and not as the farm budget (as in equation 1.2):

$$NGHGE = NEE + F_{CH_4} \times GWP_{CH_4} + F_{N_2O} \times GWP_{N_2O} \quad (1.3)$$

where GWP_{CH_4} is 28 and GWP_{N_2O} is 265. This is akin to the concept of CO_2 equivalents. F_{CH_4} is the flux of methane and F_{N_2O} is the flux of nitrous oxide.

There are alternative approaches to the analysis of GHG budgets, for example considering the control volume at the farm scale or at the farm gate as in Byrne *et al*. (2009). When we examine the GHG budget at the farm scale/farm gate we take into consideration all the parameters in the NGHGE (equation 1.3), the proportion of harvested silage that is respired by cattle (in sheds) and the proportion of ingested carbon (from silage) that is emitted as CH_4.

There are several different methodologies of determining the ecosystem fluxes of CO_2, CH_4 and N_2O including:

1. The meteorological field measurement system (scale ~1 km^2) for EC instruments: this system now exists for high-frequency measurement of not only CO_2 but also CH_4 and N_2O. These systems (FLUXNET) now span the globe in forest, grassland and peatland ecosystems delivering annual and multi-annual fluxes of the three key GHGs.
2. The small-scale (1 m^2) system of chamber measurements: although the infrastructure is low cost, the labour cost is high and the areas covered are small and may poorly represent the ecosystem scale. Chamber measurements are suitable when looking at small plots for a range of fertiliser regimes, animal densities, soil types, etc.
3. Regular soil carbon inventories (at 5- to 10-year intervals): these can quantify the soil carbon stock change from sampling period to sampling period and so determine whether the sampled areas are increasing or decreasing their stock of carbon.
4. Empirical model approaches: these models have been used, exploiting data on land use, land cover, management practices and census data.
5. Process-based models such as PaSim, DayCent, RotC, Century and Orchidee: these have been used to good success. Such models have a heavy requirement for data but have the great advantage that once calibrated with past data and found to reproduce the past, they can then be used with some confidence to examine future scenarios such as climate change and different land use practices.

Grassland soils are a large store of carbon and can act as a net sink for atmospheric CO_2 (i.e. carbon sequestration) (Soussana *et al*., 2007). N_2O is emitted

1 Therefore $g\,C\text{-}CO_2\,m^{-2}\,yr^{-1}$ means the number of grams of carbon, in the form of CO_2, per metre squared, per year

from fertilised soils. CH_4 is emitted by livestock in grazing systems and animal waste storage systems and it can also be exchanged with the soil (Soussana *et al*., 2007). There is widespread evidence in the international published literature that grasslands are a sink for carbon, when the flux of carbon (as CO_2 and CH_4) is considered between the soil/grass and the atmosphere (Lal, 2004; Vuichard *et al*., 2007; Smith *et al*., 2008; Byrne *et al*., 2009; Schulze *et al*., 2010; Soussana *et al*., 2010; Lüscher *et al*., 2014; Ripple *et al*., 2014; Chang *et al*., 2015a,b; Henderson *et al*., 2015). The three recent papers by Chang *et al*. (Chang *et al*., 2015a,b, 2016) conclude that several lines of evidence now point to European-managed (and in particular those in Britain and Ireland) grassland ecosystems being a sink for carbon. This is consistent with other studies across the EU, Asia, New Zealand, Australia and the USA. However, when other GHG trace gases such as CH_4 and N_2O are considered in addition to CO_2, [and reported in CO_2 equivalents (eq) or in GWP] the sink status is significantly reduced and in several environments the GHG exchange status is that of a source rather than a sink. The management practice in grasslands of either silage (harvest) cutting or grazing or a combination of silage cutting and grazing, influences the level of the ecosystem carbon uptake, as does the level of nitrogen applied as a fertiliser. A key parameter in the amount of carbon uptake is that of intensive grazing versus extensive grazing, with the latter now considered to increase the uptake and so the soil sequestration of carbon. Knowing the degree to which a grassland soil sequesters or emits carbon is very important, as, under Article 3.4 of the Kyoto Protocol, Parties can elect to account for grazing land management and corresponding soil carbon sinks and sources as contributing to agreed reduction targets for emissions. Ireland has elected to account for grazing land management during the period 2013–2020 under the Kyoto Protocol, and therefore it is required to develop measurement, reporting and verification (MRV) systems to demonstrate changes in grassland soils GHG fluxes.

Janssens *et al*. (2003), in an assessment of the European carbon balance, concluded that grasslands had a net carbon sink of $-66\,g\,C\text{-}CO_2\,m^{-2}\,yr^{-1}$ based on a simple model using yields and land use data. Soussana *et al*. (2007) reported on the EU project GREENGRASS, which aimed to "quantify the sources and sinks of GHG from managed grasslands and mitigation strategies". Nine grassland sites across Europe (from Ireland to Hungary) were fitted with EC instrumentation to measure CO_2 fluxes and, in some cases, N_2O fluxes. Methane fluxes were measured at four of the sites. Two years of measurements and known management practices with nitrogen fertiliser amounts ranging from 0 to $200\,kg^{-1}\,ha^{-1}\,yr^{-1}$ were included in the study. All nine sites showed a negative NEE (carbon sequestration, equation 1.1), which ranged from –13 to $-464\,g\,C\text{-}CO_2\,m^{-2}\,yr^{-1}$, with an average value across sites of $-247\,g\,C\text{-}CO_2\,m^{-2}\,yr^{-1}$. The carbon lost as CH_4 was small and ranged from 0 (no grazing cattle) to $10.4\,g\,C\text{-}CH_4\,m^{-2}\,yr^{-1}$ (of the order of 2% of carbon of NEE). The carbon exported as F_{silage} (equation 1.2) ranged from 0 (grazing only) to $476\,g\,C\text{-}CO_2\,m^{-2}\,yr^{-1}$. The carbon in F_{input} (organic manures, slurries, food concentrates) ranged from 0 to $106\,g\,C\text{-}CO_2\,m^{-2}\,yr^{-1}$. The NBP (equation 1.2) ranged from –462 g to $+266\,C\text{-}CO_2\,m^{-2}\,yr^{-1}$, with an average of $-104\,g\,C\text{-}CO_2\,m^{-2}\,yr^{-1}$, which is 43% of the atmospheric CO_2 sink (NEE). The N_2O emissions were measured (or estimated) to range from 4.4 to $687\,mg\,N_2O\text{-}N\,m^{-2}\,yr^{-1}$, or 0.6 to $87\,g\,CO_2\text{–}C\,eq\,m^{-2}\,yr^{-1}$. Averaging all sites, the NGHGE was a sink of $-212\,g\,CO_2\text{–}C\,eq\,m^{-2}\,yr^{-1}$. The Irish site at Carlow was a net NGHGE sink –329 and $-168\,g\,CO_2\text{–}C\,eq\,m^{-2}\,yr^{-1}$ for 2002 and 2003, respectively. The results of the GREENGRASS project are summarised in Figure 1.1.

In CarboEurope IP (Schultze *et al*., 2009), it was found that, across Europe, grasslands sequester more carbon *in soils* than forests (57 vs $20\,g\,C\,m^{-2}\,yr^{-1}$). Even if the emissions of non-CO_2 gases (i.e. methane) are included, the carbon sequestration in grassland soils remains higher than in forests. Chang *et al*. (2015a), in a modelling study using ORCHIDEE-GM, estimated that the NPP of European grasslands (EU-28 plus Norway and Switzerland) was $559\,g\,C\,m^{-2}\,yr^{-1}$ during the period 1961 to 2010, while the NPP of Britain and Ireland, averaged over the period 2000 to 2010, was approximately $800\,g\,C\,m^{-2}\,yr^{-1}$. Britain and Ireland was the most productive region of the nine regions of Europe. The NEE of Britain and Ireland over the period 2000 to 2010 was a sink of approximately $-160\,g\,C\,m^{-2}\,yr^{-1}$. The NEE of intensively managed grasslands was approximately $-220\,g\,C\,m^{-2}\,yr^{-1}$ while the NEE of extensively managed grasslands was about half that (of extensive) at approximately $-100\,g\,C\,m^{-2}\,yr^{-1}$. The NBP was

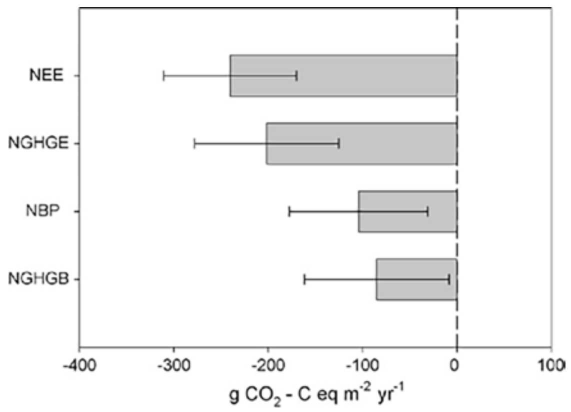

Figure 1.1. Average NEE (equation 1.1), NBP (equation 1.2), GHG budget (NGHGE, equation 1.3) and attributed GHG budget (NGHGB, equation 1.4) over the GREENGRASS grassland sites (excluding the grass–crop rotation site, LV). Results are the mean (confidence interval at $P > 0.95$) of nine sites and of 2 years per site. Reproduced from Soussana *et al.* (2007), with permission from Elsevier.

approximately –70 g C $m^{-2} yr^{-1}$ or about half that of NEE. Chang *et al*. (2015a) estimated the following components of the NGHGE (sometimes referred to as NGE) for the British Isles during the period 2000 to 2010 as NEE sink of –160 g C-CO_2 $m^{-2} yr^{-1}$; CH_4 source of +30 g C-CO_2 $m^{-2} yr^{-1}$; N_2O source of +20 g C-CO_2 eq $m^{-2} yr^{-1}$; and NGHGE –110 g C-CO_2 eq $m^{-2} yr^{-1}$ (see Figure 1.2).

In Chang *et al*. (2016), a key result was that soil carbon accumulation is accelerating in European grasslands, with a net increase of soil carbon of 384 ± 141 g C m^{-2} over the 20-year period of 1991–2010 (or ~19.2 g C $m^{-2} yr^{-1}$). The increasing soil carbon accumulation rate was attributed separately to climate change, CO_2 trends, nitrogen addition, and land cover and management intensity changes. The observation-driven trends of management intensity were found to be the dominant driver explaining the positive trend of NBP across Europe. The study confirmed the importance of management intensity

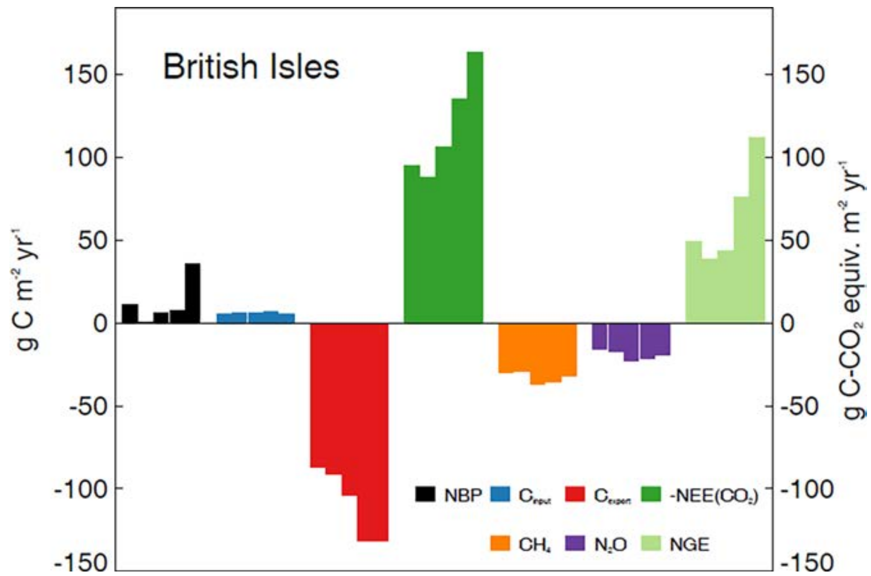

Figure 1.2. The NBP (far left, black), NGE (far right, light green) and their components divided into a number of major agricultural regions for the most recent five decades. The major agricultural regions are determined by both environmental and socio-economic factors. The five values of each component are 10-year averages for (from left to right) 1961–1970, 1971–1980, 1981–1990, 1991–2000 and 2001–2010. NBP, the carbon balance of grassland ecosystem (g C $m^{-2} yr^{-1}$); C_{input} (blue), the carbon entering the system through manure and slurry application (g C $m^{-2} yr^{-1}$); C_{export} (red), the carbon lost from the system through harvested biomass and CH_4 emission by grazing animals (g C $m^{-2} yr^{-1}$); NGE (NGHGE), the NGHGE of grassland ecosystem expressed as global warming potential (g C-CO_2 eq m^{-2} yr^{-1}), including CO_2 (dark green), CH_4 (orange) and N_2O (purple) fluxes. Positive NBP and NGE indicate net carbon and GHG sinks, respectively. The negative values of the CH_4 and N_2O fluxes indicate that the grassland ecosystem is a CH_4 and N_2O source. Reproduced from Chang *et al*. (2015a) under the Creative Commons Attribution Licence.

in drawing up a grassland carbon balance. Despite being a carbon sink, European grasslands were found to be a net GHG source of 50 g C-CO_2 eq m^{-2} yr^{-1} because CH_4 and N_2O emissions, and CO_2 released by animals offset soil carbon accumulation. However, the choice of comparative metrics, in this case GWP_{100}, is very important. Alterative metrics such as global temperature potential have been presented in the literature (IPCC, 2013, Chapter 13). That study illustrated the importance of accounting for not only the ecosystem GHG fluxes, but also the livestock-related fluxes, when estimating the GHG balance of grassland.

Hörtnagl and Wohlfahrt (2014) used EC to measure the fluxes of CO_2, CH_4 and N_2O over a temperate mountain-managed meadow in Austria that was cut three times per year (*no grazing animals* and so no enteric fermentation) and found that the site was an NGHGE (NGE) sink of –32 g CO_2 eq m^{-2} yr^{-1} in which 55% of the CO_2 sink strength of –71 g CO_2 eq m^{-2} yr^{-1} was offset by CH_4 (N_2O) emissions of 7 (32) g CO_2 eq m^{-2} yr^{-1}. Merbold *et al*. (2014) in a restored intensively managed (cutting only, no grazing) grassland at 400 m above sea level (masl) in Switzerland, report that in the first year after restoration the fluxes were all emissions, including that of CO_2: CO_2 was reported at 1245 g CO_2 eq m^{-2} yr^{-1}; CH_4 at 243 g CO_2 eq m^{-2} yr^{-1} and N_2O at 1363 g CO_2 eq m^{-2} yr^{-1}. These are exceptionally high N_2O emissions and were influenced by the application of 197 kg N ha^{-1} fertiliser/slurry. Merbold *et al*. (2014) suggest that restored (or newly ploughed/seeded) grasslands are a special case of high emissions in the first year or two after restoration. This compares with emissions of CH_4 (N_2O) of 30(20) g CO_2 eq m^{-2} yr^{-1} in Chang *et al*. (2015a).

1.4 Distribution and Characteristics of Blanket Bogs

Peatlands are wetlands with an organic soil layer of at least 30 cm, which may extend to 15–20 m (Clymo *et al.*, 1998; Turunen *et al.*, 2002). In Ireland the maximum depth is in the range of 9–12 m for raised bogs and 2–8 m for blanket bogs (Holden and Connelly, 2009, 2013). One of its notable features is that the water table remains close to the surface throughout the year. Peat consists of the remains of partially decomposed plants because the rate of plant production exceeds the rate of decay due to the waterlogged conditions in peatlands. This in turn allows the accumulation of carbon in the form of peat (Moore and Bellamy, 1974) with an estimated long-term ability of peatlands to sequester carbon in the order of 20 to 30 g C m^{-2} yr^{-1} (Gorham, 1991; Turunen *et al.*, 2002; Turunen *et al.*, 2004) making them an important ecosystem for moderating atmospheric CO_2 concentrations. Throughout the Holocene, the impact of northern peatlands on climate radiative forcing has been a net cooling of up to 0.5 W m^{-2} when both the uptake of CO_2 and the emission of CH_4 are considered (Frolking and Roulet, 2007). Disturbance of peatlands by drainage, land use changes, extraction and fires convert peatlands into sources of carbon. The impact of climate change is uncertain, but may potentially also lead to carbon losses (Holden, 2005).

Northern latitude peatlands, i.e. those peatlands that occur at latitudes higher than 45° N, cover relatively small areas of the globe, equivalent to about 3% of the terrestrial land area. However, they contain 20–25% of the terrestrial soil organic carbon (SOC) stock (Gorham, 1991; Fenner and Freeman, 2011; IPCC, 2013).

In the Republic of Ireland, peat soils cover between 17 and 21% of the national land area (Hammond, 1981; Connolly *et al.*, 2007; Eaton *et al.*, 2008; Connolly and Holden, 2007, 2009) and their SOC stock was estimated by two studies to be 53% and 62% of the national SOC stock (Tomlinson, 2005; Eaton *et al.*, 2008).

Peatlands are classified as bogs and fens according to their ecohydrology. Bogs are ombrotrophic peatlands, i.e. they depend on precipitation and aerial deposition for the supply of water, nutrients and minerals, whereas fens, or minerotrophic peatlands, are reliant on groundwater (Gore, 1983). Bogs can further be divided into raised and blanket bogs according to their development. Raised bogs are dome-shaped masses of peat occupying former lakes or shallow depressions and their formation is a continuous development after a fen stage (Foss *et al.*, 2001). The development of blanket bogs is mostly independent of basins or topographic features where water collects; they simply blanket the landscape as the name suggests (Foss *et al.*, 2001). Blanket bogs can further be divided into Atlantic and Montane bogs depending on whether their altitude is above or below 200 masl (Foss *et al.*, 2001). Blanket bogs account for less than 3% of the world's peatlands, with the blanket bogs in Ireland and the UK forming the largest single contribution of about 10–15% (Foss *et al.*, 2001; Eaton *et al.*, 2008). The peatland in this study is an Atlantic blanket bog in the south-west of Ireland.

The development and active spread of blanket bogs in Britain and Ireland was between 5100 and 3100 BP (before present) (Tallis, 1998), whereas the widespread blanket bog initiation in the south-west of Ireland was probably rather late, ranging from 3260 BP to the early first millennium BP (O'Connell, 1990). Although the exact sequence of events leading to the widespread development of blanket bogs in Ireland is still not well understood, the phenomenon is thought to have been aided by woodland and scrub clearance carried out by early farmers (O'Connell, 1990). Once blanket bogs began to form, the process was greatly aided by the prevailing cool and wet climate. Within Ireland, blanket bogs are confined to areas with high annual rainfall exceeding 1250 mm and number of rain days per annum exceeding 200 (i.e. > 2 mm d^{-1}) (Hammond, 1981; O'Connell, 1990), which maintains waterlogged conditions on the ground. After climate, the most important environmental factors influencing the development of blanket bogs are topography and geology. Blanket bog development rarely takes place in areas where the slope exceeds 25° from the horizontal and it is best developed in areas of unyielding, base-poor bedrock (O'Connell, 1990; Tallis, 1998). Therefore, while climatic factors and time-dependent soil processes form the background against which the spread of blanket bog took place, it is argued that human impact played a major role in its wide-scale expansion (O'Connell, 1990).

1.5 Blanket Peatlands – CO_2 and CH_4 Fluxes

The interest in GHG balance in peatland ecosystems has been ignored until recently (e.g. not included in the European Projects CarboEurope and NitroEurope). The recent interest (e.g. special task in WP2 – Critical Processes of the European Project GHG-Europe) has arisen from the recognition that a large soil carbon reservoir is stored in peat (an estimated one-third of the global soil carbon pool, Gorham, 1991). This is potentially available to the atmosphere if decomposition exceeds production (a possibility with climate change) (Bubier *et al.*, 1995). In large-scale GHG balance studies, peatland flux studies are considered from only a few countries (Finland, Germany, the Netherlands, Sweden and the UK; Luyssaert *et al.*, 2012) and this is probably due to the paucity of data.

Peatlands occupy a relatively small fraction of the Earth's land area, but they store a globally important carbon stock. Undisturbed peatlands currently act as a weak carbon sink (~0.1 pg C yr^{-1}), a moderate source of methane (CH_4; ~0.03 pg CH_4 yr^{-1}), and a very weak source of nitrous oxide (N_2O; ~0.00002 pg N_2O-N yr^{-1}). Anthropogenic disturbances, primarily drainage (10–20% of global peatlands), result in net CO_2 emissions, reduced CH_4 emissions and increased N_2O emissions, likely changing the peatland GHG balance to a carbon source (~0.1 pg C yr^{-1}), a 10% smaller CH_4 source, and a larger (but still small) N_2O source (~0.0004 pg N_2O-N yr^{-1}) (Frolking *et al.*, 2011).

Peatlands are wetland ecosystems where the rate of production of organic matter exceeds its rate of decomposition (Bubier *et al.*, 1995). This imbalance is due to the inhibition of decomposition processes by the high water table and consequent anoxic conditions, and results in the accumulation of partly decomposed organic material as peat (Moore and Bellamy, 1974).

The development of northern latitude peatlands is closely related to regional climate controls on precipitation, evaporation and temperature (Payette and Rochefort, 2001). The carbon exchange is thus strictly connected to the water and energy exchanges. The water budget in northern peatlands influences the ecosystem carbon sequestration (Lafleur *et al.*, 2003) and the partitioning of the available energy (Brutsaert, 2005) as well as affecting the soil chemistry (Laine *et al.*, 1995) and the vegetation composition (Belyea and Clymo, 2001).

Climate change (increased winter precipitation and decreased summer precipitation) in northern latitudes is predicted to perturb the water and energy budgets (IPCC, 2013). As a result, climate change in northern peatlands is expected to affect the hydrology (Roulet *et al.*, 1992), the vegetation composition (Weltzin *et al.*, 2003), and the carbon balance (Basiliko *et al.*, 2005; Updegraff *et al.*, 2001) of peatlands. Nevertheless, the response of the carbon budget to climate change is difficult to predict as a result of the complexity of the soil–vegetation–hydrology relationships that determine the carbon cycle in peatlands. Moreover, the heterogeneity of the microform structure of bogs, due to their high spatial variation in water table, vegetation composition and chemical status, can complicate the synthesis of the response of the ecosystem as a whole to climate change (Strack and Waddington, 2007). Overall, carbon gain or loss depends on whether the transition is towards or away from the optimal conditions for carbon accumulation for that ecosystem, and this is mainly determined by the hydrologic response (Dise, 2009).

In Ireland, blanket bogs comprise around 13% of the total land area, yet they contain between 21% and 36% of the national soil carbon stock (Eaton *et al*., 2008; Xu *et al*., 2011). Similar to raised bogs, blanket bogs are largely ombrotrophic peatlands, receiving water and nutrients mainly from precipitation, even if minerotrophic areas also occur in extensive blanket bogs (Tallis, 1998). They are important not only for carbon storage, but also in terms of biodiversity. These ecosystems are normally located over relatively flat or gently sloping terrain (Tallis, 1998). They tend to form in temperate maritime climates with consistently high rainfall (>1200 mm per annum, >200 wet days a year, with a wet day receiving at least 2 mm of rain in a day) combined with low evaporation rates, resulting in a ground surface that may remain consistently waterlogged (Lindsay, 1988; Moore, 1993). As a result of their proximity to the sea, these ecosystems also tend to have high sea-origin ion concentrations (Proctor, 1992; Tallis, 1998; Sottocornola *et al*., 2009).

Blanket bog surfaces are typically a mosaic of various undulating microforms, which differ in terms of water table level (WTL), plant composition and chemical characteristics (Sottocornola *et al*., 2009). Different vegetation communities support different CO_2 exchange dynamics, and therefore blanket bogs are likely to have different functional responses to other types of ecosystems that have been studied for such effects.

Other than by climate change, peatlands are threatened by an increase in disturbance that typically implies some form of drainage, which has a strong impact on the biogeochemical cycles and ecosystem functioning of peatlands (Waddington *et al*., 2002), as it disrupts the close connection between the water and carbon cycles of these fragile ecosystems. Only 21% of Irish blanket bogs remain in relatively pristine conditions (Foss *et al*., 2001), which highlights the need to enhance current conservation strategies and define an action plan for sustainable peatland management (Douglas, 1998; Bullock *et al*., 2012), the National Peatland Management Strategy (DAHG, 2015) and the FAO peatland policy document (FAO, 2014).

In the last 10 years, research on carbon fluxes and budgets has provided information on the carbon sequestration and functioning of some Irish peatlands. In particular, the Atlantic blanket bog of Glencar (County Kerry) has been the object of intensive flux studies that identified it as a weak sink of CO_2, sequestering an annual average of 55 g C-CO_2 m^{-2} (Sottocornola and Kiely, 2010b), which, combined with the emission of methane and carbon losses through DOC in the streams, resulted in a carbon balance uptake (sink) average of 30 g C m^{-2} yr^{-1} (Koehler *et al*., 2011). The carbon and CO_2 annual balances in this Atlantic blanket bog were reported to be very similar to those of boreal raised bogs and oligotrophic fens, although both gross ecosystem production and respiration were lower (Sottocornola and Kiely, 2010b). Moreover, these annual averages were the result of very wide interannual variation, ranging from a net annual sink of 66 g C m^{-2} to an annual source of 9 g C m^{-2}, and indicate that the meteorological conditions required for the peatland growth and carbon uptake can be intermittent in terms of both temperature and precipitation (Sottocornola and Kiely, 2010b; Koehler *et al*., 2011).

In addition to Glencar, the carbon balances of other Irish near-intact peatlands have been studied for a short time using chamber technology in the past few years and they showed small annual losses (Wilson, 2008). Short-term studies have also been carried out in disturbed Irish peatlands, revealing a wide range of GHG balances, from potentially high losses in rewetted wetlands, as anaerobic conditions and vegetation are re-established (Wilson *et al*., 2009) to uptake in forested cutaway peatlands (Byrne *et al*., 2007).

Unlike other studies on peatland carbon fluxes in Ireland, the investigation of the carbon cycle and balance in Glencar has been achieved through the short-term use of chamber technology and 10 years of continuous and non-invasive EC measurements. Such long-term and large-scale EC measurements (Sottocornola and Kiely, 2010a,b) supported other types of investigations, such as the chamber measurements, in validating the spatial variation through upscaling exercises (Laine *et al*., 2006). Such studies also created a baseline that would be of importance in comparing the carbon balances from vegetation classes identifying the different degrees of peatland disruption to a long-term reference record.

A study completed by Yurova *et al*. (2007) at a mire in Sweden found that CO_2 uptake was controlled by interactions between WTL and air temperature. It was noted that higher air temperatures (> 15°C) and a WTL that was neither too low nor too high resulted in conditions that were optimal for high NEE. In another study by Lindroth *et al*. (2007) at four mires at different latitudes in Sweden and Finland, findings were similar in that WTL and temperature explained most of the variance in NEE. In addition to this, cooler temperatures and longer daylight hours at northerly locations were found to be beneficial for higher NEE during summer.

Previous studies at an Atlantic blanket bog in Glencar, south-west Ireland, by Sottocornola and Kiely (2005, 2010a) and Koehler *et al*. (2011) demonstrated that it is a small sink for direct CO_2. It was found to have annual carbon and NEE balances similar to boreal raised bogs, but with lower gross ecosystem production (GEP) and ecosystem respiration (ER). At the same location (a pristine undisturbed peatland), Laine *et al*. (2009) reported that high water level conditions (in flooded hollows with water above ground) favoured communities acting as net sources of CO_2 and the wetter the conditions, the lower the ecosystem CO_2 sink.

1.6 Afforested Grasslands – Carbon, CH_4 and Nitrogen Fluxes

The total area of forest in Ireland (including pre-1990 and post-1990 plantations) was estimated in 2013 at 748,000 ha, or 11% of the total land area of Ireland, up from 480,000 ha (7%) in 1990 (Duffy *et al*., 2014). Ireland's forest estate is largely fragmented with a significant amount in small developments of less than 10 ha. The government has a target of expanding the national forest cover from 11% to 18% by mid-century (DAFM, 2014). More than 50% of the current estate is Sitka spruce, with other pines accounting for 25% and approximately 25% consisting of broadleaf species. For accounting procedures of the Kyoto Protocol, the composition of Irish forestry pre- and post-1990 is 59.3% Sitka spruce, 30.7% other pines, 8% larch and 2% other. As much as 75% of the estate is less than 30 years old. The increased planting of native broadleaf species in recent years is likely to enhance overall landscape biodiversity in Ireland's agriculture-dominated landscape (Reidy and Bolger, 2014). Since 1990 (and up to 2012), new forest planting has been on organic soils (~38%, 98,000 ha), on organo-mineral soils (~20%, 50,000 ha) and on mineral soils (42%, 107,000 ha) (Duffy *et al*., 2014).

The two aspects of key interest to Irish forestry are (1) the carbon sequestered in the tree biomass and (2) the carbon emissions and removals by soils (mainly organic soils). In examining GHG with respect to forestry, it is well established that the forest biomass sequesters carbon in its above-ground biomass and in its below-ground roots and soil. The amount of carbon sequestered in the biomass and root system depends on several factors including the tree species (softwood or hardwood). It is estimated that the average rate of carbon sequestration by Irish forests is approximately 3.36 $t\,C\,ha^{-1}\,yr^{-1}$ (Kilbride *et al*. 1999), based on the model developed by Dewar and Cannell (1992). More recent work by Byrne (2010) and Black *et al*. (2009) reported that first-rotation Sitka spruce stands are a carbon sink at 10 years and that this reaches a maximum of 9 $t\,C\,ha^{-1}\,yr^{-1}$ before the time of first thinning, declining to 2 $t\,C\,ha^{-1}\,yr^{-1}$ in older stands. The rate of carbon sequestration is similar to that found in Sitka spruce stands in the UK from 7 $t\,C\,ha^{-1}\,yr^{-1}$ at canopy closure to 3 $t\,C\,ha^{-1}\,yr^{-1}$ in older forestry stands (Byrne, 2010). It has been noted that the total carbon reservoir or store in Irish forestry exceeds 1 billion tonnes of CO_2, most of which is in the soil, and that the annual removal of CO_2 from the atmosphere by Ireland's forests exceeds 6 million tonnes of CO_2. Irish forests (Black and Gallagher, 2010) on peats are considered to sequester between approximately 1 $t\,C\,ha^{-1}\,yr^{-1}$ (initial colonisation at age 4–8 years) and approximately 4.5 $t\,C\,ha^{-1}\,yr^{-1}$ (pre-thinning at age 12–20 years).

However, the forest ecosystem may also emit carbon if its soils are organic or organo-mineral. Based on country-specific data, it is assumed that forests on mineral soils in Ireland do not lose CO_2 back to the atmosphere (Duffy *et al*., 2014). Forest soils may emit N_2O and may emit or take up CH_4 depending on levels of nitrogen fertilisation and level of drainage as part of afforestation. Country-specific emission factors are also applied for carbon losses for afforestation on drained peat (Duffy *et al*., 2014) This is an emission factor of 0.59 t CO_2 eq $ha^{-1} yr^{-1}$ from Irish forestry on organic soils and a smaller emission of 0.3 t CO_2 eq $ha^{-1} yr^{-1}$ for Irish forestry on organo-mineral soils. In Duffy *et al*. (2014) it is of interest to note (Duffy *et al*., 2014, Table 6.55, p 195) that for the 449,500 ha (including 181,000 ha of mineral soils) of Irish forest accounted for, that the total emissions are 475,900 t CO_2 eq yr^{-1}. This includes in situ emissions (DOC) mainly from organic soils at 0.31 t CO_2 $ha^{-1} yr^{-1}$. Emission factor values for N_2O are 2.8 kg N_2O-N $ha^{-1} yr^{-1}$ for nitrogen-rich soils and 0.7 kg N_2O-N $ha^{-1} yr^{-1}$ for nitrogen-poor soils. The default emission factor for CH_4 is 2.5 kg CH_4 $ha^{-1} yr^{-1}$.

Zenone *et al*. (2016) reported the GHG fluxes of CO_2, CH_4 and N_2O using the EC technique in a short-rotation coppice (SRC) plantation for bioenergy production. Measurements were made during the period 2010–2013, that is, during the first two rotations of the SRC. The overall GHG balance of the 4 years was an emission of 1.90 (±1.37) t CO_2 eq ha^{-1} CO_2 eq ha^{-1}; this indicated that soil trace gas emissions offset the CO_2 uptake by the plantation. CH_4 and N_2O contributed almost equally to offset the CO_2 uptake of –5.28 (±0.67) t CO_2 eq ha^{-1}, with an overall emission of 3.56 (± 0.35) t CO_2 eq ha^{-1} of N_2O and of 3.53 (±0.85) t CO_2 eq ha^{-1} of CH_4. N_2O emissions mostly occurred during one single peak a few months after the site was converted to SRC; this peak comprised 44% of the total N_2O loss during the two rotations. Accurately capturing emission events proved to be critical for deriving correct estimates of the GHG balance. The nitrogen content of the soil and the water table depth were the two drivers that best explained the variability in N_2O and CH_4, respectively. This study underlines the importance of the non-CO_2 GHGs' influence on the overall balance. Further long-term investigations of soil trace gas emissions should monitor the nitrogen content and the mineralisation rate of the soil as well as the microbial community as drivers of trace gas emissions.

Luyssaert *et al*. (2010) in a new synthesis of the European carbon balance for forestry stated that 29% (22 g C $m^{-2} yr^{-1}$) of carbon is sequestered in the forest soil with the remaining 71% (53 g C $m^{-2} yr^{-1}$) sequestered in the woody biomass. The methods applied in their study reported some different results. EC methods gave gross primary productivity (GPP) of 1107 g C $m^{-2} yr^{-1}$ and net ecosystem productivity (NEP) of 197 g C $m^{-2} yr^{-1}$, while other methods (inventories and ecosystem studies) gave NPP from 447 to 544 g C $m^{-2} yr^{-1}$ and R_h from 287 to 387 g C $m^{-2} yr^{-1}$ with harvest at less than 100 g C $m^{-2} yr^{-1}$. NBP is the carbon that remains in the long term in the ecosystem and is sequestered in wood and soil. Thus, NBP is the amount of carbon (CO_2) sequestered in forest ecosystems and represents the direct contribution of ecosystems to climate change mitigation (Luyssaert *et al*., 2010). The first estimates of NBP were between 70 and 160 g C $m^{-2} yr^{-1}$. The inventory estimates put the increase in tree biomass at 69 g C $m^{-2} yr^{-1}$ and increase in soil carbon at 20 g C $m^{-2} yr^{-1}$, or a total NBP of 89 g C $m^{-2} yr^{-1}$. The range of NBP reported by Luyssaert *et al*. (2010) was 53 to 98 g C $m^{-2} yr^{-1}$. For forests on mineral soils, as there are almost no emissions of any of the GHGs, NBP (approximately 100 g C $m^{-2} yr^{-1}$ or about 1 t C $ha^{-1} yr^{-1}$) is the real sink strength. For forests on organic soils, there are emissions of the three GHGs and so such forests may even be sources of carbon. It is of interest to note that the soil carbon sequestration in forests across Europe was estimated at about 30 g C $m^{-2} yr^{-1}$. Schulze *et al*. (2010) report that grasslands sequester more carbon in soils than forests; this is probably due to higher below-ground carbon allocation, root turnover and nitrogen fertilisation.

2 Materials and Methods

2.1 Description of Sites

We report on three GHG flux tower sites in the south-west of Ireland, which are identified in Figure 2.1. These have been established by the Hydromet Research Group at the Environmental Research Institute, UCC. The Dripsey *grassland*, which has been in operation since 2002, is located approximately 20 km north-west of Cork city, Donoughmore, County Cork, and its co-ordinates are latitude 51.986721 N, longitude 8.751765 W. The Dripsey *afforested grassland* (broadleaf forest established in 2006) has been in operation since 2006 and the flux tower is located about 200 m west of the Dripsey grassland tower. The co-ordinates of the afforested tower are latitude 51.986102 N, longitude 8.754115 W. The third site is a *blanket peatland* at Glencar in County Kerry (about 30 km south-west of the town of Killorglin in County Kerry) and its co-ordinates are latitude 51.916666 N, longitude 9.916666 W. The geographic locations of the study sites are shown in Figure 2.1. Photographs of the three sites are shown in Figure 2.2 (the Dripsey grassland), Figure 2.3 (the Dripsey afforested site) and Figure 2.4 (the Kerry peatland).

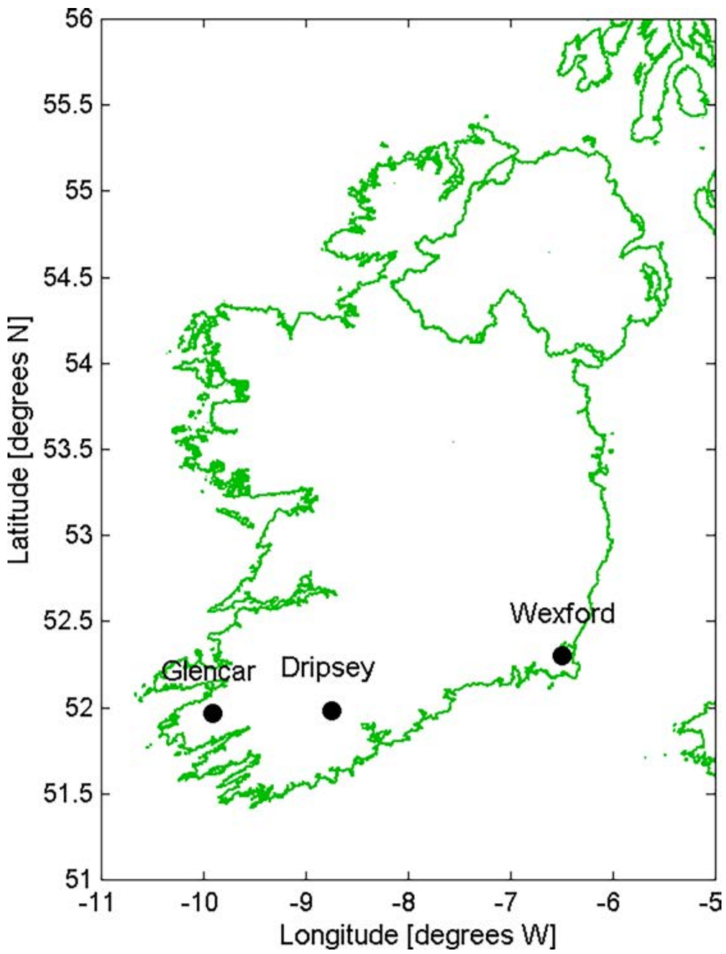

Figure 2.1. The geographic location of the three EC flux towers in the south of Ireland. The Dripsey grassland in County Cork is an intensively managed grassland (impeded drainage) at an elevation of 190 masl. The Dripsey broadleaf forest is adjacent to the Dripsey grassland site. Glencar is a pristine Atlantic blanket peatland in County Kerry at an elevation of 150 masl.

Figure 2.2. The EC tall tower (10 m high) at the Dripsey grassland in County Cork. The ecosystem is grassland and the soils have impeded drainage. The EC instruments were set at 10 m for 2002, 2003 and 2004 with an associated average footprint extent of 1000 m in the south-west direction. For 2005, 2006 and 2007 the EC instruments were set at 6 m with an associated average footprint extent of 600 m.

Figure 2.3. The Dripsey broadleaf forest (left) and the 6 m EC scaffold tower at the Dripsey forest site (right). The EC instruments are set at approximately 1.5 m above the canopy and are raised as the canopy height increases.

2.1.1 Dripsey grassland site

The Dripsey experimental grassland is located near the village of Donoughmore, County Cork, in south-west Ireland, 25 km north-west of Cork city (see Figure 2.1). The Dripsey grassland EC tower is at an elevation of ~190 masl. The soil is classified as gley (Gardiner and Radford, 1980). The topsoil is rich in organic matter to a depth of about 15 cm [about 12% organic matter overlying a dark brown B-horizon of sand texture. A yellowish-brown B-horizon of sand texture progressively changes to a brown, gravely sand that constitutes the parent material at a depth

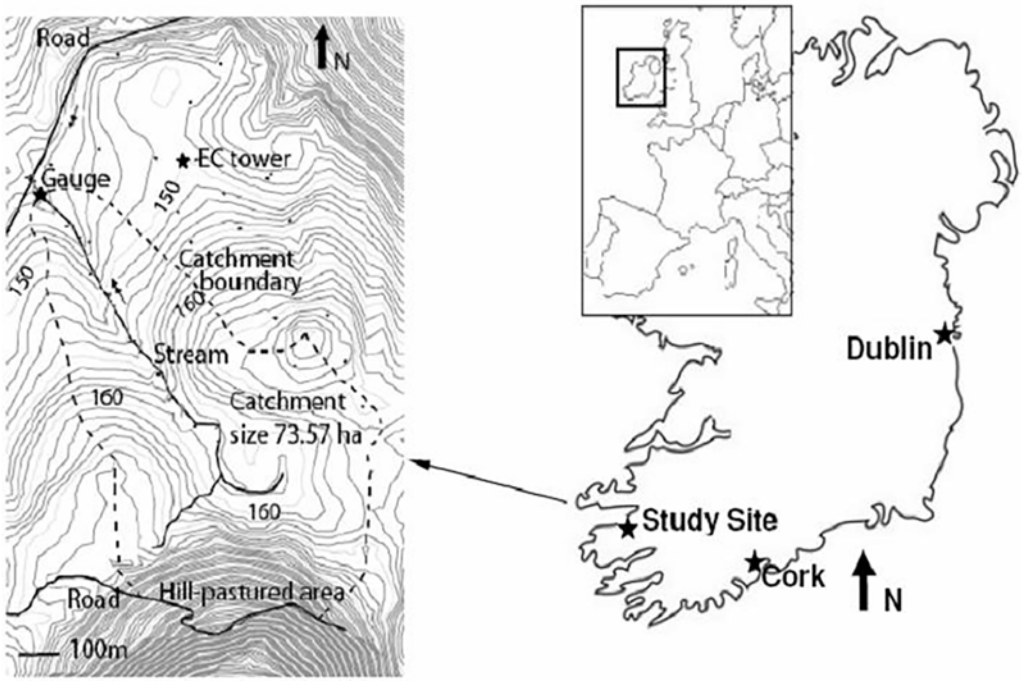

Figure 2.4. Site layout (left) and location map (right). The peatland site is located about 120 km west of Cork City. The catchment boundary is shown with a dashed line and the bog stream is shown in a solid line. The stream is gauged at the northern side. EC tower = location of an EC tower. The site is named Killorglin-Glencar, IE-Kil in the European Fluxes Database Cluster and is at latitude 51.916666 N, longitude 9.916666 W. From Koehler (2012).

of approximately 0.3 m. The underlying bedrock is Old Red Sandstone (Scanlon *et al.*, 2004). Depth-averaged over the top 30 cm, the volumetric soil porosity was 0.49 $m^3 m^{-3}$, the saturation moisture level was 0.45 $m^3 m^{-3}$, the field capacity was 0.32 $m^3 m^{-3}$, and the wilting point was 0.12 $m^3 m^{-3}$. For the top 5 cm of topsoil, the porosity was closer to 65%.

The climate is temperate and humid with mean annual precipitation (over 10 years) of approximately 1470 mm yr^{-1}. The rainfall regime is characterised by long-duration events of low intensity (values greater than 40 mm day^{-1} are rare). Short-duration events of high intensity are more seldom and occur during the summer. Daily air temperatures have a range during the year between a maximum of 20°C in summer and a minimum of 0°C in winter. The daily summer average is ~15°C and the daily winter average is ~5°C. The site experienced an annual mean wind velocity (at 3 m) of 4 m s^{-1} with 30-minute peaks up to 16 m s^{-1}. The prevailing wind comes from the south-west.

The site is agricultural grassland, typical of the land use and vegetation in that part of the country. It was reclaimed and established more than 25 years ago and some fields have been reseeded over the past 20 years. Some of the land at this elevation is reclaimed wet land. A feature of these elevated areas (> 150 masl) is the requirement for continuous maintenance of local land drainage systems. In wet years this area is poorly productive with silage bought in for winter feed. The vegetation cover at the Dripsey grassland site is grassland of moderately high-quality pasture and meadow, in which the dominant plant species is perennial ryegrass (*Lolium perenne*) with a significant fraction of clover (*Trifolium* spp.). Considering environmental conditions, warm but not hot temperatures, high humidity with good airflow and the latitude of Ireland, the metabolic pathway for carbon fixation is assumed to be through the Calvin–Benson Cycle (C3 grass).

Like much of the surrounding rural area, the landscape near the meteorological GHG flux EC tower is partitioned into small fields ranging in size from ~1 ha to 5 ha. Management strategies for boosting grassland production vary according to the individual farmers. Management data (application of fertilisers, grazing and silage cuts) was collected through monthly surveys completed by the farmers that own fields within the footprint. The land use is a mixture of fields for cattle grazing (approximately two-thirds of fields) and fields for cutting (silage harvesting) (approximately one-third of fields). Cattle grazing in non-silage fields begins in March and ends in October (approximately 7–8 months). Cattle grazing in silage fields begins in mid-summer and ends in October (approximately 3 months). The rotational field grazing periods are approximately 1 week in 4. The grass height in the grazing fields varies from 0.05 m to 0.25 m. During relatively wet years, some wet or saturated fields were not grazed (because of the risk of poaching damage to the soil) and the animals were housed indoors from late September, leaving the standing biomass undisturbed during this time. By contrast, in dry autumns cattle were grazed (at least during the day) up to November. Livestock density at the site was 2.2 LU ha^{-1} (livestock units per hectare) in 2003 (Lewis, 2003), but has reduced recently in compliance with nutrient management plans developed under the Nitrate Directive (91/676/EEC).

In the silage cut fields, the grass is harvested in the summer, typically first in mid- to late May or early June, depending on weather and growth conditions, with a second cut in August. The biomass is exported from the ecosystem as silage for winter feed. The height of grass before cutting in silage fields reaches approximately 0.4 m in summer, whereas it is 0.1 m in winter during the dormant period. Owing to the mild climatic conditions, the fields stay green all year. No measurement of the biomass of grass was made on the Dripsey grassland site. The leaf area index (LAI) measurements started in 2004 and ranged from ~2 in the winter to ~6 in the summer. The LAI was measured using a PAR/LAI Ceptometer (LP-80 AccuPAR, Decagon devices, Inc., USA). The annual yield of silage in the region has been 8–12 t dry matter $ha^{-1} yr^{-1}$ depending on the weather.

Grass productivity is typically enhanced with the application of nitrogen in fertiliser and slurry, spread at intervals of approximately 6 weeks between February and September (Lewis, 2003). Commercially prepared mineral fertiliser mixtures were used, consisting of almost equal parts ammonium nitrogen (NH_4^+-N) and nitrate nitrogen (NO_3-N). Nitrogen in chemical fertiliser was applied at the rate of less than 200 kg N $ha^{-1} yr^{-1}$, and nitrogen in slurry at approximately less than 100 kg N $ha^{-1} yr^{-1}$.

The site is covered by smallholdings of the order of 20 to 50 ha. The fields are separated by traditional stone and sod borders or timber post and wire fences for paddock rotations. The EC flux tower combined with the meteorological station is situated at an elevation of ~190 masl.

2.1.2 Dripsey afforested grassland site

In February 2005, a small sector of the Dripsey grassland (0.053 km^2 in size) was afforested with broadleaf trees. This is a sector to the west-south-west of the original grassland flux tower footprint. The afforested area had been previously used for cattle grazing and grass silage for several decades, similar to the adjacent fields. Thus, although pre-afforestation data are limited for the afforested area, its previous soil properties were probably similar to those of the adjacent grassland fields (Khandokar, 2002; Lewis, 2003). However, it was known to be wetter than the rest of the grassland site. Prior to tree planting, the area was ploughed and drained through a network of drainage ditches approximately 5 m apart and ~30 cm deep. At the time of the Peichl *et al*. (2012) study, the forest was 5 years old and composed of ~80% ash (*Fraxinus excelsior* L.) mixed with ~20% black alder (*Alnus glutinosa* L.) and minor appearances (< 2%) of pedunculate oak (*Quercus robur* L.). Forest ground vegetation consisted of ryegrass, Yorkshire fog (*Holcus lanatus*) and soft rush (*Juncus effusus*), mixed with meadow buttercup (*Ranunculus acris*), greater spearwort (*Ranunculus lingua*), common mouse-ear (*Cerastium fontanum*) and cuckooflower (*Cardamine pratensis*). Initial management treatments include the application of ground rock phosphate (25 gm^{-2}) in April 2005 and manual grass removal once every mid-summer from 2006 to 2008, supported by a one-time herbicide spray in October 2008. In November 2009, three permanent sample plots (each 400 m^2) were established in the forest. Within each plot, species, base diameter (Dbase, 0.1 m), diameter at breast height (DBH, 1.3 m), tree height and live/dead status, were recorded for each tree. Each plot also encompassed three micro-plots (1 m^2) for ground biomass measurements (see section below). An EC tower for CO_2 flux measurements was established near the forest centre in the summer of 2006 and this is 200 m to the west of the flux tower in the grassland.

2.1.3 Glencar blanket peatland site

The measurement site is an Atlantic blanket bog situated near Glencar, County Kerry, south-west Ireland (Killorglin-Glencar, IE-Kil in the European Fluxes Database Cluster, latitude: 51.916666 N; longitude: 9.916666 W), approximately 150 masl on sandstone bedrock. In the centre of the bog, the upper acrotelm peat layer is mainly sedge peat with a bulk density of 0.05 g cm^{-3} and a porosity of 95%, with peat depths ranging between 2 and 5 m (Lewis *et al.*, 2012). A stream draining the bog with a catchment area of about 74 ha lies to the south, 85% of which is relatively intact blanket bog and 15% of which is on a hill slope that consists of alternating grazed patches of grassland and drained peaty soils (Koehler *et al.*, 2011), see Figure 2.4.

The bog is spatially heterogeneous, consisting of an assortment of microforms that differ in relative elevation, plant composition and WTL (Sottocornola *et al.*, 2009). These were grouped into four categories based on relative elevation: hummocks, high lawns, low lawns and hollows (Laine *et al.*, 2006; Sottocornola *et al.*, 2009). The difference in height between the highest and lowest microforms is typically 20–40 cm. Hollows are 50–300 cm oblong depressions covered by standing water for most of the year. The division of microforms within the EC footprint was estimated as 6% hummocks, 62% high lawns, 21% low lawns and 11% hollows (Laine *et al.*, 2006).

Vascular plants account for 30% of land coverage during summer (Sottocornola *et al.*, 2009). Of these, the species most commonly encountered are *Molinia caerulea* (L.) Moench (purple moor grass), *Calluna vulgaris* (L.) Hull (common heather), *Erica tetralix* L. (cross-leaved heath), *Narthecium ossifragum* (L.) Huds. (bog asphodel), *Rhynchospora alba* (L.) Vahl (white beak-sedge), *Eriophorum angustifolium* Honck. (common cotton grass), *Schoenus nigricans* L. (black-top sedge) and *Menyanthes trifoliata* L. (buckbean). Bryophytes are not so widespread, accounting for about 25% of surface cover. The principal species here are *Racomitrium lanuginosum* (Hedw.) Brid. (woolly hair-moss) and bog mosses (*Sphagnum* spp.), both occurring in similar quantities (Sottocornola *et al.*, 2009).

2.2 Instrumentation for Measuring GHG Fluxes

Three different sets of instrumentation have been applied at the three sites:

1. meteorological instrumentation;
2. CO_2, CH_4 and N_2O flux instrumentation;
3. hydrological instrumentation.

2.2.1 Meteorological instrumentation

Meteorological variables were continuously measured at the three EC tower sites in the south of Ireland (the Dripsey grassland, the Dripsey afforested grassland and the Kerry peatland) to gain long-term weather information at the study locations. This instrumentation supports the calculation of fluxes, including evaporation, as well as supporting empirical modelling of fluxes. The meteorological instrumentation at each site is listed in Table 2.1. All sites include dataloggers for recording the measured data.

2.2.2 GHG flux instrumentation

Trace gas fluxes were estimated using a combination of a trace gas instrument and a 3D sonic anemometer. The theory is elaborated on in the next section of this report. The trace gas instrument we used to measure CO_2 fluxes was an open path infrared analyser from LICOR. For N_2O (at the Dripsey grassland site only) we used a closed path tuneable diode laser from Campbell Scientific. We did not measure CH_4 using EC, but at the peatland site we did use chamber instrumentation for CH_4 fluxes. The GHG flux instrumentation is shown in Table 2.2.

2.2.3 Hydrological instrumentation

Precipitation measurements are listed in Table 2.1. In addition to precipitation, we used V notch weirs and open channel hydraulics along with water level recorders to determine the stream flow rates at the Dripsey grassland site and at the Glencar peatland site. In both the Dripsey and Glencar sites there are small streams flowing through the catchments. In the Dripsey grassland site the catchment area is 17 ha and in the Glencar site the catchment area is 75 ha. In the Glencar site we also used an S:SCAN spectrometer to measure continuously the DOC concentration. We also

Table 2.1. Meteorological variables measured and sensors used at the three EC tower sites (DripF, Dripsey forest; DripG, Dripsey grassland; Glen, Glencar peatland)

Variable	Sensor	Manufacturer	Frequency	Location
PAR	PAR Lite	Kipp & Zonen, Netherlands	Every minute	DripG, DripF, Glen
Net radiation	CNR 1	Kipp & Zonen, Netherlands	Every minute	DripG, DripF, Glen
Atmospheric pressure	PTB101B	Vaisala, Finland	Every minute	DripG, DripF, Glen
Relative humidity	HMP45C	Vaisala, Finland	Every minute	DripG, DripF, Glen
Air temperature	HMP45C	Vaisala, Finland	Every minute	DripG, DripF, Glen
Soil temperature	107	Campbell Scientific, UK	Every minute	DripG, DripF, Glen
Soil moisture	CS615	Campbell Scientific, UK	Every minute	DripG, DripF, Glen
Ground heat flux	HFP01	Hukseflux Thermal Sensors, Netherlands	Every minute	DripG, DripF, Glen
Water table	PCDR1830	Campbell Scientific, UK	Every minute	Glen
Precipitation	ARG100	Environmental Measurements, UK	Every 0.2 mm of precipitation	DripG, DripF, Glen
Meteo datalogger	CR3000	Campbell Scientific, UK	–	Drip, DripF, Glen

Table 2.2. Sensors and equipment used for the EC gas flux measurements at the three tower sites (DripF, Dripsey forest; DripG, Dripsey grassland; Glen, Glencar peatland)

Variable	Sensor	Manufacturer	Frequency	Location
CO_2 concentration	Open-path IRGA, LI-7500	LI-COR, USA	10 Hz	DripG, DripF, Glen
N_2O concentration	Closed-path CR1000 TDL, TGA100	Campbell Scientific, USA	10 Hz	DripG
3D wind velocity	CSAT3	Campbell Scientific, USA	10 Hz	DripG, DripF, Glen
CO_2 flux datalogger	CR3000	Campbell Scientific, UK	–	DripG, DripF, Glen
N_2O flux datalogger	PC-based data acquisition	Campbell Scientific, UK	–	DripG

measured WTLs at the Dripsey grassland and at the Glencar peatland sites.

2.3 Eddy Covariance Methods for Measurement of GHG Fluxes

The EC method is a micrometeorological technique that measures the turbulent flux across the vegetation canopy–atmosphere layer to determine the net difference of material moving across this interface (Lenschow, 1995; Baldocchi, 2003). Originally used for the measurement of evaporation from croplands, it has in the past two decades been utilised and very much perfected for GHG fluxes from many different ecosystem types. Two fast-response instruments are necessary for EC measurements: a 3D sonic anemometer and a gas analyser, both operating at high frequency (we used 10 Hz) to cover the full range of the turbulent motion (Table 2.2). CO_2 concentrations were measured with an open-path infrared gas analyser (IRGA), installed beside the sonic anemometer. The instrumentation required to estimate the CO_2/H_2O fluxes is shown in Figure 2.5. At the Dripsey grassland site only, the N_2O concentrations were measured with a closed-path trace gas analyser (TGA). This system consisted of a sensor intake, positioned beside the sonic anemometer, and a tube that carries the sample air to the gas analyser, which is a tuneable diode laser absorption spectrometer tuned for N_2O in this experiment.

2.3.1 Eddy covariance technique and footprint analysis

The EC approach is based on the statistical separation of the mean term of the wind velocity or trace gas concentration (varying over several hour-periods) from their turbulent parts (varying over periods of tens of

Figure 2.5. The Campbell Scientific CSAT 3D sonic anemometer in the background with the LICOR open path trace gas analyser for CO_2 and H_2O in the foreground.

seconds), using Reynolds' rule of averaging (Stull, 1988):

$$\xi = \overline{\xi} + \xi' \quad (2.1)$$

where ξ is any instantaneous turbulent variable, $\overline{\xi}$ is its mean term and ξ' is its fluctuating component.

The CO_2 flux across the canopy–atmosphere layer is defined as the statistical covariance of the wind speed in the vertical direction and the CO_2 concentration:

$$F_c = \overline{w\rho_c} \quad (2.2)$$

Following Reynolds' rule of averaging, equation (2.2) can be decomposed as:

$$F_c = \overline{w}\overline{\rho_c} + \overline{w'\rho_c'} \quad (2.3)$$

This equation indicates that the total vertical flux of any scalar is the sum of a mean vertical flux $\overline{w}\overline{\rho_c}$ and an eddy flux $F_c = \overline{w'\rho_c'}$ (Moncrieff *et al*., 1997). One assumption normally made is that over a suitable interval of time there is no mass movement of air in the vertical, i.e. $\overline{w} = 0$.

$$F_c = \overline{w'\rho_c'} \quad (2.4)$$

This approximation is not completely exact since $\overline{w}$ is not zero, but is too small to be detected by instruments and is therefore computed on the basis of temperature and humidity density, using a correction algorithm, the Webb correction (Moncrieff *et al*., 1997).

In the same way, N_2O fluxes are computed as:

$$F_n = \overline{w'\rho_n'} \quad (2.5)$$

No Webb correction was needed for the N_2O fluxes, as the sample air was dried before reaching the gas analyser and the length of the inlet tube was sufficient to damp the temperature fluctuation of the sample air. The time lag due to the distance travelled by the sample air from the intake to the N_2O analyser was determined by calculating the peak correlation between vertical wind speeds and N_2O concentrations (Laville *et al*., 1999).

For the present study, the CO_2 fluxes were measured and computed using equation 2.4, while N_2O fluxes were computed using equation 2.5. An averaging time of 30 minutes was chosen, as is generally applied in EC studies. The EC CO_2 sensors were mounted at 10 m above ground level in the Dripsey grassland site (for years 2002 to 2004) and at 6 m thereafter. In the Dripsey forest site the EC sensors were mounted approximately 1.5 m above the top of the forest canopy. In the Glencar site the EC sensors were mounted at 2.5 m. The N_2O gas analyser at the Dripsey grassland site had its air intake at 6 m above ground level while the gas analyser itself was positioned at ground level (see Figure 2.6).

The measured CO_2 fluxes were considered to correspond to the NEE because the stored flux in the canopy was considered negligible in grassland and peatland ecosystems for most of the day (Lafleur *et al.*, 2003). The micrometeorological convention (used in this report for EC measurements) treats fluxes from the atmosphere as negative and fluxes from the ecosystem as positive. The source area of the EC-measured gas flux is called the footprint. Briefly, the footprint extension can be approximated on a footprint length to sensor height ratio of 100:1 combined with the probability density distribution of the wind direction. Different models can be used to estimate the footprint in a mathematical way. For our footprint analyses we used an analytical model developed by Hsieh *et al*. (2000). This model analytically relates atmospheric stability, sensor height and the ecosystem's surface roughness to flux and footprint to estimate the location of the peak and of the length of the distribution curve that defines the footprint. This footprint analysis approach was used to estimate the origin of the measured fluxes for each 30-minute averaging interval in the three study sites and the 30-minute footprints were averaged over the full records to provide overall measurement areas for each site.

2.3.2 Eddy covariance data processing and filtering

All data collected were added to a single file that included an entry for every half hour since the beginning of measurements. If no data were available, these entries were left empty and flagged for later gap-filling. Data processing and filtering techniques used for the data from this site were very similar to those used previously, details of which can be found in Jaksic *et al*. (2006), Sottocornola and Kiely (2010a,b) and Koehler *et al*. (2011). Any variation on these approaches is described in this section. Filtering was mostly a result of the poor performance of the LI-7500 and sonic anemometer during precipitation events, or signal noise originating from very weak signals. The data are now published on the European Fluxes Database Cluster site under the site name of Dripsey, IE-Dri and Killorglin-Glencar, IE-Kil (www.europe-fluxdata.eu).

The simplified model developed by Hsieh *et al*. (2000) was used to estimate the fetch length requirement (x_f) for reaching the 90% constant flux layer during neutral, stable and unstable conditions. Fluxes were discarded if x_f was more than 300 m away, which accounted for the removal of < 1% of data based on the findings of Hsieh *et al*. (2000). Co-ordinate rotations are subject to larger errors as the rotational angle increases, especially when wind speeds are low and turbulence is high. Therefore, fluxes associated with unrealistic rotated U-values were removed. This accounted for the removal of only < 0.1% of data when wind speeds were practically zero, typically at night-time.

As a final step, sensible (H) and latent (LE) heat fluxes were filtered based on a fixed linear fit with net radiation (R_n), from which a fixed cut-off value above and below the line of fit was pre-determined. Cut-off values were 75 W m^{-2} for upper and lower H as well as upper LE, whereas the lower cut-off for LE was 60 W m^{-2}. Removal of H and LE in this way provided an unbiased approach for data removal throughout all the seasons, and most removal occurred during periods when R_n, and hence energy transfer, was ≈0. In both cases, this method accounted for less than 4% of overall filtering. The amount of good H-values remaining after filtering ranged between 58% (2011) and 80% (2004), whereas for LE it was between 53% (2009) and 78% (2004).

A series of post-field data processing steps were performed after obtaining the raw fluxes (equations 2.4 and 2.5), and filters were established to ensure the quality of the measured gas fluxes. CO_2 fluxes were excluded if they exceeded what we considered realistic threshold values (see Sottocornola, 2007). The filters used were rather conservative and recognised 59% of the total daytime CO_2 fluxes and 25% of total night-time CO_2 fluxes in Glencar as being good. For further details on data treatment see Sottocornola *et al.* (2010a,b); Koehler *et al*. (2011); Leahy *et al*. (2012); Peichl *et al*. (2013); and McVeigh *et al*. (2014).

Similar filters were used for CO_2 flux data using a pre-determined fixed fit. For daytime fluxes, an exponential fit with photosynthetic active radiation (Q_{PAR}) was used, whereas a linear fit with T_{soil_5cm} (soil temperature at 5-cm depth) was used for night-time data. Alternatively, incoming solar radiation or T_a (air temperature) could have been used to give a nearly identical outcome.

Daytime data were filtered in two stages: first using non-density-corrected CO_2 fluxes to account for poor measurements; and, second, using density-corrected fluxes to account for poor corrections, which were mostly over-corrections (Webb *et al*., 1980). For non-corrected data, the upper cut-off was 7 μmol m^{-2} s^{-1} and the lower cut-off was 5 μmol m^{-2} s^{-1}. For corrected fluxes, upper and lower cut-offs ranged from 1.5 μmol m^{-2} s^{-1} to 4.5 μmol m^{-2} s^{-1} depending on the season. Removal in this way mainly accounted for periods when incoming solar radiation was near zero, resulting in a noisy CO_2 flux signal that had to be filtered.

Night-time data were filtered using only an upper cut-off of 0.5 μmol m^{-2} s^{-1}. Spurious results occurred across the whole temperature range due to the limitations of the EC method to measure accurately at night (Aubinet, 2008). No friction velocity u_* filter was applied because no clear correlation between flux magnitude and u_* was apparent. The amount of good daytime fluxes remaining after filtering ranged from 44% (2009) to 68% (2004), whereas it ranged from 21% (2009) to 35% (2007) for night-time data.

The partitioning of NEE of CO_2 along with the separate study of ER and GEP are necessary to evaluate the sensitivity of ecosystems to climate change (Barr *et al*., 2007; Dunn *et al*., 2007). To calculate ER, the Lloyd and Taylor (1994) exponential regression was used to model the daytime ER by considering night-time NEE to be ER, and applying a night-time-derived ER model to daytime, assuming that the temperature dependence is the same during day and night (Reichstein *et al*., 2005). To calculate GEP, the following equation was used:

$$GEP = ER - NEE \qquad (2.6)$$

2.3.3 Gap-filling of missing eddy covariance fluxes

The missing CO_2 gas fluxes were replaced (i.e. gap-filled) by non-linear regression equations relating good fluxes and meteorological variables (e.g. air temperature, soil temperature, Q_{PAR}, water table). Data were divided into bimonthly datasets (or monthly datasets in Glencar) and separate gap-filling equations were established for day and night-time data. Daytime data were gap-filled using rectangular equations between good CO_2 fluxes and Q_{PAR} (Frolking *et al*., 1998) [or polynomial equations in one variable of different orders and air temperature, in Glencar (Sottocornola *et al*., 2007, 2010a,b)]. Night-time data were gap-filled using either a look-up table method (Falge *et al*., 2001) or exponential equations [Arrhenius in Dripsey (Lloyd and Taylor, 1994)], relating the half-hour CO_2 flux with soil temperature (T_{soil}) for the full period of measurement. These regression equations were defined using the Curve Fitting Function of MATLAB 7.0.1 software (MathWorks Inc., USA). The look-up table method was used in Dripsey because this is a more suitable approach when the measurement data are then modelled.

The gap-filling functions tested were non-linear regressions (see Goulden *et al*., 1996; Falge *et al*., 2001; Lai *et al*., 2002). For night-time data, the ER is linked to the soil temperature (Kirschbaum, 1995) and to a lesser extent to soil moisture. The correlation with different temperatures (air, surface, different soil depths) showed best correlation with soil temperature at a depth of 5 cm, whereas respiration was less well correlated to soil moisture [consistent with the analysis of Novick *et al*. (2004) for a warm temperate grassland and with Nieveen *et al*. (2005)]. Different soil temperature response functions were tested and parameterised statistically [sum of squares error (SSE), coefficient of determination (R^2), adjusted coefficient of determination (adjusted-R^2), and root mean squared error (RMSE)]. A linear relationship, an exponential relationship, the Arrhenius function and a Q_{10} relationship were all considered. The best fit regression model (with highest R^2) for the Dripsey site (for night-time respiration $F_{RE,night}$) was that obtained using the van 't Hoff simple empirical exponential fit (Lloyd and Taylor, 1994), defined in equation (2.7):

$$F_{RE,night} = ae^{bTs} \qquad (2.7)$$

where T_s is the soil temperature at 5-cm depth in °C. The coefficient *a* (sometimes noted as R_{10}) represents the sum of plant and soil respiration at 10°C (μmol CO_2 m^{-2} s^{-1}). For 2002 at the Dripsey grassland site, *a* was found to be 1.476 ± 0.087 μmol CO_2 m^{-2} s^{-1} and for 2003 it was 1.109 ± 0.072 μmol CO_2 m^{-2} s^{-1}. The coefficient *b* for 2002 was estimated to be 0.095 ± 0.005°C^{-1} and for 2003 was 0.122 ± 0.005°C^{-1}. The R^2 for 2002 was 0.324 and for 2003 was 0.381. The coefficients and statistics are reported in Jaksic *et al.* (2007). Equation 2.7 was applied to the data for each full year. A criticism of the van 't Hoff form of the respiration equation (Lloyd and Taylor, 1994) is that it underestimates respiration at low temperatures and overestimates respiration rates at high temperatures. In the temperate climate of this Dripsey study, the range of daily soil temperature (at 5-cm depth) was 3°C to 16°C. In this study the van 't Hoff form fits the data well, particularly because of the narrow spread of soil temperature on either side of 10°C (Jaksic *et al.*, 2006).

For daytime, the NEE ($F_{NEE,day}$ in μmol CO_2 $m^{-2}s^{-1}$) is linked to the photosynthetically active radiation Q_{PAR} (μmol quantum $m^{-2}s^{-1}$) [e.g. Michaelis and Menten, 1913 (translated); Smith, 1938; Goulden *et al.*, 1996]. The different light response functions evaluated included a linear relationship, Smith formula (Smith, 1938; Falge *et al.*, 2001), Michaelis–Menten formula (rectangular hyperbola) (Michaelis and Menten, 1913; Falge *et al.*, 2001), Misterlich formula (Falge *et al.*, 2001), and Ruimy formula (Ruimy *et al.*, 1995; Lai *et al.*, 2002). The best fit was achieved with the Misterlich formula defined in equation 2.8:

$$F_{NEE,day} = -F_{GPP,opt}\left(1 - e^{\left(\frac{-\alpha Q}{F_{GPP,opt}}\right)}\right) + \gamma \qquad (2.8)$$

where Q is the photosynthetic photon flux density (Q_{PAR}, μmol quantum $m^{-2}s^{-1}$); α is ecosystem quantum yield [(μmol CO_2 $m^{-2}s^{-1}$) (μmol quantum $m^{-2}s^{-1}$)$^{-1}$]; and γ is the ER during the day (μmol CO_2 $m^{-2}s^{-1}$). $F_{GPP,opt}$ is the GPP at "saturating light" (μmol CO_2 $m^{-2}s^{-1}$) (Michaelis and Menten, 1913; Smith, 1938) and was set at the mean value for this experiment of –24 μmol CO_2 $m^{-2}s^{-1}$. As Q varies seasonally, the regressions are performed on 2-month bins and the values of the coefficients (α and γ) are shown in Jaksic *et al.* (2006).

Gaps also occurred in meteorological data, due to electricity outages, replacement or unsatisfactory performance of instruments. However, this was rare and when an outage occurred it was rapidly fixed. Short meteorological gaps (up to 4 hours) were replaced by the interpolation between the last measured data before and the first measured data after the gap, except for radiation and precipitation. With gaps longer than 4 hours, the meteorological data were replaced by the average of the previous and following 7 days for the missing half-hour as recommended by the CarboEurope procedure (Falge *et al.*, 2001). The latter method was applied to radiation data as well, unless any radiation measurement was present so that missing values could be replaced by linear relationships between radiation variables. Missing precipitation data were replaced using linear relationships with precipitation data from nearby weather stations (Cork Airport for Dripsey and Valentia for Glencar).

2.4 The Chamber Methodology for Measuring CO_2 and CH_4 Fluxes

The chamber technique measures gas fluxes by integrating the gas concentration (CO_2 and CH_4 in Glencar) measurements inside a closed environment (chamber of size 0.6 m × 0.6 m in plan) over a period of time. This means that the chamber technique measures a rather limited number of values, typically no more than a few per day on the days that measurements are taken. As such, the chamber technique is not a continuous measurement like the EC measurements. Also the chamber measurement is applicable at the scale of the chamber size (of order 1 m) by comparison with an order of 1 km for the EC technique.

A set of coupled CO_2 measurements were carried out for each sample plot using a portable infrared gas analyser (EGM-4, PP Systems, UK). The instantaneous NEE was first measured under a stable ambient illumination at 15-second intervals over a 60- to 240-second period. The same procedure was then repeated with the chamber covered with an opaque canvas cover to get an estimate of the instantaneous ER rate (R_E). The CO_2 flux rates were calculated from the linear change in gas concentration as a function of time. The ecological sign convention, in which fluxes from the biosphere to the atmosphere are negative, was used for chamber work. Gross photosynthesis (P_G) was estimated as the sum of flux rate values measured in light (NEE) and dark (R_E).

The CH_4 measurement chambers (dimensions: 0.6 × 0.6 m × 0.25 m) were vented (as the CO_2 chambers were) to ensure pressure equilibrium between the headspace and the outside, and were equipped with fans to ensure even mixing within. Air samples were collected from the chamber headspace inside four 40-ml polypropylene syringes at 5-minute intervals (10-minute intervals in wintertime). Samples were stored at ambient temperature and analysed for CH_4 concentrations within 48 hours in the lab on a Shimadzu GC-14-B gas chromatograph equipped with a drierite moisture trap and a flame ionisation detector, and N_2 as the carrier gas (Laine, 2006).

To relate the CO_2 and CH_4 gas fluxes to prevailing meteorological conditions, a set of parameters (Q_{PAR}, water level, T_{air}, T_{soil} at 5, 10, 20 and 30-cm depths) were measured in connection with the gas exchange measurements. Continuous meteorological measurements of the tower stations (Table 2.1) were used to upscale chamber measurements to the ecosystem and to the annual timescale.

To facilitate the chamber CH_4 flux measurements, 28 plots were selected from which 24 were equipped with constant collars, while floating chambers were used for the remaining four plots. To relate the CH_4 flux to environmental conditions, air temperature, soil temperature at different depths (5-cm, 10-cm, 20-cm and 30-cm depth) and WTL adjacent to each sample plot were recorded simultaneously with the CH_4 readings. Air and soil temperature were measured using thermocouples (fine wire type K thermocouple, Radionics Ltd, Ireland). The WTL was determined from perforated PVC pipes protruding 10 cm above the peat surface to account for standing water above the surface. For the majority of hollow plots a different technique was used, as the ground was too soft and wet to keep the PVC pipes in place. Instead bamboo sticks were inserted in the peat that reached down to the underlying solid ground of the bog and the water table level was marked at the day of installation. The absolute change between the mark and the water table level on the days of the CH_4 flux measurements was recorded.

The closed chamber method was used to estimate the flux of CH_4 from the peatland. CH_4 measurements conducted from August 2003 until September 2005 are described in Laine *et al.* (2007). Further CH_4 chamber measurements were carried out at biweekly to monthly intervals during 2008. As a result of relatively mild winters with little frost, it was possible to sample all the year round. Four replicate plots were sampled for each of the three microforms: hummock, high lawn and low lawn. In contrast to Laine *et al.* (2007) the hollows were further divided into hollows with a mud bottom, hollows covered by mosses only, by vascular plants without *Menyanthes trifoliata* or by vascular plants including *M. trifoliata.* Four replicates were sampled for each defined hollow type. As it was not possible to install collars at four of the hollow plots, the chamber size was reduced from 0.6 × 0.6 × 0.25 m to 0.3 × 0.3 × 0.3 m to use floating chambers. Apart from the size, the remaining chamber features and additional measurements of soil temperature at different depths and water table depth for each plot were the same as in Laine *et al.* (2007). Accordingly the same non-linear regression approach as in Laine *et al.* (2007) was used to reconstruct CH_4 fluxes for the period 2003 to 2008:

$$CH_4 = (c + d \times WTL)(\exp(b \times T_{soil\ 20cm})) \tag{2.9}$$

where *b*, *c* and *d* are parameters, WTL is water table level and $T_{soil\ 20cm}$ is the soil temperature at 20 cm depth. Equation 2.9 was parameterised for each sample plot separately based on the periodic chamber measurements between 2003 and 2005 and during 2008, and then used to estimate the CH_4 flux for the whole period 2003 to 2008. If the linear function describing the relationship of the WTL to CH_4 flux did not increase the explanatory power of equation 2.9, it was replaced with a constant, *a*. Four plots had to be taken out of the final flux calculation, as the fit of the non-linear regression was not satisfactory; nevertheless at least three replicates were available for each microform. For the CH_4 flux integration, a continuous (30-minute) time series of $T_{soil\ 20cm}$ and WTL for each sample plot were reconstructed from the $T_{soil\ 20cm}$ and WTL continuously measured at the meteorological station. The annual CH_4 flux was calculated through an upscaling based on the known average distribution of the microforms around the EC tower (as defined by Laine *et al*., 2006). The standard error of the average annual CH_4 flux from each microform type was computed and weighted according to the microform distribution to estimate an error for the annual CH_4 fluxes (Laine *et al*., 2007).

2.5 Methods for Measuring DOC Fluxes

At the northern outfall of the catchment (close to the road and to Dromalonhurt bridge), stream height was recorded every 30 minutes starting 1 January 2007 using a pressure transducer (1830 Series, Druck Limited, UK). Stream height was converted to discharge using a rating curve:

$$Q = 0.685 \times s^{1.79}, \quad \text{number of measurements} = 10,\ r^2 = 0.995 \tag{2.10}$$

where *Q* is discharge in $m^3 s^{-1}$ and *s* is stream height in m. The total discharge was calculated by integrating the 30-minute discharge data. The rating curve was established from manual measurements of instantaneous discharge carried out at a range of stream heights using an OTT current meter (OTT Messtechnik GmbH & Co KG, Germany). The error related to the discharge calculation was determined from the standard error of the rating curve and an error of 5% was included to account for drainage basin area uncertainties (Fraser *et al.*, 2001).

Continuous measurements (30-minute intervals) of DOC began in January 2007 using an S-can spectro::lyser (scan Messtechnik GmbH, Austria). The instrument is constantly immersed in the stream at the gauge site (Figure 2.2) and works according to the measuring principle of ultraviolet–visible (UV-Vis) spectroscopy. The measured spectrum ranges from 200 to 735 nm and the absorbance is determined every 2.5 nm. The calculation of the DOC concentration is based on the inclusion of over 80 wavelengths, some to actually calculate the concentration but most for correction of turbidity. The spectro::lyser's lenses were automatically cleaned before each 30-minute measurement by a puff of pressurised air and manually every 1–2 weeks. Additionally, the spectro::lyser readings were zeroed using distilled water approximately every 4 months. These precautions reduced the drifting of the spectro::lyser as a result of environmental conditions. The drifting between two subsequent manual cleaning (usually below 1 mg L^{-1}) and calibration events was corrected assuming a constant linear drift over time. Moreover, as the automatic in-stream spectro::lyser is not specifically designed for peatland waters, its measurements were calibrated on a regular basis with results from chemical laboratory analyses. A 24-bottle auto-sampler (6712 portable sampler, Teledyne Isco, Inc., USA) was used approximately every 6 weeks from April to October 2007 to collect water samples at intervals between 1 and 3 hours at the same location as the spectro::lyser. The auto-sampler was installed in the stream to monitor a range of flow conditions. DOC concentration in the water samples was measured in the laboratory using a TOC-V cpH (SHIMADZU Scientific Instruments, USA), which works according to an oxidative combustion–infrared method. Spectro::lyser measurements and laboratory analyses compared well during both dry periods and storm events regarding the general trend of DOC concentration, i.e. increase or decrease in concentration. A constant difference between laboratory and field measurements over the sampling time was observed; therefore the spectro::lyser measurements were corrected for linear drifting between consecuetive bottle auto-sampler collections.

The DOC flux was computed as the product of DOC concentration and stream flow discharge. For the years 2003 to 2006, the measured stream height and DOC concentration were not available and were therefore modelled as follows. The monthly discharge was regressed against monthly precipitation (data 2007–2008):

$$Q = precip \times 0.896 + 6.138,\ r^2 = 0.90,\ \text{RMSE} = 35.7 \tag{2.11}$$

where Q is discharge and *precip* is the monthly precipitation, both in mm.

The best relationship for DOC concentration was an s-shaped function of binned daily mean air temperature (T_{air} in °C) and daily mean DOC concentration (*DOC* in mg L^{-1}) (see Figure 2.6).

$$DOC = 3.763 + \frac{5.144}{1 + \exp(-0.6888 \times T_{air} + 7.387)},\quad r^2 = 0.92,\ \text{RMSE} = 0.63 \tag{2.12}$$

An error estimate for equations 2.11 and 2.12 was computed as described for the relationship between stream height and discharge (equation 2.11) (Fraser *et al.*, 2001), resulting in a lower and upper estimate of the DOC flux for the period 2003 to 2006. To calculate the DOC flux for the period 2003 to 2006 the estimated daily DOC concentration was averaged over the month and multiplied by the estimated monthly discharge resulting in estimates of 12.6 ± 3.2 g C m^{-2} for 2007 and 15.8 ± 3.2 g C m^{-2} for 2008, compared to our measured values of 11.9 ± 1.2 and 15.0 ± 1.3 g C m^{-2} for 2007 and 2008, respectively.

Additionally, DOC concentration in precipitation was measured over a 1-year period ($n = 7$) with three replicates each time using a funnel with an attached bottle. The bottles were left out in the field for up to 3 days during a rainy period and were analysed for DOC concentration thereafter as described below. The product of the mean DOC concentration over the 1-year period and the annual amount of precipitation were used to estimate the DOC input in precipitation for each year. For the stream water, a 24-bottle auto-sampler was used every 6–8 weeks and the samples

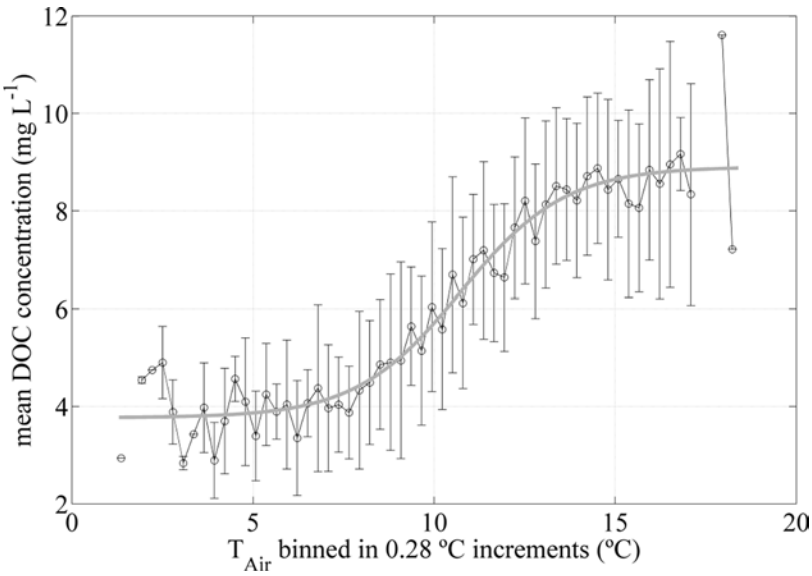

Figure 2.6. S-shaped relationship of binned mean daily T_{air} and corresponding mean daily DOC concentration. From Koehler (2012).

were analysed for dissolved and total organic carbon using a TOC-V cpH. The flux of particulate organic carbon (POC), which is the difference between total and dissolved organic carbon, was estimated using the average percentage of POC calculated from the bottle auto-sampler results.

3 Results

3.1 Dripsey Grassland

In Figure 3.1 we show the time series of environmental variables (T_{air}, T_{soil_5cm}, monthly rainfall) and water vapour flux (evapotranspiration), energy (net radiation) and CO_2 fluxes at the Dripsey grassland site in County Cork from its inception in 2002 to 2012. Overall there is not a significant difference in environmental variables over the 10-year period.

The air temperature rarely exceeded 25°C and never decreased beyond –6°C, while the soil temperature at 5-cm depth rarely exceeded 20°C and never decreased beyond 0°C. The mild temperatures enable a long grass growing season (8–9 months) from mid-February/early March to late October/mid-November. The monthly rainfall has never exceeded 300 mm and has never been lower than 15 mm. The rainfall, which is higher in winter than in summer, does show sufficient rain levels in the summer months to enable productivity. The average annual rainfall is approximately 1500 mm.

Photosynthetic active radiation (Q_{PAR}) in the spectral range of 400 to 700 nm, that is, radiation that photosynthetic organisms are able to use in the process of photosynthesis, had a maximum each summer of approximately 2100 μmol m^{-2} s^{-1}.

The sensible heat flux, H, had a maximum of just above 200 W m^{-2} while evapotranspiration (LE) had a maximum of just above 300 W m^{-2}. These maximum values occurred in the height of summer, indicating

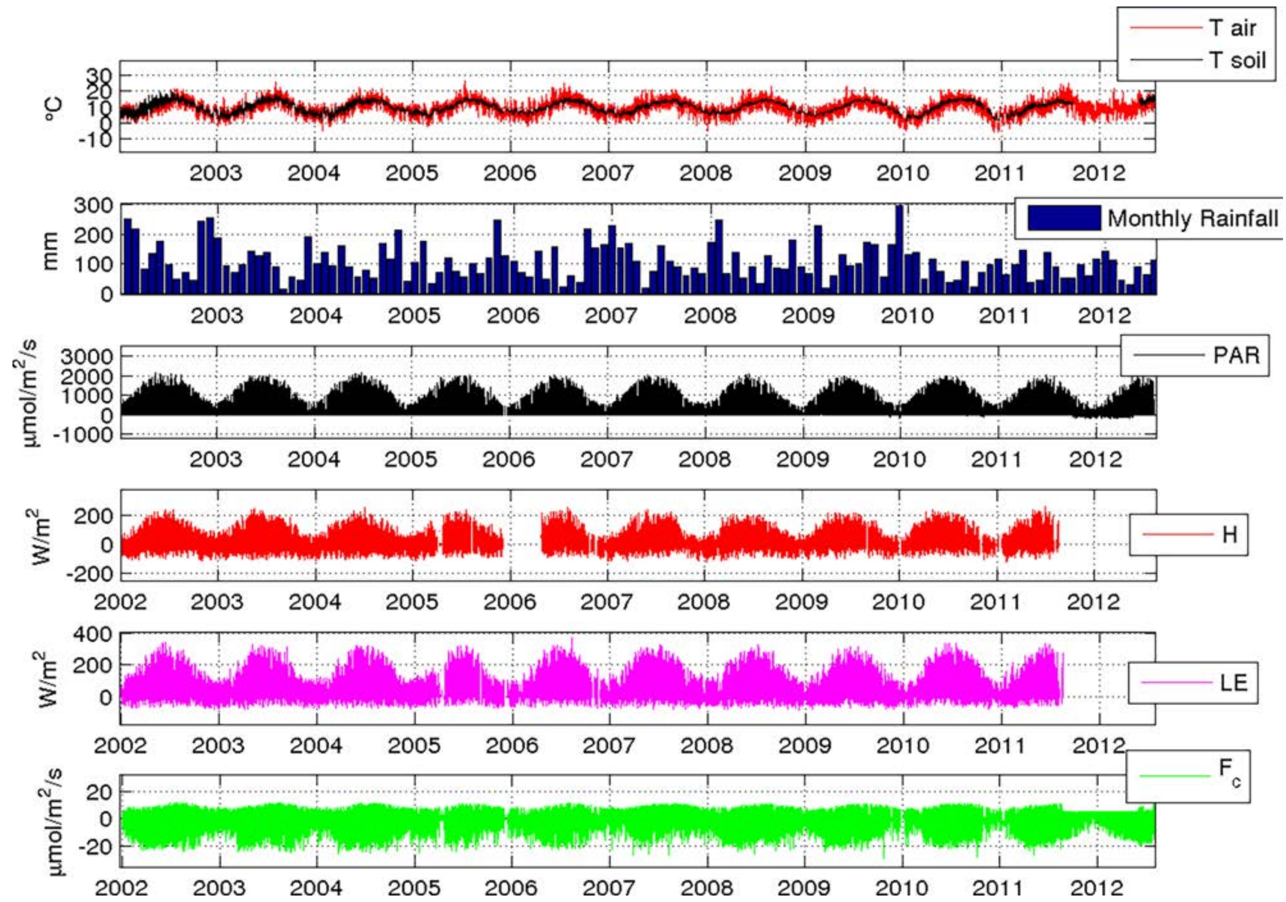

Figure 3.1. Time series of environmental variables and results for water, energy and CO_2 fluxes at Dripsey grassland site from 2002 to 2012.

that there is more than enough moisture to permit maximum evapotranspiration.

The sixth graph in Figure 3.1 is the instantaneous CO_2 flux (F_c) in units of µmol m^{-2} s^{-1}. The maximum uptake (near mid-day in summer time) was approximately 35 µmol m^{-2} s^{-1} while the maximum respiration (at night-time in the summer) was approximately 8 µmol m^{-2} s^{-1}. While maximum and minimum values are similar in each year, there are significant differences in the length of the uptake period and this is primarily due to three influencing factors:

- Rainfall – too little limits productivity, too much tends to occur at the same time as lack of sunshine, also limiting productivity.
- Management practices – silage cutting is followed by a 3-week period of no uptake and only respiration, so cutting at the height of summer (e.g. beginning of June) reduces the overall annual CO_2 uptake.
- Soil temperatures in February/March and October/November – if the soil temperature falls below 6°C, grass growth does not occur, and this defines the beginning and end of the growing season.

In Figure 3.2 we show for the Dripsey grassland site the cumulative CO_2 fluxes over each year expressed in g C m^2 ha^{-1}. The negative sign means uptake (sink). We note that 100 g C m^2 ha^{-1} is the same as 1 t C ha^{-1} yr^{-1}. The annual cumulative value ranges from a low in 2005 of –85 g C m^{-2} ha^{-1} yr^{-1} to a high in 2008 of –340 g C m^{-2} ha^{-1} yr^{-1} (–0.85 to –3.4 t C ha^{-1} yr^{-1}) and a mean over the 8 years of –201 g C m^{-2} yr^{-1}. It is noted from Figure 3.2 that the start of growing season varies in each year and starts within the first 35 to 70 days of the year. We note the start of the growing season as where the curvature of the cumulative flux line changes or where dC/dt = 0. On average, the growing season starts at approximately day 50. The growing season terminates between day 250 and day 280, and on average, day 270. This gives a growing season length of 220 ± 30 days. This indicates the robustness of this grassland ecosystem over the years. The limits to annual productivity seem to be in the first

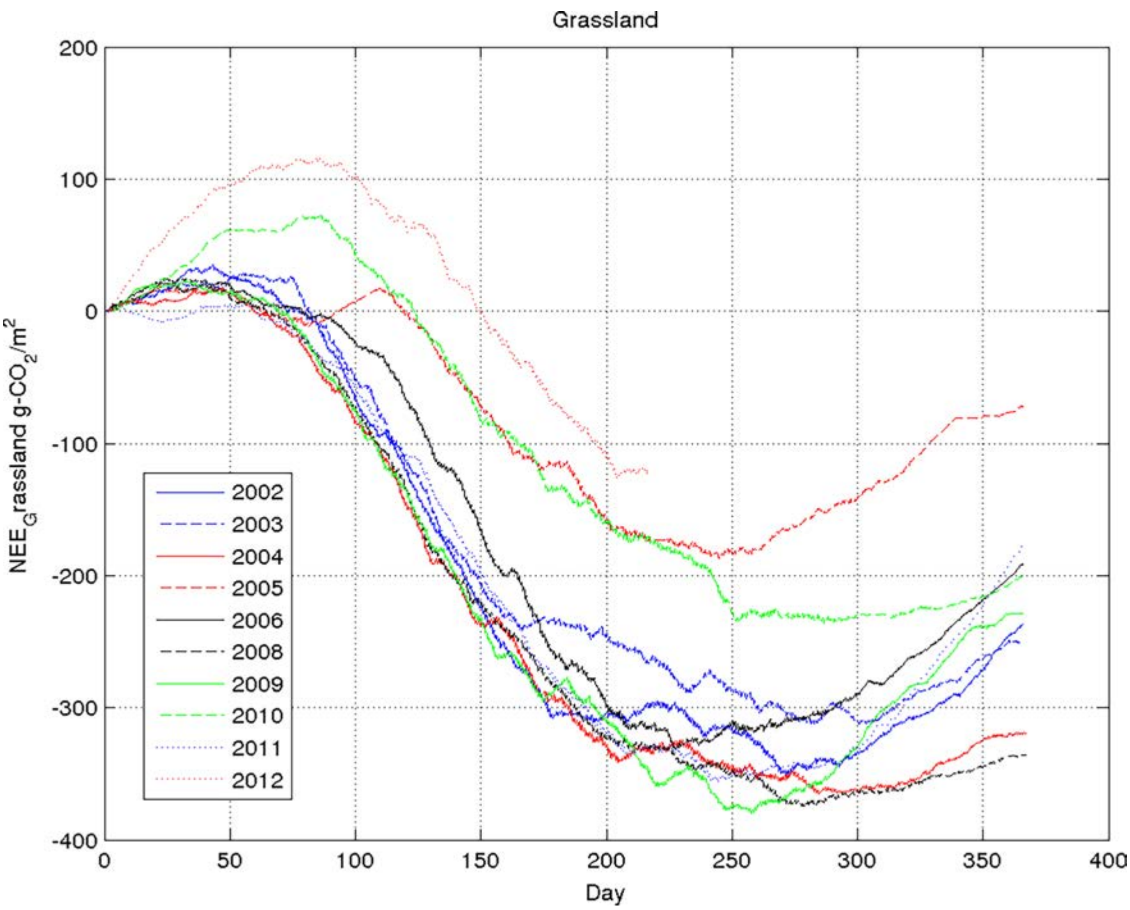

Figure 3.2. Cumulative CO_2 fluxes in g C m^{-2} ha^{-1} at the Dripsey grassland site in County Cork for the years 2002 to 2012. Data for 2007 not included.

2 months and the final 2 months of the year when temperature varies most from year to year. For this grassland ecosystem, temperature, and particularly winter temperatures, are a strong control on CO_2 fluxes. The timing of silage cutting also impacts the cumulative fluxes as cutting events are followed by an approximately 3-week respiration period.

The rate of growth during the key part of the growing season (day 70 to 100) is approximately 3 g C m^{-2} ha^{-1} day^{-1}. This suggests significant productivity for the approximately 4-month period from the beginning of the growing season (in March) to the beginning of silage cutting in June.

3.2 Dripsey Broadleaf Forest

In Figure 3.3 we show for the Dripsey forest site in County Cork the time series for 2009 to 2012 of environmental variables (T_{air}, T_{soil_5cm}, the monthly rainfall) and water, energy and CO_2 fluxes. This site was afforested with broadleaf species in 2005, having previously been part of the Dripsey grassland site. The environmental variables are similar to that of the adjacent Dripsey grassland site.

We do not include the N_2O fluxes in this report and refer the reader to the following papers: Scanlon and Kiely (2003); Leahy *et al.* (2004); Mishurov and Kiely (2010a,b); and Rafique *et al.* (2011).

In Figure 3.4 we show for the Dripsey forest site the cumulative CO_2 fluxes over each year expressed as g C m^{-2} ha^{-1}. The annual cumulative ranges from a low in 2010 of –46 g C m^2 ha^{-1} yr^{-1} to a high in 2011 of –212 g C m^{-2} ha^{-1} yr^{-1} (–0.46 to –2.12 t C ha^{-1} yr^{-1}), with an annual mean of –130 g C m^2 ha^{-1} yr^{-1}. Our first year of flux measurement was 2009 and at that stage the forest was still very young, having been established only in 2005.

3.3 Glencar Blanket Peatland

In Figures 3.5 and 3.6 we show the time series of environmental variables (T_{air}; $T_{soil\ 5cm}$; monthly rainfall)

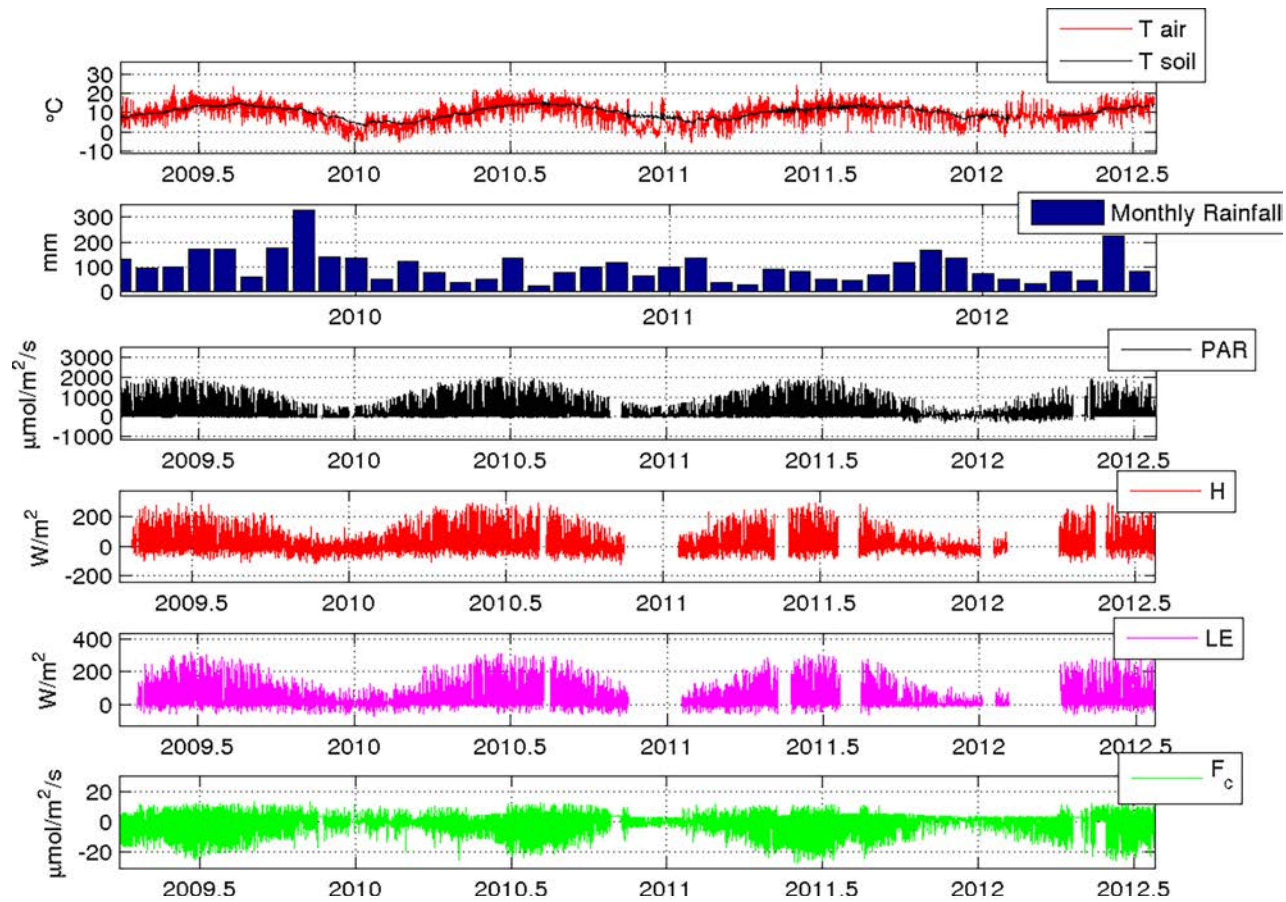

Figure 3.3. Time series of environmental variables and results for water, energy and CO_2 fluxes at the Dripsey forest site from 2009 to 2012.

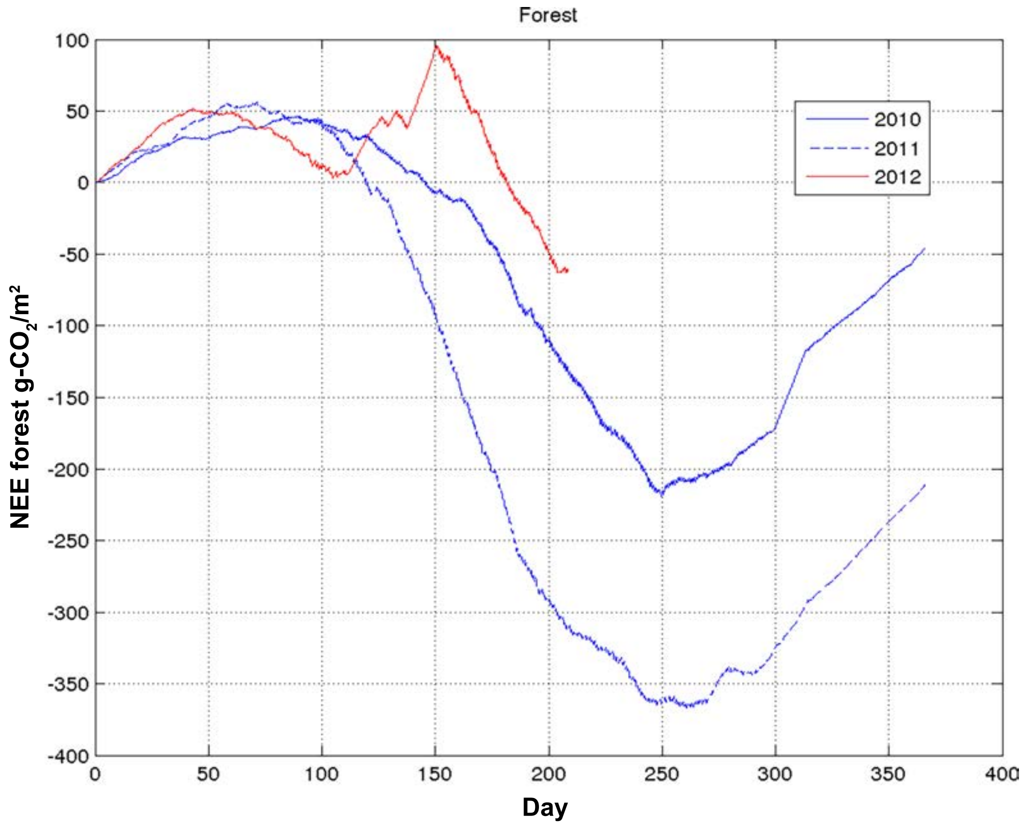

Figure 3.4. Cumulative CO_2 fluxes in g C m^{-2}ha^{-1} at the Dripsey forest site in County Cork for the years 2009 to 2011.

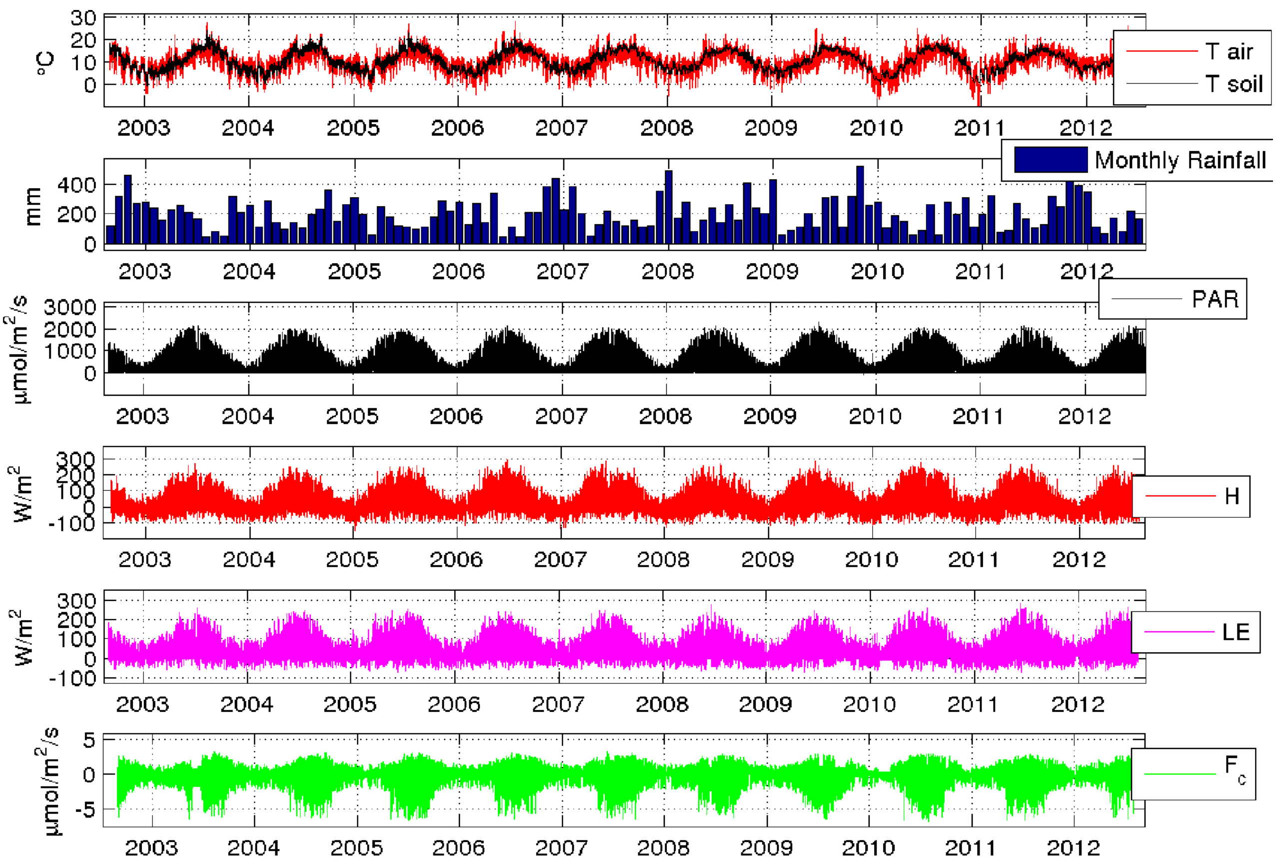

Figure 3.5. Time series of environmental variables and results for water, energy and CO_2 fluxes at the Glencar peatland site from 2003 to 2012.

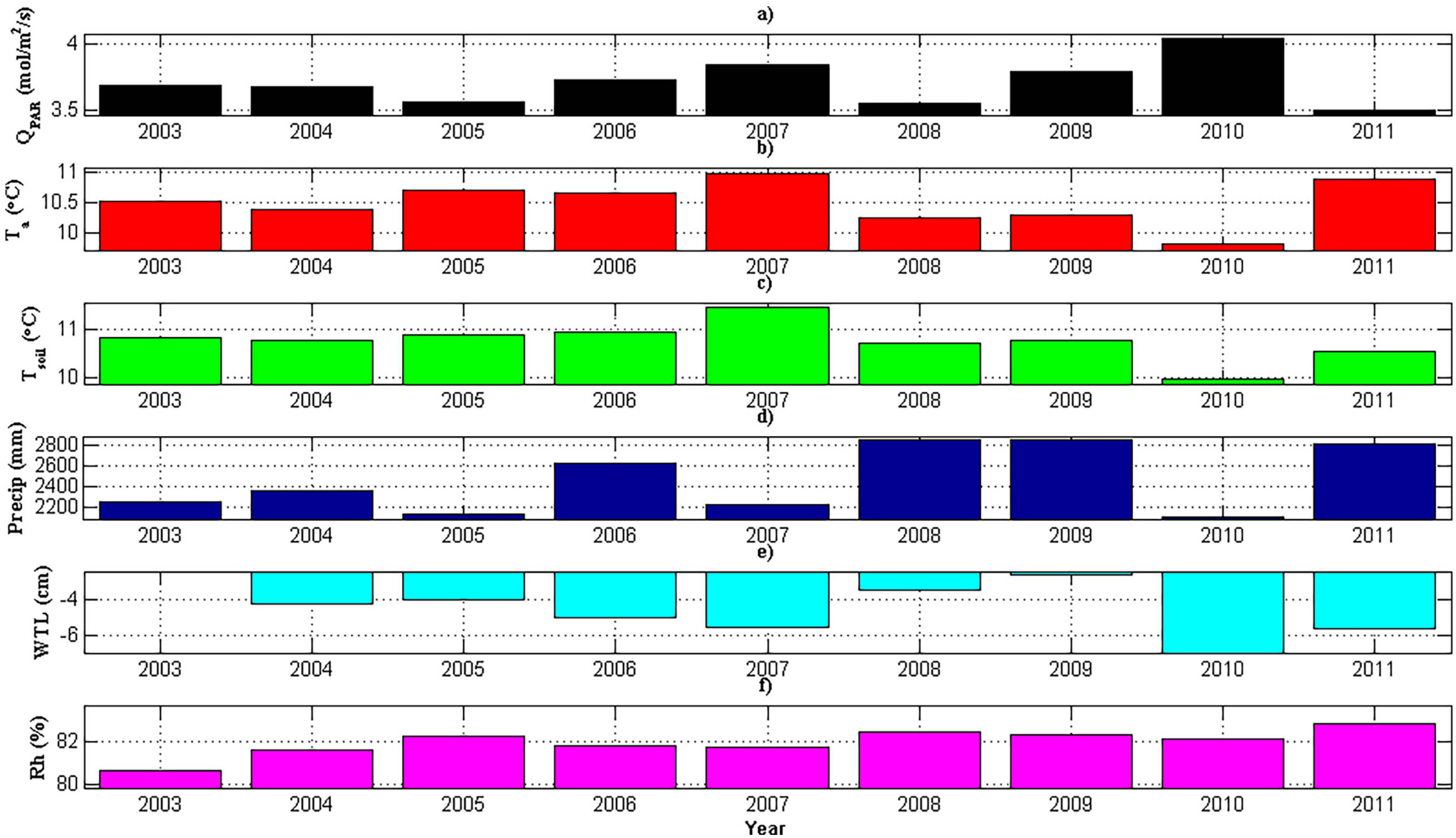

Figure 3.6. Annual values for meteorological variables during each year of measurements. (a) Total Q_{PAR}, (b) average air temperature, (c) average soil temperature at 5-cm depth, (d) total precipitation, (e) average eater table level, and (f) average relative humidity. Reproduced from McVeigh *et al.* (2014), with permission from Elsevier.

Table 3.1. For the Glencar Blanket Peatland annual sums or averages for each year for various meteorological and CO_2 exchange variables. ER, ecosystem respiration; GEP, gross ecosystem production; NEE, net ecosystem CO_2 exchange; precip, precipitation; Q_{PAR}, photosynthetically active radiation; Rh, relative humidity; T_a, air temperature; $T_{soil\ 5\text{-}cm}$, soil temperature at 5-cm depth; WTL, water table level

	2003	2004	2005	2006	2007	2008	2009	2010	2011
Q_{PAR} (μmol $m^{-2} s^{-1}$)	3.68	3.67	3.55	3.73	3.84	3.54	3.79	4.04	3.49
T_a (°C)	10.51	10.38	10.70	10.66	10.97	10.25	10.30	9.82	10.88
$T_{soil,5cm}$ (°C)	10.84	10.77	10.89	10.95	11.46	10.71	10.78	9.97	10.55
Precip (mm)	2254.2	2355.6	2134.9	2617.5	2229.9	2843.1	2854.4	2106.1	2810.5
WTL (cm)	–2.42	–4.20	–4.01	–4.99	–5.50	–3.50	–2.63	–7.01	–5.63
Rh (%)	80.65	81.62	82.25	81.82	81.73	82.41	82.32	82.08	82.84
NEE (g C-CO_2 m^{-2})	–67.9	–75.9	–79.2	–32.3	–32.1	–57.4	–59.3	–42.9	–54.2
ER (g C-CO_2 m^{-2})	236.0	233.6	234.7	236.5	244.8	227.4	231.3	220.8	223.1
GEP (g C-CO_2 m^{-2})	303.8	309.4	313.9	268.8	276.9	284.8	290.6	263.7	277.3

Reproduced from McVeigh *et al.* (2014), with permission from Elsevier.

and water, energy and carbon dioxide fluxes at the Glencar blanket peatland site in County Kerry, from its inception in 2003 to 2012.

The 10 complete years of measurements between September 2002 and August 2012 in Glencar were characterised by a wide range of environmental conditions (see Figures 3.5 and 3.6, and Table 3.1). These ten years saw some of the warmest months coupled with the wettest months and years, as well as some of the coldest winters on Met Éireann's national archives (http://www.met.ie/climate-ireland/rainfall.asp and http://www.met.ie/climate-ireland/surface-temperature.asp).

Summer 2006 experienced the highest average seasonal temperature (16.4°C) as well as the highest half-hourly temperature recorded in Glencar (27.9°C). During the winters of 2009/2010 and 2010/2011, temperatures across Britain and Ireland dropped to record lows, with half-hour average temperatures as low as –11.1°C measured in Glencar during December 2010, in what was the second coldest Irish winter on record between 1961 and 2010 according to the Irish National Meteorological Service (Met Éireann) records. Monthly values of T_{air} at Glencar ranged from 3°C (December 2010) to 16°C (July 2006). Annual T_{air} values were lowest in 2010 at 9.8°C and highest in 2007 at 11°C, with an overall annual average of 10.5°C.

The three wettest years occurred during 2008, 2009 and 2011, after data from Glencar were last reported by Sottocornola and Kiely (2010a,b). Summers were generally drier than winters, although August 2008 had the greatest amount of rainfall recorded in a single half hour, amounting to nearly 14 mm. Seasonal precipitation variance was quite high, whereby monthly values ranged from 42 mm (August 2003) to 520 mm (November 2009), the latter resulted in widespread flooding nationwide. The year 2009 was the wettest of the 10 years measured, with 2854 mm of rainfall, whereas 2010 was the driest at 2106 mm, with an overall 10-year average of 2467 mm. The year 2009 was also the wettest on record nationally for the period 1941–2010 according to Met Éireann records.

The WTL follows a similar seasonal and annual pattern to that of precipitation; the WTL is generally higher (i.e. closer to the surface) in winter than summer. The interannual variation (IAV) in WTL was relatively high, with one of the highest annual mean levels in 2009 (–2.6 cm) to the lowest in 2010 (–7.0 cm).

R_h was typically lowest on average during the spring and early summer months, showing minimal IAV, being lowest during 2003 (81%) and highest in 2011 (83%). LE fluxes during 2011 and 2004 were the highest recorded over the 10 years, averaging at 32.5 and 32.9 W m^{-2}, respectively. The opposite was found for 2003, having one of the highest WTLs, yet one of the

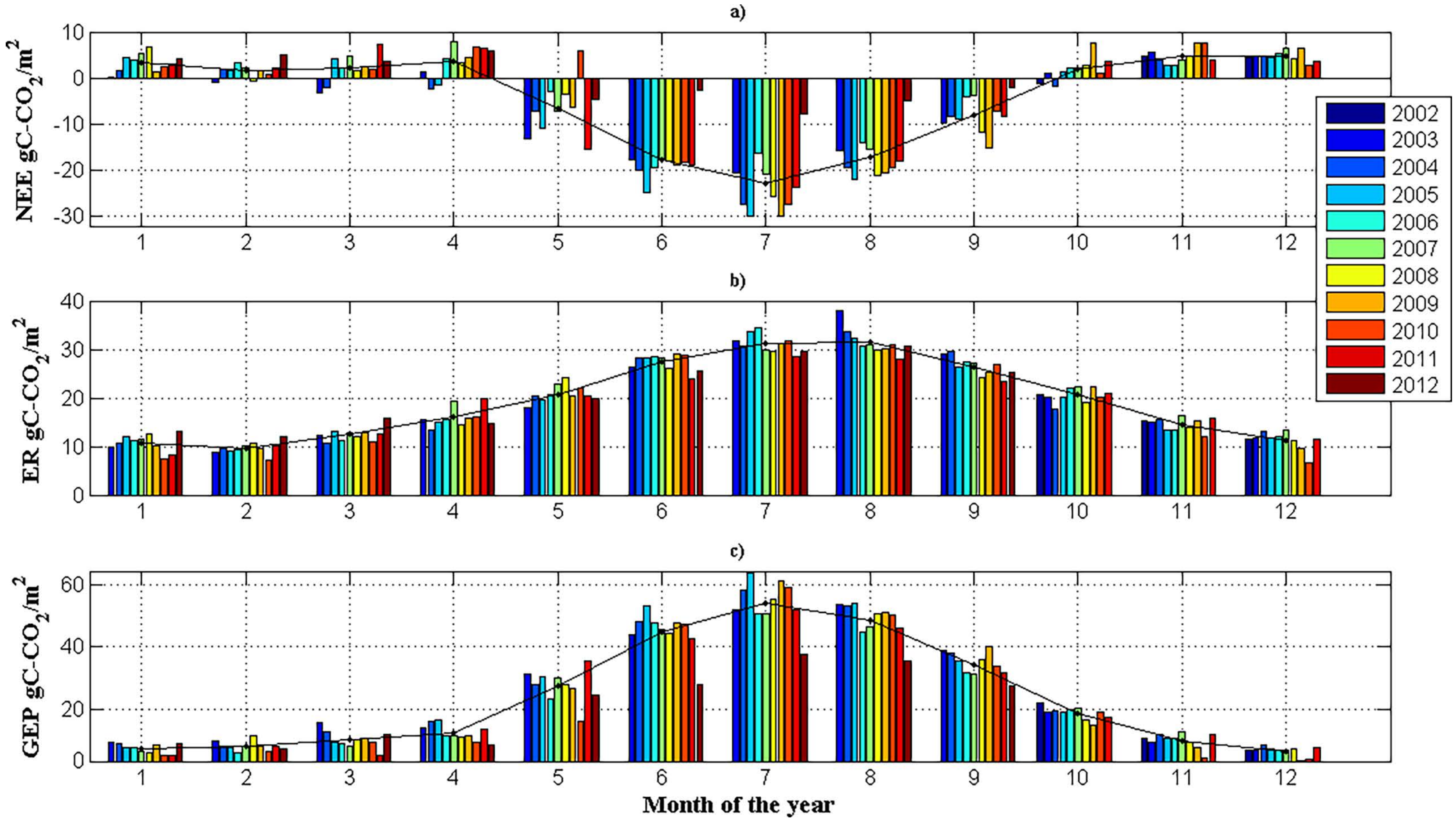

Figure 3.7. Monthly sums of CO_2 flux components across all years. (a) NEE (Net ecosystem exchange), (b) ER (Ecosystem respiration), (c) GEP (Gross ecosystem production). The black dots joined by solid lines represent averages for each month across all years (2003–2011). Reproduced from McVeigh *et al.* (2014), with permission from Elsevier.

lowest R_h rates. Monthly average WTL varied from –13 cm to 0 cm and monthly average R_h varied from 74% to 88%.

ER and GEP were highest during the summer months, with GEP displaying a larger seasonal variation (Figure 3.3). Monthly ER values ranged between 6.7 g C-CO_2 m^{-2} (December 2010) and 38 g C-CO_2 m^{-2} (August 2003). Monthly GEP values ranged between 3.2 g C-CO_2 m^{-2} (December 2009) and 63.7 g C-CO_2 m^{-2} (July 2005). On an annual basis, ER was highest during 2007 and GEP during 2005 (Figure 3.7).

The start of the growing season varied between 23 April in 2004 and 27 May in 2010, while the end of the growing season ranged between 15 September in 2011 and 5 October in 2005: a growing season period of about 5 months.

Cumulative values for NEE, GEP and ER indicate that on an annual basis the Glencar peatland acted as a net (annual) sink of direct CO_2 NEE throughout the entire period of measurements, ranging between an annual NEE of –80 g C-CO_2 m^{-2} in 2005 and –32 g C-CO_2 m^{-2} in 2007, with an overall annual average of –55.7 ± 18.9 g C-CO_2 m^{-2} (Figure 3.8).

3.3.1 Total carbon budget of Glencar peatland

The annual average of the 10 years (2003 to 2012) for NEE was –55.7 g C m^{-2} yr^{-1} (McVeigh *et al.*, 2014) and the annual average of the 6 years (2003 to 2008) was –48.1 g C m^{-2} yr^{-1} (Koehler *et al.*, 2011). The range of NEE and the annual average is very similar in the two studies. The range of NEE within the 10 years was a low of –32 g C m^{-2} yr^{-1} (2007) to a high of –80 g C m^{-2} yr^{-1} (2005). The fluxes of CH_4 and DOC are shown in Table 3.2 for the 6-year period of 2003–2008. The range of CH_4 fluxes over this period was 3.6 to 4.6 g C m^{-2} yr^{-1}, with an annual average over the 6 years of 4.1 g C m^{-2} yr^{-1}. The range of DOC fluxes over the 6 years was 11.9 to 16.5 g C m^{-2} yr^{-1}.

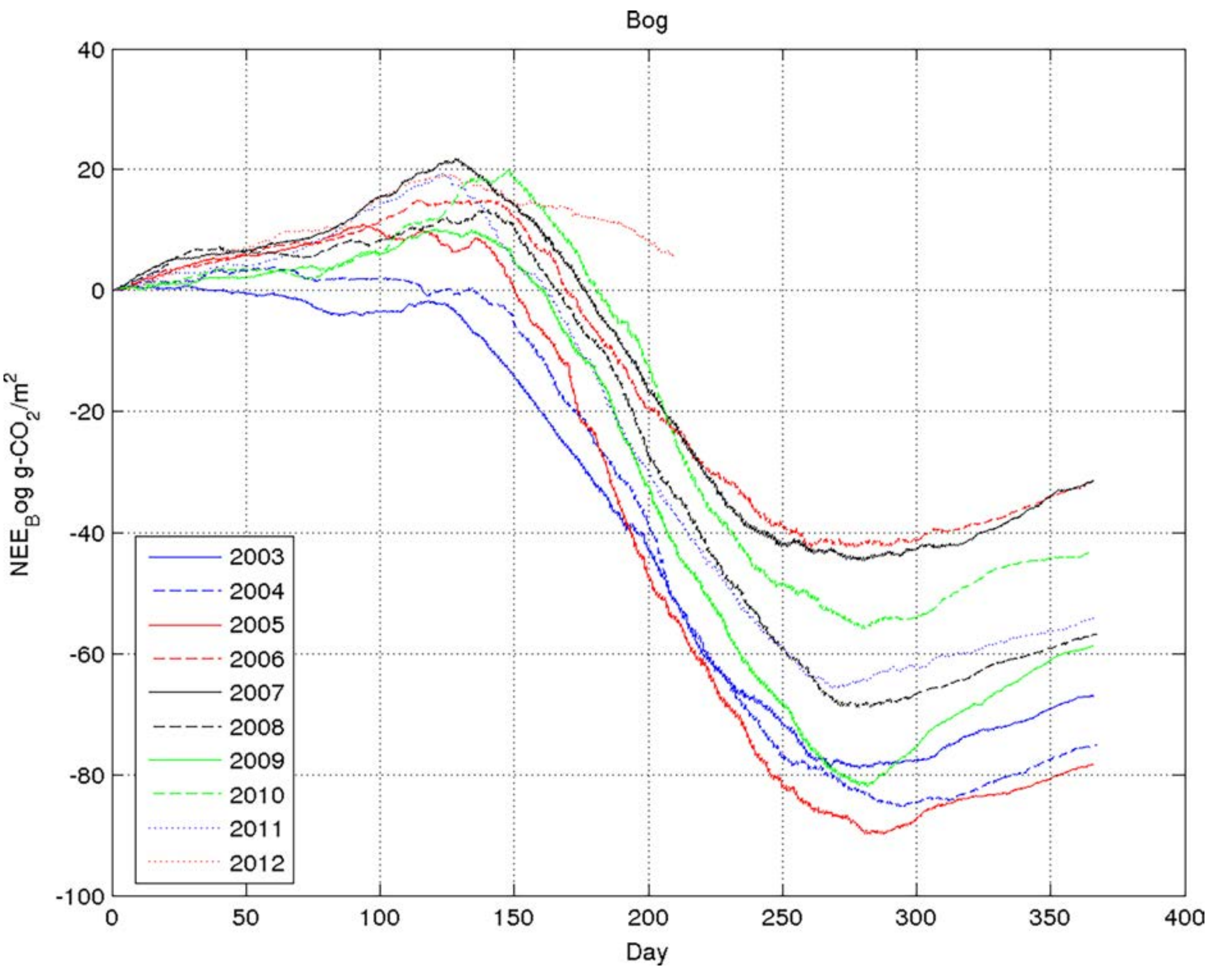

Figure 3.8. Cumulative CO_2 fluxes in g C m^{-2} ha^{-1} at the Glencar blanket peatland site in County Kerry for the years 2003 to 2012.

Table 3.2. NEE, CH_4, DOC and carbon balance for Glencar for the years 2003 to 2008 based on measurements and predictions. The given error estimate for each flux is calculated as described in the materials and methods (from Koehler *et al*., 2011)

Year	NEE g C-CO2 m–2 yr^{-1}	CH_4 g C-CH_4 m^{-2} yr^{-1}	DOC g C m^{-2} yr^{-1}	C balance g C m^{-2} yr^{-1}
2003	–66.8 ± 5.2	3.8 ± 1.6	13.5 ± 3.2	–49.6 ± 6.3
2004	–67.2 ± 3.0	3.6 ± 1.6	13.1 ± 3.1	–50.5 ± 4.6
2005	–84.0 ± 4.8	4.5 ± 1.9	13.9 ± 3.2	–65.6 ± 6.1
2006	–12.5 ± 3.4	4.6 ± 2.0	16.5 ± 3.2	8.6 ± 5.1
2007	–13.5 ± 2.3	4.2 ± 1.9	11.9 ± 1.2	2.8 ± 3.2
2008	–42.7 ± 4.7	3.6 ± 1.6	15.0 ± 1.3	–24.1 ± 5.1
Averages	–48.1	4.1	14.0	–30.0

When we sum the three component fluxes (CO_2, CH_4 and DOC) over the 6-year period, we get a range of carbon balance of +2.8 to –65.6 g C m^{-2} yr^{-1}, with an annual average of –30.0 g C m^{-2} yr^{-1}. Combining the annual import and export of carbon for the Glencar bog resulted in a mean 6-year carbon balance of –29.7 ± 30.6 (±1 standard deviation) g m^{-2} yr^{-1} with NEE being the largest and most variable component of the carbon balance. During the 6 years, NEE was always negative, i.e. a net uptake of CO_2. The calculation of the total carbon balance (C-CO_2 + C-DOC + C-CH_4) showed that the 2 years 2006 and 2007 were small carbon sources while the remaining 4 years were sinks for carbon. On average, the carbon loss as CH_4 and DOC ranged from 9 and 29% of the mean NEE, respectively. As in Roulet *et al.* (2007), we combined all the seasons with the lowest and the highest NEE, CH_4 and DOC to bracket the potential maximum and minimum carbon balance between +15 and –85 g m^{-2} yr^{-1}. This estimation is conservative and therefore may overestimate the range of the carbon balance.

4 Discussion, Conclusions and Recommendations

4.1 Summary of Annual CO_2 Fluxes

In Table 4.1, we present a summary of the annual CO_2 fluxes at the three sites and note that:

- At the Dripsey grassland site the mean of 8 years is –2.2 t C ha^{-1} yr^{-1} and the range is –0.71 to –3.19 t C ha^{-1} yr^{-1}.
- At the Glencar bog site the mean of 9 years is –0.55 t C ha^{-1} yr^{-1} and the range is –0.31 to –0.78 t C ha^{-1} yr^{-1}.
- At the Dripsey forest site the mean of 2 years is –1.3 t C ha^{-1} yr^{-1} and the range is –0.46 to –2.12 t C ha^{-1} yr^{-1}.

4.2 Discussion of Grassland CO_2 Fluxes

Our study shows that intensively managed and fertilised grassland in a humid temperate climate has the potential to sequester carbon to the soil. EC measurements over a range of wet, normal and dry years resulted in annual NEE (uptake or sequestration) of –0.71 to –3.19 t C ha^{-1} yr^{-1}. Although there were large differences in soil moisture status between the different years, this was not responsible for the interannual difference in NEE because the soil moisture status was well above wilting point at all times during the years, ensuring that the vegetation did not experience any water stress. We conclude that this humid grassland was not very sensitive to the precipitation variability. Harvesting reduces NEE in the month of harvesting. However, integrated over the summer harvest period, the effect of harvesting was similar in all years. We conclude that the IAV in NEE is of the order of uncertainty of the EC measurements.

Table 4.1: Annual CO_2 fluxes in t C $ha^{-1}yr^{-1}$ at the three EC sites; (1) the Dripsey grassland in County Cork; (2) the Glencar blanket peatland site in County Kerry; and (3) the Dripsey forest site in County Cork. NA, not applicable

YEAR	Dripsey GRASSLAND	Glencar BOG	Dripsey FOREST
		t C $ha^{-1}yr^{-1}$	
2003	–2.50	–0.67	NA
2004	–3.19	–0.75	NA
2005	–0.71	–0.78	NA
2006	–1.91	–0.32	NA
2007	error	–0.31	NA
2008	–3.35	–0.57	NA
2009	–2.29	–0.59	NA
2010	–2.01	–0.43	–0.46
2011	–1.77	–0.54	–2.12
Mean	–2.21	–0.55	–1.30

4.3 Discussion of Peatland CO_2 Fluxes

We describe 9 years of EC CO_2 flux measurements in an Atlantic blanket bog in Ireland. The measured NEE was partitioned into its components of ER and GEP. The IAV of the CO_2 fluxes was investigated using correlation coefficient analyses with measured hydrometeorological parameters. The annual NEE was negative (i.e. uptake) for all years (thus the peatland was a sink for CO_2), ranging between –31 and –78 g C-CO_2 m^{-2} (average –55 g C-CO_2 m^{-2}). During the study period, NEE was negative for the same 5 months in each year (May to September). NEE showed the highest CO_2 uptake (as a result of the highest GEP) in the summer with intermediate rather than extreme meteorological conditions, thus with low vapour pressure deficit, intermediate soil water content, air temperature and light radiation, which might be partly explained by the role of the bryophyte community. Under climate change predictions of higher temperature, the IAV analysis suggests that ER might increase in winter. Furthermore, the predicted lower precipitation and higher temperature in future summers are expected to lead to lower GEP. The resulting reduction in NEE will be partly compensated for by a higher GEP in warmer winters and in dryer autumns. Moreover, the CO_2 uptake will benefit from a longer growing season, while wetter conditions will probably lower the ER in spring. The length of the growing season was found to be driven by warmer winter and September soil temperatures.

The interannual variability in NEE ranges from –31 to –78 g C-CO_2 m^{-2} yr^{-1}, which is a “sink” that is about five times less than that in Irish grasslands and more than 10 times less than that of forestry in Ireland.

We show that NEE is not the only important component of the peatland carbon balance, but that the CH_4 flux and stream water DOC flux are also crucial components. NEE accounts for about 73% of the average carbon balance, while the CH_4 flux and stream water DOC flux contribute with about 6% and 21%, respectively. However, for two of the years, the sum of the CH_4 and DOC flux exceeded the NEE, making the site a source of carbon for the 2 years 2006 and 2007. NEE had a significant IAV while both the CH_4 flux and stream water DOC flux showed low IAV. Therefore, the annual behaviour of NEE is the most important component determining the bog’s annual carbon status. The existence of similar self-regulating processes in peatlands was suggested in the literature to be a possible mechanism determining comparable peat accumulation rates in different peatland types as observed for Glencar, Mer Bleue (Canada) and Degerö Stormyr (Sweden).

In summary, the Glencar pristine blanket peatland is:

- a sink for CO_2 of the order of –55 g C-CO_2 m^{-2} yr^{-1};
- a source of DOC of the order of +14 g C-DOC m^{-2} yr^{-1};
- a source of CH_4 of the order of +4 g C-CH_4 m^{-2} yr^{-1};
- has a total carbon balance of the order of –30 g C m^{-2} yr^{-1}.

4.4 Discussion of Afforested Grassland CO_2 Fluxes

The forest site in Dripsey was established in February 2005 using 20% black alder and 80% ash, with saplings of approximately 0.5 m in height. Growth was slow in the first few years with heights achieved of approximately 2 m in 2010 and approximately 3 m in 2011. We report annual EC CO_2 fluxes for the 2 years 2010 and 2011. The mean of the 2 years was –1.3 t C ha^{-1} yr^{-1} and the range was –0.46 to –2.12 t C ha^{-1} yr^{-1}. In the first year (2010) of measurements the forest was a small sink for CO_2 and it was a bigger sink for CO_2 in the second year (2011). As the forest height had reached approximately 5 m by 2015, we expect the CO_2 fluxes to have increased to significantly higher than the –2.12 t C ha^{-1} yr^{-1} achieved in 2011.

4.5 Conclusions

Ireland has a unique combination of climate and soils that enable some of the highest levels of carbon uptake in its ecosystems relative to anywhere else in the world. Its three main ecosystems are grasslands, peatlands and forests. A long growing season combined with a plentiful supply of precipitation throughout all seasons, and reasonable amounts of sunshine, make Ireland one of the most productive eco-regions in the world. In grasslands, the growing season can be as long as 10 months of the year, enabling a grassland management practice of outdoor grazing for almost the full year in the milder south of the country. The carbon fluxes in the three ecosystems examined in this study all report sinks in the annual NEE. The Dripsey grassland averaged a NEE in excess of –2.0 t C ha^{-1} yr^{-1}, while the Glencar blanket peatland averaged an annual NEE in excess of –0.5 t C ha^{-1} yr^{-1}. The Dripsey afforested grassland study was too short to draw firm conclusions on its annual NEE, but the second year of the study had a NEE in excess of –2.0 t C ha^{-1} yr^{-1}, with a likelihood that as the forest matured the NEE would be significantly increased.

4.6 Recommendations

Ireland, through the funding support of the Environmental Protection Agency (EPA), initiated a GHG flux monitoring programme in 2002. This funding established EC and chamber flux sites at the key ecosystems across Ireland. With this support Ireland was a significant contributor and beneficiary of the two large-scale EU projects – CarboEurope and NitroEurope – that followed in 2005 and 2008. This Irish work has continued for almost a decade under EPA support and has provided input to GHG policy for Ireland. In 2012 the international project ICOS was established to bring the monitoring of GHG fluxes of different ecosystems to the next level. This is where instrumentation is being standardised and all data are fed in real time into central databases across the EU. The EPA represents Ireland at ICOS. However, Ireland has been unable to continue funding flux studies and is now a bystander at ICOS conventions and remains outside the active science progress being made in Europe and across the world. It is now time for Ireland to step up and re-energise GHG flux research, without which it will be difficult to make the case for Ireland at international GHG policy conventions.

References and Other Sources

Adamson, J.K., Scott, W.A., Rowland, A.P. and Beard, G.R., 2001. Ionic concentration in a blanket peat bog in northern England and correlations with deposition and climate variables. *European Journal of Soil Science* 52: 69–79.

Aubinet, M., 2008. Eddy covariance CO_2 flux measurements in nocturnal conditions: an analysis of the problem. *Ecological Applications* 18(6): 1368–1378.

Aurela, M., Laurila, T. and Tuovinen J.-P., 2002. Annual CO_2 balance of a subarctic fen in northern Europe: importance of the wintertime efflux. *Journal of Geophysical Research Atmospheres* 107(D21).

Aurela, M., Laurila, T. and Tuovinen, J.-P., 2004. The timing of snow melt controls the annual CO_2 balance in a subarctic fen. *Geophysical Research Letters* 31(16).

Aurela, M., Lohila, A., Tuovinen, J.-P., Hatakka, J., Riutta, T. and Laurila, T., 2009. Carbon dioxide exchange on a northern boreal fen. *Boreal Environmental Research* 14(4): 699–710.

Baldocchi, D.D., 2003. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. *Global Change Biology* 9: 479–492.

Barr, A.G., Black, T.A., Hogg, E.H., Griffis, T.J., Morgenstern, K., Kljun, N., Theede, A. and Nesic, Z., 2007. Climatic controls on the carbon and water balances of a boreal aspen forest, 1994–2003. *Global Change Biology* 13(3): 561–576.

Basiliko, N., Moore, T.M., Lafleur, P.M. and Roulet, N.T., 2005. Seasonal and inter-annual decomposition, microbial biomass, and nitrogen dynamics in a canadian bog. *Soil Science* 170(11): 902–912.

Belyea, L.R. and Clymo, R.S., 2001. Feedback control of the rate of peat formation. *Proceedings of the Royal Society London. Series B* 268: 1315–1321. DOI: 10.1098/rspb.2001.1665.

Belyea, L.R. and Baird, A.J., 2006. Beyond “the limits to peat bog growth”: cross-scale feedback in peatland development. *Ecological Monographs* 76(3): 299–322.

Belyea, L.R. and Malmer, N., 2004. Carbon sequestration in peatland: patterns and mechanisms of response to climate change. *Global Change Biology* 10: 1043–1052. DOI: 10.1111/j.1365–2486.2004.00783.x.

Black, K. and Gallagher, G., 2010. The greenhouse gas balance of peatland forest. *COFORD CONNECTS*. Environment No. 11.

Black, K., Byrne, K.A., Mencuccini, M., Tobin, B., Nieuwenhuis, M., Reidy, B., Bolger, T., Saiz, G., Green, C., Farrell, E.P. and Osborne, B., 2009. Carbon stocks and stock changes across a Sitka spruce chronosequence on surface water gley soils. *Forestry* 82(3): 255–272.

Brutsaert, W., 2005. *Hydrology*. Cambridge University Press, Cambridge.

Bubier, J.L., Moore, T.R., Bellisario, L., Comer, N.T. and Crill, P.M., 1995. Ecological controls on methane emissions from a northern peatland complex in the zone of discontinuous permafrost, Manitoba, Canada. *Global Biogeochemical Cycles* 9(4): 455–470.

Bubier, J.L., Bhatia, G., Moore, T.R., Roulet, N.T. and Lafleur, P.M., 2003a. Spatial and temporal variability in growing-season net ecosystem carbon dioxide exchange at a large peatland in Ontario, Canada. *Ecosystems* 6(4): 353–367.

Bubier, J., Crill, P.M., Mosedale, A., Frolking, S. and Linder, E., 2003b. Peatland responses to varying interannual moisture conditions as measured by automatic CO_2 chambers. *Global Biogeochemical Cycles* 17(2).

Bullock, C.H., Collier, M. and Convery, F.J., 2012. Peatlands, their economic value and priorities for their future management – the example of Ireland. *Land Use Policy* 29(4): 921–928.

Byrne, K.A., 2010. The role of plantation forestry in Ireland in the mitigation of greenhouse gas emissions. *Irish Forestry* 67(1–2).

Byrne, K.A. and Farrell, E.P., 2007. Commercial afforestation. In Wilson, D. and Farrell, E.P. (eds), *CARBAL. Carbon Gas Balances in Industrial Cutaway Peatlands in Ireland*. University College Dublin, Dublin, pp. 12–14.

Byrne, K.A., Kiely, G. and Leahy, P., 2009. Carbon sequestration determined using farm scale carbon balance and eddy covariance. *Agricultural Ecosystems and Environment* 121(4): 357–364.

Cantarel, A.A.M., Bloor, J.M.G., Pommier, T., Guillaumaud, N., Moirot C., Soussane, J.F. and Poly F., 2012. Four years of experimental climate change modifies the microbial drivers of N2O fluxes in an upland grassland ecosystem. *Global Change Biology* 18(8): 2520–2531.

Cantarel, A.A.M., Bloor, J.M.G. and Soussana, J.-F., 2013. Four years of simulated climate change reduces above-ground productivity and alters functional diversity in a grassland ecosystem. *Journal of Vegetation Science* 24(1): 113–126.

Chang, J.F., Viovy, N., Vuichard, N., Ciais, P., Wang, T., Cozic, A., Lardy, R., Graux, A.-I., Klumpp, K., Martin, R. and Soussana, J.-F., 2013. Incorporating grassland management in ORCHIDEE: model description and evaluation at 11 eddy-covariance sites in Europe. *Geoscientific Model Development* 6(6): 2165–2181.

Chang, J., Viovy, N., Vuichard, N., Ciais, P., Campioli, M., Klumpp, K., Martin, R., Leip, A. and Soussana, J.-F., 2015a. Modelled changes in potential grassland productivity and in grass-fed ruminant livestock density in Europe over 1961–2010. *PLOS ONE* 10(5): e0127554.

Chang, J., Ciais, P., Viovy, N., Vuichard, N., Sultan, B. and Soussana, J.-F., 2015b. The greenhouse gas balance of European grasslands. *Global Change Biology* 21(10): 3748–3761.

Chang, J., Ciais, P., Viovy, N., Vuichard, N., Herrero, M., Havlík, P., Wang, X., Sultan, B. and Soussana, J.F., 2016. Effect of climate change, CO_2 trends, nitrogen addition, and land-cover and management intensity changes on the carbon balance of European grasslands. *Global Change Biology* 22(1): 338–350.

Clymo, R.S., Turunen, J. and Tolonen, K., 1998. Carbon accumulation in peatland. *Oikos* 81: 368.

Connolly, J. and Holden, N.M., 2009. Mapping peat soils in Ireland: updating the derived Irish peat map. *Irish Geography* 42(3): 343–352.

Connolly, J. and Holden, N., 2013. *Identification, Mapping, Assessment and Quantification of the Effects of Disturbance on the Peat Soil Carbon Stock in Ireland.* STRIVE 98: Environmental Protection Agency, Johnstown Castle, Ireland. Available online: http://www.epa.ie/pubs/reports/research/land/STRIVE_98_web.pdf

Connolly, J., Holden, N.M. and Ward, S.M., 2007. Mapping peatlands in Ireland using a rule-based methodology and digital data. *Soil Science Society American Journal* 71: 492–499.

Christensen, T.R., Panicov, N., Masterpanov, M. and Joabsson, A., 2003. Biotic control on CO_2 and CH_4 exchange in wetlands – a closed ecosystem study. *Biogeochemistry* 64: 337–354.

DAFM (Department of Agriculture Food and the Marine), 2014. Forests, Products and People. Available online: https://www.agriculture.gov.ie/forestservice/forestservicegeneralinformation/forestpolicyreviewforestsproductsandpeople/

DAHG (Department of Arts, Heritage and the Gaeltacht), 2015. *National Peatland Strategy*. National Parks and Wildlife Service, Dublin.

Dewar, R.C. and Cannell, M., 1992. Carbon sequestration in the trees, products and soils of forest plantations: an analysis using UK examples. *Tree Physiology* 11: 49–71.

Dinsmore, K.J., Billett, M.F., Skiba, U.M., Rees, R.M., Drewer, J. and Helfter, C., 2010. Role of the aquatic pathway in the carbon and greenhouse gas budgets of a peatland catchment. *Global Change Biology* 16(10): 2750–2762.

Dise, N.B., 2009. Peatland response to global change. *Science* 326: 810–811.

Douglas, C., 1998. Blanket bog conservation. In O'Leary, G. and Gormley, F. (eds), *Towards a Conservation Strategy for the Bogs of Ireland*. Irish Peatland Conservation Council, Dublin, pp. 205–222.

Duffy, P., Hanley, E., Hyde, B., O'Brien, P., Ponzi, J. Cotter, E. and Black, K., 2014. *Greenhouse Gas Emissions 1990–2012*. Reported to the United Nations Framework Convention On Climate Change. Ireland National Report. Environmental Protection Agency, Johnstown Castle, Ireland.

Dunn, A.L., Barford, C.C., Wofsy, S.C., Goulden, M.L. and Daube, B.C., 2007. A long-term record of carbon exchange in a boreal black spruce forest: means, responses to interannual variability, and decadal trends. *Global Change Biology* 13(3): 577–590.

Eaton, J.M., McGoff, N.M., Byrne, K.A., Leahy, P. and Kiely, G., 2008. Land cover change and soil organic carbon stocks in the Republic of Ireland 1851–2000. *Climatic Change* 91(3–4): 317–334.

Eppinga, M.B., de Ruiter, P.C., Wassen, M.J. and Rietkerk, M., 2009a. Nutrients and hydrology indicate the driving mechanisms of peatland surface patterning. *The American Naturalist*, 173: 803–818.

Eppinga, M.B., Rietkerk, M., Wassen, M.J. and de Ruiter, P.C., 2009b. Linking habitat modification to catastrophic shifts and vegetation patterns in bogs. *Plant Ecology* 200: 53–68.

Falge, E., Baldocchi, D., Olson, R.J., Anthoni, P., Aubinet, M., Bernhofer, C., Burba, G., Ceulemans, R., Clement, R., Dolman, H., Granier, A., Gross, P., Gru¨nwald, T., Hollinger, D., Jensen, N.-O., Katul, G., Keronen, P., Kowalski, A., Ta Lai, C., Law, B.E., Meyers, T., Moncrieff, J., Moors, E., Munger, J.W., Pilegaard, K., Rannik, U., Rebmann, C., Suyker, A., Tenhunen, J., Tu, K., Verma, S., Vesala, T., Wilson, K. and Wofsy, S., 2001. Gap filling strategies for defensible annual sums of net ecosystem exchange. *Agricultural and Forest Meteorology* 107: 43–69.

FAO (Food and Agiculture Organization of the United Nations), 2014. Towards climate-responsible peatlands management. FAO, Rome.

Farrell, C.A. and Doyle, G.J., 2003. Rehabilitation of industrial cutaway Atlantic blanket bog in County Mayo, north-west Ireland. *Wetlands Ecology and Management* 11(1): 21–35.

Fenner, N. and Freeman, C., 2011. Drought-induced carbon loss in peatlands. *Nature Geoscience* 4: 895–900.

Fiorelli, J.-L., Drouet, J.-L., Duretz, S. and Soussane J.F., 2014. Evaluation of greenhouse gas emissions and design of mitigation options: a whole farm approach based on farm management data and mechanistic models. *International Journal of Sustainable Development* 17(1): 22–34.

Foss, P.J., O'Connell, C.A. and Crushell, P. (eds), 2001. *Bogs & Fens of Ireland. Conservation Plan 2005*. Irish Peatland Conservation Council, Dublin.

Fraser, M.D., Fychan, R. and Jones, R., 2001. The effects of harvest date and inoculation on the yield, fermentation characteristics and feeding value of forage pea and field bean silages. *Grass and Forage Science* 56: 218–230.

Frolking, S. and Roulet, N.T., 2007. Holocene radiative forcing impact of northern peatland carbon accumulation and methane emissions. *Global Change Biology* 13(5): 1079–1088.

Frolking, S.E., Bubier, J.L., Moore, T.R., Ball, T., Bellisario, L.M., Bhardwaj, A., Carroll, P., Crill, M., Lafleur, P.M., McCaughey, J.H., Roulet, N.T., Suyker, A.E., Verrna, S.B., Waddington, J.M. and Whiting, G.J. 1998. Relationship between ecosystem productivity and photosynthetically active radiation for northern peatlands. *Global Biogeochemical Cycles* 12: 115–126.

Frolking, S., Talbot, J., Jones, M.C., Treat, C.C., Kauffman, J.B., Tuittila, E.-S. and Roulet, N., 2011. Peatlands in the Earth's 21st century climate system. *Environmental Review* 19: 371–396.

Gardiner, M.T. and Radford, T., 1980. *Soil Associations of Ireland and Their Potential Land Use. National Soil Survey of Ireland*. An Foras Talúntais, Dublin.

Gore, A.J.P., 1983. Introduction. In Gore, A.J.P. (ed.), *Ecosystems of the world 4A – Mires: Swamp, Bog, Fen and Moor*. Elsevier, Amsterdam, pp. 1–34.

Gorham, E., 1991. Northern peatlands: role in the carbon cycle and probable responses to climate warming. *Ecological Applications* 1(2): 182–195.

Goulden, M.L., Munger, J.W., Fan, S.M., Daube, B.C. and Wofsy, S.C., 1996. Measurement of carbon storage by long-term eddy correlation: methods and a critical assessment of accuracy. *Global Change Biology* 2: 169–182.

Graux, A-I., Lardy, R., Bellocchi, G. and Soussana, J.-F., 2012. Global warming potential of French grassland-based dairy livestock systems under climate change. *Regional Environmental Change* 12(4): 751–763.

Graux, A-I., Bellocchi, G., Lardy, R. and Soussana, J.-F., 2013. Ensemble modelling of climate change risks and opportunities for managed grasslands in France. *Agricultural and Forest Meteorology* 170(SI): 114–131.

Hammond, R.F., 1981. *The Peatlands of Ireland 60*. An Foras Talúntais, Dublin.

Hammond, R.F., Van der Krogt, G. and Osinga, T., 1990. Vegetation and water-tables on two raised bog remnants in County Kildaire. In Doyle, G.J. (ed.), *Ecology and Conservation of Irish Peatlands*. Royal Irish Academy, Dublin, pp. 121–134.

Henderson, B., Falcucci, A., Mottet, A., Early, L., Werner, B., Steinfeld, H. and Gerber, P., 2015. Marginal costs of abating greenhouse gases in the global ruminant livestock sector. *Mitigation and Adaptation Strategies for Global Change* 22(1): 1–26.

Hilbert, D.W., Roulet, N. and Moore, T., 2000. Modelling and analysis of peatlands as dynamical systems. *Journal of Ecology* 88(2): 230–242.

Holden, J., 2005. Peatland hydrology and carbon release: why small-scale process matters. *Philosophical Transactions of the Royal Society of London, Series A: Physical Sciences and Engineering* 363: 2891–2913.

Holden, N.M. and Connolly, J., 2011. Estimating the carbon stock of a blanket peat region using a peat depth inference model. *CATENA* 86(2): 75–85.

Hörtnagl, L. and Wohlfahrt, G., 2014. Methane and nitrous oxide exchange over a managed hay meadow. *Biogeosciences* 11: 7219–7236.

Hsieh, C.I., Katul, G. and Chi, T-W., 2000. An approximate analytical model for footprint estimation of scaler fluxes in thermally stratified atmospheric flows. *Advances in Water Resources* 23(7): 765–772.

Hui, D.F., Luo, Y.Q., Katul, G., 2003. Partitioning interannual variability in net ecosystem exchange between climatic variability and functional response. *Tree Physiology* 23(7): 433–442.

IPCC (Intergovernmental Panel on Climate Change), 2001. *Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate*. Cambridge University Press, Cambridge.

IPCC (Intergovernmental Panel on Climate Change) Working Group I Contribution to AR5, 2013. *Climate Change 2013: The Physical Science Basis*. Cambridge University Press, Cambridge.

Jaksic, V., Kiely, G., Albertson, J., Katul, G. and Oren, R., 2006. Net ecosystem exchange of grassland in contrasting wet and dry years. *Agriculture and Forest Meteorology* 139: 323–334.

Janssens, I.A., Freibauer, A., Schlamadinger, B., Ceuleman, R., Ciais, P., Dolman, A.J., Heimann, M., Nabuurs, G-J., Smith, P., Valentini, R. and Schulze, E.D., 2003. The carbon budget of terrestrial ecosystems at country-scale – a European case study. *Biogeosciences* 2: 15–26.

Khandokar, F., 2002. Phosphorus in soils of pasture farms subject to chemical and slurry fertilization. Master's Thesis. University College Cork, Cork.

Kiely, G., McGoff, N.M., Eaton, J.M., Xu, X., Leahy, P. and Carton, O., 2008. *SoilC – Measurement and modelling of soil carbon stocks and stock changes in Irish soils*. Environmental Protection Agency, Johnstown Castle, Ireland.

Kilbride, C.M., Byrne, K.A. and Gardiner, I.J., 1999. *Carbon sequestration and Irish Forests*. COFORD, Dublin.

Kirschbaum, M.U.F., 1995. The temperature dependence of soil organic matter decomposition, and the effect of global warming on soil organic C storage. *Soil Biology and Biochemisty* 27(6): 753–760.

Koehler, A-K., Sottocornola, M. and Kiely, G., 2011. How strong is the current carbon sequestration of an Atlantic blanket bog? *Global Change Biology* 17(1): 309–319.

Lafleur, P.M., Roulet, N.T., Bubier, J.L., Frolking, S. and Moore, T.R., 2003. Interannual variability in the peatland-atmosphere carbon dioxide exchange at an ombrotrophic bog. *Global Biogeochemical Cycles* 17(2): 14.

Lafleur, P.M., Moore, T.R., Roulet, N.T. and Frolking, S., 2005. Ecosystem respiration in a cool temperate bog depends on peat temperature but not water table. *Ecosystems* 8(6): 619–629.

Lai, D.Y.F., Roulet, N.T., Humphreys, E.R., Moore, T.R. and Dalva, M., 2012. The effect of atmospheric turbulence and chamber deployment period on autochamber CO_2 and CH_4 flux measurements in an ombrotrophic peatland. *Biogeosciences* 9(8): 3305–3322.

Laine, J., Vasander, H. and Laiho, R., 1995. Long-term effects of water level drawdown on the vegetation of drained pine mires in southern Finland. *Journal of Applied Ecology* 32: 785–802.

Laine, A., Sottocornola, M., Kiely, G. and Byrne, K.A., Wilson, D. and Tuittila, E.-S., 2006. Estimating net ecosystem exchange in a patterned ecosystem: example from blanket bog. *Agricultural and Forest Meteorology* 138(1–4): 231–243.

Laine, A., Byrne, K.A., Kiely, G. and Tuittila, E.-S., 2007. Patterns in vegetation and CO_2 dynamics along a water level gradient in a lowland blanket bog. *Ecosystems* 10(6): 890–905.

Laine, A., Byrne, K.A., Kiely, G. and Tuittila, E.-S., 2009. The short-term effect of altered water level on carbon dioxide and methane fluxes in a blanket bog. *Suoseura* 60(3–4): 65–83.

Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. *Science* 304(5677): 1623–1627.

Laville, P., Jambert, C., Cellier, P. and Delmas, R., 1999. Nitrous oxide fluxes from a fertilized maize crop using micrometeorological and chamber methods. *Agricultural and Forest Meteorology* 96: 19–38.

Leahy, P., Kiely, G. and Scanlon, T., 2004. Managed grasslands: a greenhouse gas sink or source? *Geophysical Research Letters* 31: L20507.

Leahy, P. and Kiely, G., 2012. The effect of introducing a winter forage rotation on CO2 fluxes at a temperate grassland. *Agriculture, Ecosystems and Environment* 156: 49–56.

Lenschow, D.H., 1995. Micrometeorological techniques for measuring biosphere–atmosphere trace gas exchange. In Matson, P.A. and Harriss, R.C. (eds), *Biogenic Trace Gases: Measuring Emissions from Soil and Water*. Blackwell Science, Oxford, pp. 126–163.

Lewis, C., Albertson, J., Xu, X. and Kiely, G., 2012. Spatial variability of hydraulic conductivity and bulk density along a blanket peatland hillslope. *Hydrological processes* 26(10): 1527–1537.

Limpens, J., Berendse, F., Blodau, C., Canadell, J.G., Freeman, C., Holden, J., Roulet, N., Rydin, H. and Schaepman-Strub, G., 2008. Peatlands and the carbon cycle: from local processes to global implications – a synthesis. *Biogeosciences* 5(5): 1475–1491.

Lindroth, A., Lund, M., Nilsson, M., Aurela, M., Christensen, T.R., Laurila, T., Rinne, J., Riutta, T., Sagerfors, J., Strom, L., Tuovinen, J.-P. and Vesala, T., 2007. Environmental controls on the CO2 exchange in north European mires. *Tellus. Series B, Chemical and physical meteorolog*y 59(5): 812–825.

Lindsay, R.A., Charman, D.J., Everingham, F., O'Reilly, R.M., Palmer, M.A., Rowell, T.A. and Stroud, D.A., 1988. *The Flow Country: The Peatlands of Caithness and Sutherland*. Nature Conservation Council, Peterborough.

Lloyd, J. and Taylor, J.A., 1994. On the temperature-dependence of soil respiration. *Functional Ecology* 8(3): 315–323.

Lund, M., Lafleur, P.M., Roulet, N.T., Lindroth, A., Christensen, T., Aurela, M., Chojnicki, B.H., Flanagan, L.B., Humphreys, E.R., Laurila, T., Oechel, W.C., Olejnik, J., Rinne, J., Schubert, P. and Nilsson, M.B., 2010. Variability in exchange of CO_2 across 12 northern peatland and tundra sites. *Global Change Biology* 16(9): 2436–2448.

Lüscher, A., Mueller-Harvey, I., Soussana, J.F., Rees, R.M. and Peyraud, J.L., 2014. Potential of legume-based grassland–livestock systems in Europe: a review. *Grassland and Forage Science* 69(2): 206–228.

Luyssaert, S., Ciais, P., Piao, S.L., Schulze, E.-D., Jung, M., Zaehle, S., Schelhaas, M.J., Reichstein, M., Churkina, G., Papale, D., Abril, G., Beer, C., Grace, J., Loustau, D., Matteucci, G., Magnani, F., Nabuurs, G.J., Verbeeck, H.W., Sulkava, M., van der Werf, G.R., Janssens, I.A. and members of the CARBOEUROPE - IP Synthesis Team, 2010. The European carbon balance. Part 3: forests. *Global Change Biology* 16(5): 1429–1450.

Luyssaert, S., Abril, G., Andres, R., Bastviken, D., Bellassen, V., Bergamaschi, P., Bousquet, P., Chevallier, F., Ciais, P., Corazza, M., Dechow, R., Erb, K.-H., Etiope, G., Fortems-Cheiney, A., Grassi, G., Hartman, J., Jung, M., Lathiere, J., Lohila, A., Moosdorf, N., Njakou Djomo, S., Otto, J., Papale, D., Peters, W., Peylin, P., Raymond, P., Rodenbeck, C., Saarnio, S., Schulze, E.-D., Szopa, S., Thompson, R., Verkerk, P.J., Vuichard, N., Wang, R., Wattenbach, M. and Zaehle, S., 2012. The European CO_2, CO, CH_4 and N_2O balance between 2001 and 2005. *Biogeosciences Discussions* 9(2): 2005–2053.

McVeigh, P., Sottocornola, M., Foley, N., Leahy, P., Kiely, G., 2014. Meteorological and functional response partitioning to explain the interannual variability of CO_2 exchange at an Irish Atlantic Blanket Bog. *Agriculture and Forest Meteorology* 194: 8–19.

Marcolla, B., Cescatti, A., Manca, G., Zorer, R., Cavagna, M., Fiora, A., Gianelle, D., Rodeghiero, M., Sottocornola, M. and Zampedri, R., 2011. Climatic controls and ecosystem responses drive the inter-annual variability of the net ecosystem exchange of an alpine meadow. *Agricultural and Forest Meteorology* 151(9): 1233–1243.

Merbold, L., Eugster, W., Stieger, J., Zahniser, M., Nelson, D. and Buchmann, N., 2014. Greenhouse gas budget (CO_2, CH_4 and N_2O) of intensively managed grassland following restoration. *Global Change Biology* 20(6): 1913–1928.

Michaelis, L. and Menten, M., 1913. Kinetik der Invertinwirkung. *Biochemische Zeitschrift* 49: 333–369.

Mishurov, M. and Kiely, G., 2010a. Gap-filling techniques for the annual sums of nitrous oxide fluxes. *Agriculture and Forest Meteorology* 151(12): 1763–1767.

Mishurov, M. and Kiely, G., 2010b. N_2O flux dynamics of grassland undergoing afforestation. *Agriculture, Ecosystems and Environment* 139(1–2): 59–65.

Moncrieff, J., Valentini, R., Greco, S., Seufert, G. and Ciccioli, P., 1997. Trace gas exchange over terrestrial ecosystems: methods and perspectives in micrometeorology. *Journal of Experimental Botany* 48(310): 1133–1142.

Moore, P.D., 1993. The origin of blanket mire, revisited. In Chambers, F.M. (ed), *Climate Change and Human Impact on the Landscape*. Chapman and Hall, London, pp. 217–224.

Moore, P.D. and Bellamy, D.H., 1974. *Peatlands*. Paul Elek Scientific Books Ltd, London.

Moore, T.R., Roulet, N.T. and Waddington, M.J., 1998. Uncertainty in predicting the effect of climatic change on the carbon cycling of Canadian peatlands. *Climatic Change* 40(2): 229–245.

Nieveen, J.P., Campbell, D.I., Schipper, L.A. and Blair, I.J., 2005. Carbon exchange of grazed pasture on a drained peat soil. *Global Change Biology* 11: 607–618.

Nilsson, M., Sagerfors, J., Buffam, I., Laudon, H., Eriksson, T., Grelle, A., Klemedtsson, L., Weslien, P. and Lindroth, A., 2008. Contemporary carbon accumulation in a boreal oligotrophic minerogenic mire – a significant sink after accounting for all C-fluxes. *Global Change Biology* 14(10): 2317–2332.

Novick, K.A., Stoy, P.C., Katul, G., Ellsworth, D.S., Siqueira, M.B.S., Juang, J.R. and Oren, R., 2004. Carbon dioxide and water vaporexchange in a warm temperate grassland. *Oecologia* 138: 259–274.

O'Brien, R.M., 2007. A caution regarding rules of thumb for variance inflation factors. *Quality and Quantity* 41(5): 673–690.

O'Connell, M., 1990. Origins of Irish lowland blanket bog. In Doyle, G. (ed), *Ecology and Conservation of Irish Peatlands*. Royal Irish Academy, Dublin, pp. 49–71.

Olefeldt, D., Roulet, N.T., Bergeron, O., Crill, P., Bäckstrand, K. and Christensen, T.R., 2012. Net carbon accumulation of a high-latitude permafrost palsa mire similar to permafrost-free peatlands. *Geophysical Research Letters* 39(L03501).

Payette, S. and Rochefort, L., 2001. Introduction. In Payette, S. and Rochefort, L. (eds), *Écologie des tourbière*. Les Presses de l'Université Laval, Québec, pp. 1–5.

Peichl, M., Leava, N.A. and Kiely, G., 2012. Above- and belowground ecosystem biomass, carbon and nitrogen allocation in recently afforested grassland and adjacent intensively managed grassland. *Plant and Soil* 350(1–2): 281–296.

Peichl, M., Sonnentag, O., Wohlfahrt, G., Baldocchi, D.D., Flanagan, L.B., Kiely, G., Galvagno, M., Gianelle, D., Marcolla, B., Pio, C., Migliavacca, M., Jones, M.B. and Saunders, M., 2013. Convergence of potential net ecosystem production among contrasting C_3 grasslands. *Ecology Letters* 16: 502–512.

Proctor, M.C.F., 1992. Regional and local variation in the chemical-composition of ombrogenous mire waters in Britain and Ireland. *The Journal of Ecology* 80(4): 719–736.

Proctor, M.C.F., 2006. Temporal variation in the surface-water chemistry of a blanket bog on Dartmoor, southwest England: analysis of 5 years' data. *European Journal of Soil Science* 57(2): 167–178.

Rafique R., Hennessy, D. and Kiely, G., 2011. Nitrous oxide emission from grassland under different management systems. *Ecosystems* 14(4): 563–582.

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grunwald, T., Havrankova, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J-M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D. and Valentini, R., 2005. On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. *Global Change Biology* 11(9): 1424–1439.

Reidy, B. and Bolger, T., 2013. Soil carbon stocks in a Sitka spruce chronosequence following afforestation. *Irish Forestry* 70: 200–219.

Renou-Wilson, F., Bolger, T., Bullock, C., Convery, F., Curry ,J.P., Ward, S., Wilson, D. and Müller, C., 2011. *Bogland: Sustainable Management of Peatlands in Ireland*. Environmental Protection Agency, Johnstown Castle, Ireland.

Rees, R.M., Augustin, J., Alberti, G., Ball, B.C., Boeckx, P., Cantarel, A., Castaldi, S., Chirinda, N., Chojnicki, B., Giebels, M., Gordon, H., Grosz, B., Horvath, L., Juszczak, R., Kasimir, Klemedtsson, A., Klemedtsson, L., Medinets, S., Machon, A., Mapanda, F., Nyamangara, J., Olesen, J.E., Reay, D.S., Sanchez, L., Sanz Cobena, A., Smith, K.A., Sowerby, A., Sommer, M., Soussana, J.F., Stenberg, M., Topp, C.F.E., van Cleemput, O., Vallejo, A., Watson, C.A. and Wuta, M., 2013. Nitrous oxide emissions from European agriculture – an analysis of variability and drivers of emissions from field experiments. *Biogeosciences* 10(4): 2671–2682.

Richardson, A.D., Hollinger, D.Y., Aber, J.D., Ollinger, S.V. and Braswell, B.H., 2007. Environmental variation is directly responsible for short- but not long-term variation in forest-atmosphere carbon exchange. *Global Change Biology* 13(4): 788–803.

Ripple, W.J., Smith, P., Haberl, H., Montzka, S.A., McAlpine, C. and Boucher, D.H., 2014. Ruminants, climate change and climate policy. *Nature Climate Change* 4: 2–5.

Roulet, N., Moore, T., Bubier, J. and Lafleur, P., 1992. Northern fens: methane flux and climatic change. *Tellus. Series B, Chemical and Physical Meteorolog*y 44(2): 100–105.

Roulet, N.T., Lafleur, P.M., Richard, P.J.H., Moore, T.R., Humphreys, E.R. and Bubier, J., 2007. Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland. *Global Change Biology* 13(2): 397–411.

Ruimy, A.G., Jarvis, P.G., Baldocchi, D.D. and Saugier, B., 1995. *$C0_2$ Fluxes over Plant Canopies and Solar Radiation: A Review.* University of Berkeley, Berkeley, CA.

Sagerfors, J., Lindroth, A., Grelle, A., Klemedtsson, L., Weslien, P. and Nilsson, M., 2008. Annual CO_2 exchange between a nutrient-poor, minerotrophic, boreal mire and the atmosphere. *Journal of Geophysical Research – Biogeosciences* 113(G1).

Scanlon, T. and Kiely, G., 2003. Ecosystem scale measurements of nitrous oxide fluxes for an intensely grazed, fertilised grassland. *Geophysical Research Letters* 30(16): 1852.

Scanlon, T., Kiely, G. and Quishi, X., 2004. A nested catchment approach for defining the hydrological controls on phosphorus transport. *Journal of Hydrology* 291(3–4): 218–231.

Schulze, E-D., Ciais, P., Luyssaert, S., Schrumpf, M., Janssens, I.A., Thiruchittampalam, B., Theloke, J., Saurat, M., Bringezu, S., Lelieveld, J., Lohila, A., Rebmann, C., Jung, M., Bastviken, D., Abril, G., Grassi, G., Leip, A., Freibauer, A., Kutsch, W., Don, A., Nieschulze, J., Börner, A., Gash, J.H. and Dolman, A.J., 2010. The European carbon balance. Part 4: integration of carbon and other trace-gas fluxes. *Global Change Biology* 16(5): 1451–1469.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M. and Smith, J., 2008. Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* 363: 789–813.

Sottocornola, M., 2007. Four years of observations of carbon dioxide fluxes, water and energy budgets, and vegetation patterns in an Irish Atlantic blanket bog. PhD Thesis. University College Cork, Cork.

Sottocornola, M. and Kiely, G., 2005. An Atlantic blanket bog is a modest CO_2 sink. *Geophysical Research Letters* 32(23).

Sottocornola, M. and Kiely, G., 2010a. Hydro-meteorological controls on the CO_2 exchange variation in an Irish blanket bog. *Agricultural and Forest Meteorology* 150(2): 287–297.

Sottocornola, M. and Kiely, G., 2010b. Energy fluxes and evaporation mechanisms in an Atlantic blanket bog in southwestern Ireland. *Water Resources Research* 46 (11): W11524.

Sottocornola, M., Laine, A., Kiely, G., Byrne, K.A. and Tuittila, E.-S., 2009. Vegetation and environmental variation in an Atlantic blanket bog in south-western Ireland. *Plant Ecology* 203(1): 69–81.

Soussana, J.F., Allard, V., Pilegaard, K., Ambus, P., Amman, C., Campbell, C., Ceschia, E., Clifton-Brown, J., Czobel, S., Domingues, R., Flechard, C., Fuhrer, J., Hensen, A., Horvath, L., Jones, M., Kasper, G., Martin, C., Nagy, Z., Neftel, A., Raschi, A., Baronti, S., Rees, R.M., Skiba, U., Stefani, P., Manca, G., Sutton, M., Tuba, Z. and Valentini, R., 2007. Full accounting of the greenhouse gas (CO_2, N_2O, CH_4) budget of nine European grasslands. *Agriculture, Ecosystems and Environment* 121: 121–134.

Soussana, J.-F., 2013. Grassland and climate change. *Fourrages* 215: 171–180.

Soussana, J.F., Tallec, T. and Blanfort, V., 2010. Mitigation the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands. *Animal* 4: 334–350.

Strack, M. and Waddington, J.M., 2007. Response of peatland carbon dioxide and methane fluxes to a water table drawdown experiment. *Global Biogeochemical Cycles* 21(1).

Strack, M., Waddington, M.J. and Tuittila, E.-S., 2004. Effect of water table drawdown on northern peatland methane dynamics: Implications for climate change. *Global Biogeochemical Cycles* 18: GB4003.

Strack, M., Waddington, M.J., Rochefort, L. and Tuittila, E.-S., 2006. Response of vegetation and net ecosystem carbon dioxide exchange at different peatland microforms following water table drawdown. *Journal of Geophysical Research* 111: G02006.

Stull, R.B., 1988. *An Introduction to Boundary Layer Meteorology*. Springer Science and Business Media, Berlin.

Sulman, B.N., Desai, A.R., Saliendra, N.Z., Lafleur, P.M., Flanagan, L.B., Sonnentag, O., Mackay, D.S., Barr, A.G. and van der Kamp, G., 2010. CO_2 fluxes at northern fens and bogs have opposite responses to inter-annual fluctuations in water table. *Geophysical Research Letters* 37(L19702).

Tallec, T., Klumpp, K., Guix, N. and Soussana, J.-F., 2012. Do agricultural practices have a higher impact than climatic variability on the soil carbon storage potential of grassland? *Fourrages* 210: 99–107.

Tallis, J.H., 1998. Growth and degradation of British and Irish blanket mires. *Environmental Review* 6(2): 81–122.

Teal, J.M. and Howes, B.L., 1996. Interannual variability of a salt-marsh ecosystem. *Limnology and Oceanography* 41(4): 802–809.

Teklemariam, T.A., Lafleur, P.M., Moore, T.R., Roulet, N.T. and Humphreys, E.R., 2010. The direct and indirect effects of inter-annual meteorological variability on ecosystem carbon dioxide exchange at a temperate ombrotrophic bog. *Agricultural and Forest Meteorology* 150(11): 1402–1411.

Tomlinson, R.W., 2005. Soil carbon stocks and changes in the Republic of Ireland. *Journal of Environmental Management* 76: 77–93.

Turunen, J., Tomppo, E., Tolonen, K. and Reinikainen, A., 2002. Estimating carbon accumulation rates of undrained mires in Finland – application to boreal and subarctic regions. *Holocene* 12(1): 69–80.

Turunen, J., Roulet, N.T., Moore, T.R. and Richard, P.J.H., 2004. Nitrogen deposition and increased carbon accumulation in ombrotrophic peatlands in Eastern Canada. *Global Biogeochemical Cycles* 18: GB3002.

Updegraff, K., Bridgham, S.D., Pastor, J., Weishampel, P. and Harth, C., 2001. Response of CO_2 and CH_4 emissions from peatlands to warming and water table manipulation. *Ecological Applications* 11(2): 311–326.

van der Molen, M.K., Dolman, A.J., Ciais, P., Eglin, T., Gobron, N., Law, B.E., Meir, P., Peters, W., Phillips, O.L., Reichstein, M., Chen, T., Dekker, S.C., Doubková, M., Friedl, M.A., Jung, M., van den Hurk, B.J.J.M., de Jeu, R.A.M., Kruijt, B., Ohta, T., Rebel, K.T., Plummer, S., Seneviratne, S.I., Sitch, S., Teuling, A.J., van der Werf, G.R. and Wang, G., 2011. Drought and ecosystem carbon cycling. *Agricultural and Forest Meteorology* 151(7): 765–773.

Van Oijen, M., Balkovi, J., Beer, C., Cameron, D.R., Ciais, P., Cramer, W., Kato, T., Kuhnert, M., Martin, R., Myneni, R., Rammig, A., Rolinski, S., Soussana, J.-F., Thonicke, K., Van der Velde, M. and Xu, L., 2014. Impact of droughts on the carbon cycle in European vegetation: a probabilistic risk analysis using six vegetation models. *Biogeosciences* 11(22): 6357–6375.

Vital, J-A., Gaurut, M., Lardy, R., Viovy, N., Soussana, J.-F., Belllocchi, G. and Martin, R., 2013. High-performance computing for climate change impact studies with the Pasture Simulation model. *Computers and Electronics in Agriculture* 98: 131–135.

Vuichard, N., Ciais, P., Viovy, N., Calanca, P. and Soussana, J.-F., 2007. Estimating the greenhouse gas fluxes of European grasslands with a process-based model: 2. simulations at the continental level. *Global Change Biology* 21(1).

Waddington, M.J., Warner, K.D. and Kennedy, G.W., 2002. Cutover peatlands: a persistent source of atmospheric CO_2. *Global Biogeochemical Cycles* 16(1):1–7.

Webb, E.K., Pearman, G.I. and Leuning, R., 1980. Correction of flux measurements for density effects due to heat and water-vapor transfer. *Quarterly Journal of the Royal Meteorological Society* 106(447): 85–100.

Weltzin, J.F., Bridgham, S.D., Pastor, J., Chen, J. and Harth, C., 2003. Potential effects of warming and drying on peatland plant community composition. *Global Change Biology* 9(2): 141–151.

Wilson, D., 2008. Death by a thousand cuts: small-scale peat extraction and the Irish peatland carbon store. In Farrell, C.A. and Feehan, J. (eds), *After Wise Use – The Future of Peatlands*. Proceedings of the 13th International Peat Congress. International Peat Society (Finland), Tullamore (Ireland), pp. 700–704.

Wilson, D., Alm, J., Laine, J., Byrne, K.A., Farrell, E.P. and Tuittila, E.-S., 2009. Rewetting of cutaway peatlands: are we re-creating hot spots of methane emissions? *Restoration Ecology* 17(6): 796–806.

Wind-Mulder, H.L., Rochefort, L. and Vitt, D.H., 1996. Water and peat chemistry comparisons of natural and post-harvested peatlands across Canada and their relevance to peatland restoration. *Ecological Engineering* 7: 161–181.

Worrall, F., Burt, T.P., Rowson, J.G., Warburton, J. and Adamson, J.K., 2009. The multi-annual carbon budget of a peat-covered catchment. *Science of the Total Environment* 407(13): 4084–4094.

Wu, J., Roulet, N.T., Sagerfors, J. and Nilsson, M.B., 2013. Simulation of six years of carbon fluxes for a sedge-dominated oligotrophic minerogenic peatland in northern Sweden using the McGill Wetland Model (MWM). *Journal of Geophysical Research – Biogeosciences* 118(2): 795–807.

Xu, X., Liu, W., Zhang, C. and Kiely, G., 2011. Estimation of soil organic carbon stock and its spatial distribution in the Republic of Ireland. *Soil Use and Management* 27(2): 156–162.

Yurova, A., Wolf, A., Sagerfors, J. and Nilsson, M., 2007. Variations in net ecosystem exchange of carbon dioxide in a boreal mire: modeling mechanisms linked to water table position. *Journal of Geophysical Research Biogeosciences* 112(G2).

Zenone, T., Zona, D., Gelfand, I., Gielen, B., Camino.-Serrano, M. and Ceuleman, R., 2016. CO_2 uptake is offset by CH_4 and N_2O emissions in a poplar short-rotation coppice. *Global Change Biology Bioenergy* 8(3): 524–538.

Zwicke, M., Alessio, G A., Thiery, L., Falcimagne, R., Baumont, R., Rossignol, N., Soussana, J.F. and Picon-Cochard, C., 2013. Lasting effects of climate disturbance on perennial grassland above-ground biomass production under two cutting frequencies. *Global Change Biology* 19(11): 3435–3448.

Abbreviations

BP	Before present
C	Carbon
CH_4	Methane
CO_2	Carbon dioxide
DOC	Dissolved organic carbon
EC	Eddy covariance
EPA	Environmental Protection Agency
eq	Carbon dioxide equivalent
ER	Ecosystem respiration
$F_{re,night}$	Night-time respiration
GEP	Gross Ecosystem Production
GHG	Greenhouse gas
GPP	Gross primary productivity
GWP	Global warming potential
H	Sensible heat fluxes
IAV	Interannual variation
ICOS	Integrated Carbon Observation System
LAI	Leaf area index
LE	Latent heat fluxes
masl	Metres above sea level
N	Nitrogen
N_2O	Nitrous oxide
NBP	Net biome production
NEE	Net Ecosystem Exchange
NGHGE (NGE)	Net greenhouse gas exchange
NPP	Net ecosystem productivity
POC	Particulate organic carbon
Q_{PAR}	Photosynthetic active radiation
R^2	Coefficient of determination
R_{animal}	Respiration from the grazing animal
R_E	ER rate
R_h	Heterotrophic respiration
RMSE	Root mean squared error
R_n	Net radiation
SOC	Soil organic carbon
SRC	Short rotation coppice
UCC	University College Cork
WTL	Water table level
x_f	Fetch length requirement

Appendix 1

Recent UCC PhD Theses Funded by the EPA on Carbon Fluxes

1. Anna Laine – (2007): Carbon Gas Fluxes in an Irish Lowland Blanket Bog.
2. Matteo Sottocornola – (2007): Four Years of Observations of Carbon Dioxide Fluxes, Water and Energy Budgets, and Vegetation Patterns in an Irish Atlantic Blanket Bog.
3. Ann-Kristin Koehler – (2010): The Carbon Balance of a Blanket Peat Catchment.
4. Mikhail Mishurov – (2010): Nitrous Oxide Flux Evaluation by Eddy Covariance.
5. Rashid Rafique – (2011): Measurements and Modelling of Nitrous Oxide Emissions from Irish Grasslands.
6. Michael Wellock – (2011): The Impact of Afforestation on the Carbon Stocks of Irish Soils.
7. Ciaran Lewis – (2013): Measurement and Modelling of Soil Hydrological Properties for use in the Distributed Rainfall Runoff Model – GEOtop.

Key Papers Based on Hydromet Research on Carbon and Nitrogen Fluxes

Yang, J., Xu, X., Liu, M., Xu, C., Luo, W., Song, T., Du, H., **Kiely**, **G**. (2016). Effects of Napier grass management on soil hydrologic functions in a karst landscape, southwestern China. *Soil and Tillage* 157: 83–92.

Papale, D., Black, T.A., Carvalhais, N., Cescatti, A., Chen, J., Jung, M., **Kiely**, **G**., Lasslop, G., Mahecha, M.D., Margolis, H., Merbold, L., Montagnani, L., Moors, E., Olesen, J.E., Reichstein, M., Tramontana, G., van Gorsel, E., Wohlfahrt, G., Ráduly, B. (2016). Effect of spatial sampling from European flux-towers for estimating carbon and water fluxes with artificial neural networks. *Journal of Geophysical Research*: *Biogeosciences*.

van Dijk, A.I.J.M., Gash, J.H., van Gorsel, E., **Kiely**, **G**., Merbold, L., Montagnani, L., Moors, E., Sottocornola, M., Varlagin Williams, C.A., Wohlfahrt, G. (2015). Rainfall interception and the coupled surface water and energy balance. *Agricultural and Forest Meteorology* 214: 402–415. Published: 15 December 2015.

Verma, M., Friedl, M.A., Law, B.E., **Kiely**, **G**., Black, T.A., Wohlfahrt, G., Moors, E.J., Montagnani, L., Marcolla, B., Toscano, P., Varlagin, A., Roupsardo, O., Cescatti, A., Arain, M.A., D'Odorico, P. *(*2015). Improving the performance of remote sensing models for capturing intra- and inter-annual variations in daily GPP: an analysis using global FLUXNET tower data. *Agricultural and Forest Meteorology* 214: 416–429. Published: 15 December 2015.

Jiang, B., Zhang, Y., Liang, S.L., Wohlfahrt, G., Arain, A.,Cescatti, A., Georgiadis, T., Jia, K., **Kiely G**., Lund, M. (2015). Empirical estimation of daytime net radiation from shortwave radiation and ancillary information. *Agricultural and Forest Meteorology* 211: 23–36. Published: 15 October 2015

Petrescu, A.M.R., Lohila, A., Tuovinen, J-P., Baldocchi, D.D., Desai, A.R., Roulet, N.T., Vesala, T., A. Johannes Dolman, Oechel, W.C., Marcolla, B., Friborg, T., Rinne, J., J. Hatala Matthes, Merbold, L., Meijide, A., **Kiely**, **G**., Sottocornola, M., Sachs, T., Zona, D., Varlagin, A., Lai, D.Y.F., Veenendaal, E., F.-Parmentier, J.W., Skiba, U., Land, M., Hensen, A., J. van Huissteden, Flanagan, L.B., Shurpali, N.J., Grünwald, T., Humphreys, E.R., M. Jackowicz-Korczynski, Aurela, M.A., Laurila, T., Grüning, C., Corradi, C.A.R., A.P. Schrier-Uijl, Christensen, T.R., Tamstorf, M.P., Mastepanov, M., Martikainen, P.J., Verma, S., Bernhofer, C., Cescatti, A. (2015).The uncertain climate footprint of wetlands under human pressure. *Proceedings of the National Academy of Sciences of the United States of America* 112(15): 4594–4599. Published: 14 April 2015.

Xia, J., Niu, S., Cias, P., Janssen, I.A., Chen, J., Amman, C., Arain, A., Blanken, P.D., Cescatti, A., Bonal, D., Buchmann, N., Curtis, P.S., Chen, S., Dong, J., Flanagan, L.B., Frankenberg, C., Georgiadis, T., Gough, C.M., Hui, D., **Kiely**, **G**., Lia, J., Lund, M., Magliulo, V., Marcolla, B., Merbold, L., Montagnani, L., Moors, E.J., Olesena, J.E., Piao, S., Raschid, A., Roupsard, O., Suyker, A.E., Urbania, M., Vaccari, F.P., Varlagin, A., Vesalajj, T., Wilkinson, M., Weng, E., Wohlfahrt, G., Yan, L., Luo, Y. (2015). Joint control of terrestrial gross primary productivity by plant phenology and physiology. *Proceedings of the National Academy of Sciences of the United States of America* 112(9): 2788–2793. Published: 3 March 2015.

Rafique, R., Kumar, S., Luo, Y., **Kiely**, **G**., Asrar, G. (2015). An algorithmic calibration approach to identify globally optimal parameters for constraining the DayCent model. *Ecological Modelling* 297: 196–200. Published: 10 February 2015.

Mallick, K., Jarvis, A., Wohlfahrt, G., **Kiely**, **G**., *et al*. (2015). Components of near-surface energy balance derived from satellite soundings – Part 1: noontime net available energy. *Biogeosciences* 12(2): 433–451. Published: 2015.

Xu X., Liu, W., McGoff, N., Eaton, J., Leahy, P., **Kiely**, **G**. (2014). Spatial and seasonal variations of dissolved organic carbon (DOC) concentrations in Irish rivers: the importance of Hydrology and DOC sources. *Environmental Management* 53(5): 959–967. Published: May 2014.

Pratola, C., Barrett, B., Gruber, A., **Kiely**, **G**. (2014). Evaluation of a global soil moisture product from finer spatial resolution SAR data and ground measurements at Irish sites. *Remote Sensing* 6(9): 8190–8219. Published: September 2014.

Yuan, W., Cai, W., Liu, S., Dong, W., Chen, J., Arain, A., Blanken, P.D., Cescatti, A., Wohlfahrt, G., Georgiadis, T., Genesio, L., Gianelle, D., Grelle, A., **Kiely**, **G**., Knohl, A., Liu, D., Marek, M., Merbold, L., Montagnani, L., Panfer, O., Peltoniemi, M., Rambal, S., Raschi, A., Varlagin, A., Xia, J. (2014). Vegetation-specific model parameters are not required for estimating gross primary production. *Ecological Modelling* 292: 1–10. Published: 24 November 2014.

Jozsa, J., **Kiely**, **G**., Borthwick, A.G.L. (2014). Sediment flux and its environmental implications. *Journal of Environmental Informatics* 24(2): 111–120. Published: December 2014.

Song, B., Niu, S., Luo, R., Luo, Y., Chen, J., Yu, G., Olejnik, J., Wohlfahrt, G., **Kiely**, **G**., Noormets, A., Montagnani, L., Cescatti, A., Magliulo, V., Law, B.E., Lund, M., Varlagin, A., Raschi, A., Peichl, M., Nilsson, N.B., Merbold, L. (2014). Divergent apparent temperature sensitivity of terrestrial ecosystem respiration. *Journal of Plant Ecology* 7(5): 419–428. Published: October 2014.

Wellock, M.L., Rafique, R., LaPerle, C.M., Peichl, M., **Kiely**, **G**. (2014). Changes in ecosystem carbon stocks in a grassland ash (Fraxinus excelsior) afforestation chronosequence in Ireland. *Journal of Plant Ecology* 7(5): 429–438. Published: October 2014.

Yuan, W., Cai, W., Xia, J., Che, J., Liue, S., Donga, W., Merbold, L., Law, B., Arain, A., Beringer, J., Bernhofer, C., Black, A., Blankenl, P.D., Cescatti, A., Chen, Y., Francois, L., Gianelle, D., Janssens, I.A., Jung, M., Kato, T., **Kiely**, **G**., Liu, D., Marcolla, B., Montagnani, L., Raschi, A., Roupsard, O., Varlagin, A., Wohlfahrt, G. (2014). Global comparison of light use efficiency models for simulating terrestrial vegetation gross primary production based on the La Thuile database. *Agricultural and Forest Meteorology* 192: 108–120. Published: 15 July 2014.

Mallick, K., Jarvis, A., Wohlfahrt, G., **Kiely**, **G**., Hirano, T., Miyata, A., Yamamoto, S., Hoffmann, L. (2014). Components of near-surface energy balance derived from satellite soundings – Part 2: noontime latent heat flux. *Biogeosciences* 11(24): 7369–7382. Published: 2014.

Kuppel, S., Peylin, P., Maignan, F., Chevallier, F., **Kiely**, **G**., Montagnani, L., Cescatti, A. (2014). Model–data fusion across ecosystems: from multisite optimizations to global simulations. *Geoscientific Model Development* 7(6): 2581–2597. Published: 2014.

Verma, M., Friedl, M.A., Richardson, A.D., **Kiely**, **G**., Cescatti, A., Law, B.E., Wohlfahrt, G., Gielen, B., Roupsard, O., Moors, E.J., Toscano, P., Vaccari, F.P., Gianelle, D., Bohrer, G., Varlagin, A., Buchmann, N., van Gorsel, E., Montagnani, L., Propastin, P. (2014). Remote sensing of annual terrestrial gross primary productivity from MODIS: an assessment using the FLUXNET La Thuile dataset. *Biogeosciences* 11(8): 2185–2200. Published: 2014.

McVeigh, P., Sottocornola, M., Foley, N., Leahy, P., **Kiely**, **G**. (2014). Meteorological and functional response partitioning to explain the interannual variability of CO_2 exchange at an Irish Atlantic Blanket Bog. *Agriculture and Forest Meteorology* 194: 8–19.

Kim, D.G., Rafique, R., Leahy, P., Cochrane, M., **Kiely**, **G**. (2014). Estimating the impact of changing fertilizer use, land-use and climate on nitrous oxide emission in Irish agricultural lands. *Plant and Soil* 374(1–2): 55–71**.**

Wellock, M., Rafique, R., LaPerle, C., Peichl, M., **Kiely**, **G**. (2013). Changes in ecosystem carbon stocks in a grassland-ash afforestation chronosequence in Ireland. *Plant Ecology*. Published: December 2013.

Lewis, C., Albertson, J., Zi, T., **Kiely**, **G**. (2013). How does afforestation affect the hydrology of a blanket peatland? A modelling study. *Hydrological Processes* 27(25): 3577–3588. Published: 15 December 2013.

Chen, T., Chen, B., Black, A., **Kiely**, **G**., Hirano, T., Wolhfart, G. (2013). Comparison of terrestrial evapotranspiration estimates using the mass transfer method and the Penman-Monteith equation in lands surface models. *Journal of Geophysical Research Biogeosciences* 118: 1–17.

Lewis, C., Rafique, R., Foley, N., Leahy, P., Morgan, G., Albertson, J., Kumar, S., **Kiely**, **G**. (2013). Seasonal export of Phosphorus from intensively fertilised nested grassland catchments. *Journal of Environmental Sciences* 25(9): 1847–1857.

Ludlow, F., Stine, A.R., Leahy, P., Murphy, E., Mayewski, P.A., Taylor, D., Killen, J., Baillie, M.G.L., Hennessy. M., **Kiely**, **G**. (2013). Mediaeval Irish chronicles reveal persistent volcanic forcing of severe winter cold events, 431–1649 CE. *Environmental Research Letters* 8.

Khalil, M.I., **Kiely**, **G**., O'Brien, P., Müller, C. (2013). Organic carbon stocks in agricultural soils in Ireland using combined empirical and GIS approaches. *Geoderma* 193: 225–235. Published: February 2013.

Peichl, M., Sonnentag, O., Wohlfahrt, G., Baldocchi, D.D., Flanagan, L.B., **Kiely**, **G**., Galvagno, M., Gianelle, D., Marcolla, B., Pio, C., Migliavacca, M., Jones, M.B., Saunders, M. (2013). Convergence of potential net ecosystem production among contrasting C_3 grasslands. *Ecology Letters* 16: 502–512. Published: April 2013, 10.1111/ele.12075.

Stoy, P., Mauder, M., Foken, T., Marcolla, B., Boegh, E., Ibrom, A., Arain, M.A., Arneth, A., Aurela, M., Bernhofer, C., Cescatti, A., Dellwik, E., Duce, P., Gianelle, D., van Gorsel, E., **Kiely**, **G**., Knohl, A., Mangolis, H., McCaughey, H., Merbold, L., Montagnani, L., Papale, D., Reichstein, M., Serrano-Ortiz, P., Sottocornola, M., Saunders, M., Spano, D., Vaccari, F., Varlagin, A. (2013). A data-driven analysis of energy balance closure across FLUXNET research sites: the role of landscape scale heterogeneity. *Agricultural and Forest Meteorology* 171–172: 137–152. Published: April 2013.

Dao, L., Morrison, L., **Kiely**, **G**., Zhang, C. (2013). Spatial distribution of potentially bioavailable metals in surface soils of a contaminated sports ground in Galway, Ireland. *Environmental Geochemistry and Health* 35; 227–238. Published: April 2013, 10.1007/s10653–012–9478–7.

Jung, M., Reichstein, M., Margolis, H.A., Cescatti, A., Richardson, A., Arain, A., Arneth, A., Bernhofer, C., Bonal, D., Chen, J., Gianelle, D., Gobron, N., **Kiely**, G., Kutsch, W., Lasslop, G., Law, B., Lindroth, A., Merbold, L. Montagnani, L., Moors, E., Papale, D., Sottocornola, M., Vaccari, F.P., Williams, C. (2012). Correction to "Global patterns of land-atmosphere fluxes of carbon dioxide, latent heat, and sensible heat derived from eddy covariance, satellite, and meteorological observations". *Journal of Geophysical Research Biogeosciences* 117: G04011. Published: December 2012, 1029/2012jg002190,2012.

Wang T., Brender, P., Ciais, P., Piao, S., Mahech, M.D., Chevallier, F., Reichstein, M., Ottlé, C., Maignan, F., Arain, A., Bohrer, G., Cescatti, A., **Kiely**, G., Law, B.E., Lutz, M., Montagnanik, L., Moors, E., Osborne, B., Panferov, O., Papale, D., Vaccari, F.P. (2012). State-dependent errors in a land surface model across biomes inferred from eddy covariance observations on multiple timescales. *Ecological Modelling* 246: 10–25 Published: 10 November 2012.

Liu, W., Xu, X., **Kiely**, **G**. (2012). Spatial variability of remotely sensed soil moisture in a temperate-humid grassland catchment. *Ecohydrology.* DOI: 10.1001/eco.254.

Xu, X., Lewis, C. Liu, W., Albertson, J.D., **Kiely**, **G**. (2012). Analysis of single-ring infiltrometer data: comparison of BEST and Wu methods. *Agricultural Water Management* 107: DOI:34–41.10.1016/j.agwat.2012.01.004. Published: May 2012.

Lewis C., John, A., Zi, T., Xu, X., **Kiely**, **G**. (2012). How does afforestation affect the hydrology of a blanket peatland? A modelling study. *Hydrological Processes.* DOI: 10.1002/hyp.9486.

Peichl, M., Carton, O., **Kiely**, **G**. (2012). Management and climate effects on carbon dioxide and energy exchanges in a maritime grassland. *Agriculture, Ecosystems and Environment* 158: 132–146. DOI: 10.1016/j.agee.2012.06.001.

Leahy, P., **Kiely**, **G**. (2012). The effect of introducing a winter forage rotation on CO2 fluxes at a temperate grassland. *Agriculture, Ecosystems and Environment* 156: 49–56. DOI:10.1016/j.agee.2012.05.001.

Lewis, C., Albertson, J., Xu, X., **Kiely**, **G**. (2012). Spatial variability of hydraulic conductivity and bulk density along a blanket peatland hillslope. *Hydrological Processes* 26(10): 1527–1537. Published: 15 May 2012, 10.1002/hyp.8252.

Rafique, R., Anex, R., Hennessey, D., **Kiely**, **G**. (2012). What are the impacts of grazing and cutting events on the N_2O dynamics in a humid temperate grassland? *Geoderma* 181: 36–44. Published: July 2012, 10.1016/j.geoderma.2012.03.006.

Niu, S., Luo, Y., Fei, S., Yuan, W., Zhang, Z., Schimel, D., Amiro, D., Ammann, A., Arain, M.A., Arneth, A., Aubinet, M., Barr, A., Beringer, J., Bernhofer, C., Black, T.A., Buchmann, N., Cescatti, A., Chen, J., Davis, K.J., Dellwik, E., Desai, A.R., Dolman, H., Drake, B.G., Francois, L., Gianelle, D., Goldstein, A., Gu, L., Helfter, C., Hirano, T., Hollinger, D.Y., Janssens, I., Jones, M., **Kiely**, G., *et al.* (2011). Thermal optimality of net ecosystem exchange of carbon over time and space. *New Phytologist* 194(3): 775–783. Published: May 2012, 10.1111/j.1469–8137.2012.04095.x.

Rebel, K., de Jeu, R., Ciais, P., Viovy, N., Piao, S., **Kiely**, **G**., Dolman, A.J. (2012). A Global analysis of satellite derived and DGVM surface soil moisture products. *HESS – Hydrology and Earth System Science* 16(3): 833–847. Published: 2012, 10.5194/hess-16–833–2012.

Peichl, M., Leava, N.A., **Kiely**, **G**. (2012). Above- and belowground ecosystem biomass, carbon and nitrogen allocation in recently afforested grassland and adjacent intensively managed grassland. *Plant and Soil* 350(1–2): 281–296. Published: January 2012, 10.1007/s11104–011–0905–9.

Groenendijk, M, Dolman, A.J., Ammann, C., Arneth, A., Cescatti, A., Dragoni, D., Gash, J.H.C., Gianelle, D., Gioli, B., **Kiely**, **G**., Knohl, A., Law, B.E., Lund, M., Marcolla, B., van der Molen, M.K., Montagnani, L., Moors, E., Richardson, A.D., Roupsard, O., Verbeeck, H., Wohlfahrt, G. (2011). Seasonal variation of photosynthetic model parameters and leaf area index from global Fluxnet eddy covariance data. *Journal of Geophysical Research-Biogeosciences* 116: G04027 2. Published: 15 December 2011, 10.1029/2011JG00174.

Jung, M., Reichstein, M., Margolis, H.A., Cescatti, A., Richardson, A., Arain, A., Arneth, A., Bernhofer, C., Bonal, D., Chen, J., Gianelle, D., Gobron, N., **Kiely**, G., Kutsch, W., Lasslop, G., Law, B., Lindroth, A., Merbold, L. Montagnani, L., Moors, E., Papale, D., Sottocornola, M., Vaccari, F.P., Williams, C. (2011). Global patterns of land-atmosphere fluxes of carbon dioxide, latent heat, and sensible heat derived from eddy covariance, satellite, and meteorological observations. *Journal of Geophysical Research* DOI:10.1029/2010JG001566. Published: September 2011.

Rafique, R., Peichl, M., Hennessey, D., **Kiely**, **G**. (2011). Evaluating management effects on nitrous oxide emissions from grasslands using the process based model DNDC. *Atmospheric Environment* DOI:10.1016/j.atmosenv.2011.07.046.

Wellock, M., Laperle, C., **Kiely**, **G**. (2011). What is the impact of afforestation on the carbon stocks of Irish mineral soils. *Forest Ecology and Management* DOI:10.1016/j.foreco.2011.07.07. [8 pages; IF 2.51]

Wellock, M., Reidy, B., Laperle, C., Bolger, T., **Kiely**, **G**. (2011). Soil carbon stocks of afforested peatlands in Ireland. *FORESTRY* 84(4): 441–451. Published: October 2011, 10.1093/forestry/cpr046.

Mishurov, M., **Kiely**, **G**. (2010). Gap-filling techniques for the annual sums of nitrous oxide fluxes. *Agriculture and Forest Meteorology.* DOI:10.1016/j.agrformet.2011.07.014.

Zhang, C., Tang, Y., Xu, X., **Kiely**, **G**. (2011). Towards spatial geochemical modelling: use of geographically weighted regression for mapping soil organic carbon contents in Ireland. *Applied Geochemistry* 26(7): 1239–1248. Published: July 2011, 10.1016/j.apgeochem.2011.04.014.

Xu, X., Liu, W., Zhang, C., **Kiely**, **G**. (2011). Estimation of soil organic carbon stock and its spatial distribution in the Republic of Ireland. *Soil Use and Management* 27(2): 156–162. Published: June 2011, doi:10.1111/j.1475–2743.2011.00342.x.

Rafique, R., Hennessy, D., **Kiely**, **G**. (2011). Nitrous oxide emission from grassland under different management systems. *Ecosystems* 14(4): 563–582. Published: June 2011, 10.1007/s10021–011–9434-x.

Asama, Z.Z., Poulsen, T.J., Nizami, A.S, Rafique, R., **Kiely**, G., Murphy, J.D. (2011). How can we improve biomethane production per unit of feedstock in biogas plants? *Applied Energy* 88(6): 2013–2018. Published: June 2011, 10.1016/j.apenergy.2010.12.036.

Xu, X., Liu, W., **Kiely**, **G**. (2011). Modeling the change in soil organic carbon (SOC) of grassland in response to climate change: effects of measured versus modeled carbon pools for initializing RothC model *Agriculture, Ecosystems and Environment* 140(3–4): 372–381. Published: March 2011, 10.1016/j.agee.2010.12.018.

Leahy, P., **Kiely**, **G**. (2011). Short duration rainfall extremes in Ireland: influence of climatic variability *Water Resources Management* 25(3): 987–1003. Published: February 2011, 10.1007/s11269-010-9737-2.

Nizami, A.S., Molander, S., Asam, Z., Rafique, R., Korres, N.E., **Kiely**, **G**., Murphy, J.D. (2011). Comparative analysis using EIA for developed and developing countries: case studies of hydroelectric power plants in Pakistan, Norway and Sweden. *International Journal of Sustainable Development and World Ecology* 18(2): 134–142. Published: 2011, 10.1080/13504509.2011.559399

Peichl, M., Leahy, P., **Kiely**, **G**. (2011). Six-year stable annual uptake of carbon dioxide in intensively managed humid temperate grassland. *Ecosystems* 14(1): 112–126. Published: January 2011, 10.1007/s10021–010–9398–2.

Koehler, A-K., Sottocornola, M., **Kiely**, **G**. (2011). How strong is the carbon sequestration of an Atlantic blanket bog. *Global Change Biology* 17(1): 309–319. Published: January 2011, 10.1111/j.1365–2486.2010.02180.x

Rafique, R., Poulsen, T.G., Nizami A-S., Asam, Z.Z, Murphy, J.D., **Kiely**, **G**. (2010). Effect of thermal, chemical and thermo-chemical pre-treatments to enhance methane production. *Energy* 35(12): 4556–45616.

Yi, C., Ricciuto, D., Li, R., Wolbeck, J., Xu, X., Nilsson, M.,…**Keily**, **G**., *et al*., (2010). Climate control of terrestrial carbon exchange across biomes and continents. *Environmental Research Letters* 5(3): 034007. DOI:10.1088/1748–9326/5/3/034007.

Sottocornola, M., **Kiely**, **G**. (2010). Energy fluxes and evaporation mechanisms in an Atlantic bog in south west Ireland. *Water Resources Research* 46: W11524. Published 2010, 10.1029/2010WR009078.

Mishurov, M., **Kiely**, **G**. (2010). N_2O flux dynamics of grassland undergoing afforestation. *Agriculture, Ecosystems and Environment* 139(1–2): 59–65.

Kim, D.G., Mishurov, M., **Kiely**, **G**. (2010). Effect of increased N use and dry periods on N2O emissions from a fertilised grassland. *Nutrient Cycling in Agroecosystems* 88(3): 397–410. DOI:10.1007/s10705–010–9365–5.

Sottocornola, M., **Kiely**, **G**. (2010). Hydrometeorological controls on the CO_2 exchange variation in an Irish blanket bog. *Agriculture and Forest Meteorology* 150(2): 287–297.

Garbulsky, M.F., Peñuelas, J., Papale, D., Ardö, J., Goulden, M.L., **Kiely**, G., Richardson, A.D., Rotenberg, E., Veenendaal, E.M., Filella, I. (2010). Patterns and controls of the variability of radiation use efficiency and primary productivity across terrestrial ecosystems. *Global Ecology and Biogeography* 19(2): 253–267.

Gilmanov, T.G., Aires, L., Barcza, Z., Baron, V.S., Belelli, L., Beringer, J., Billesbach, D., Bonal, D., Bradford, J., Ceschia, E., Cook, D., Corradi, C., Frank, A., Gianelle, D., Gimeno, C., Gruenwald, T., Guo, H.Q., Hanan, N., Haszpra, L., Heilman, J., Jacobs, A., Jones, M.B., Johnson, D.A., **Kiely**, **G**., Li, S.G., Magliulo, V., Moors, E., Nagy, Z., Nasyrov, M., Owensby, C., Pinter, K., Pio, C., Reichstein, M., Sanz, M.J., Scott, R., Soussana, J.F., Stoy, P.C., Svejcar, T., Tuba, Z., Zhou, G.S. (2010). Productivity, respiration, and light-response parameters of world grassland and agroecosystems derived from flux-tower measurements. *Rangeland Ecology and Management* 63(1): 16–39. Published: January 2010.

Xu, X., **Kiely**, **G**., Lewis, C. (2009). Estimation and analysis of soil hydraulic properties through infiltration experiments: comparison of BEST and DL fitting methods. *Soil Use and Management* 25(4): 354–361. Published: December 2009.

Sottocornola, M., Laine, A., **Kiely**, **G**., Byrne, K., Tuitilla, E.S. (2009). Vegetation and environmental variation in an Atlantic blanket bog in South-western Ireland. *Plant Ecology* 203(1): 69–81. Published: July 2009, 10.1007/s11258–008–9510–2.

Koehler, A.K., Murphy, K., **Kiely**, **G**., Sottocornola, M. (2009). Seasonal variation of DOC concentration and annual loss of DOC from an Atlantic blanket bog in South Western Ireland. *Biogeochemistry* 95(2–3): 231–242. Published: September 2009.

Hsieh, C-I., Huang, C-W., **Kiely**, **G**. (2009). Long term estimation of soil heat flux by single layer soil temperature. *International Journal of Biometeorology* 53(1): 113–123. Published: January 2009.

Laine, A., Byrne, K.A., **Kiely**, **G**., Tuittila, E-S. (2009). The short-term effect of altered water level on carbon dioxide and methane fluxes in a blanket bog. *Suoseura* 60: 65–83.

Warner, S., **Kiely**, **G**., Morgan, G., O'Halloran, J. (2009). Does quantifying the antecedent flow conditions improve stream phosphorus export estimation? *Journal of Hydrology* 387(1–2); 97–104. Published: 15 November 2009.

Kiely, **G**., Xu, X., Hsieh C-I., Leahy, P., Sottocornola, M., Laine, A., Mishurov, M., Albertson, J.D., Katul, G., Oren, R., Carton, O. (2009). CELTICFLUX: Measurement and modeling of GHG fluxes from grasslands and a peatland in Ireland. *AsiaFlux Newsletter* 28(2): 4–12. Published: March 2009.

Leahy, P., **Kiely**, **G**., Corcoran, G. (2008). Structural optimization and input selection of an artificial neural network for river level prediction. *Journal of Hydrology* 355(1–4): 192–201. Published: June 2008.

Eaton, J., McGoff, N., Leahy, P., Byrne, K., **Kiely**, **G**. (2008). Land cover change in Ireland 1851–2000. *Climatic Change* 91(3–4): 317–334. Published: December 2008, 10. 1007/s10584–008–9412–2.

Laine, A., Byrne, K.A., **Kiely**, **G**., Tuittila, E.S. (2007). Patterns in vegetation and CO_2 dynamics of a lowland blanket bog along a water level gradient. *Ecosystems* 10(5): 890–905. Published: September 2007.

Laine, A., Wilson. D., **Kiely**, **G**., Byrne, K.A. (2007). Methane flux dynamics in an Irish lowland blanket bog. *Plant and Soil* 299(1–2): 181–193. Published October 2007.

Byrne, K.A., **Kiely**, **G**., Leahy, P. (2007). Carbon sequestration determined using farm scale carbon balance and eddy covariance. *Agricultural Ecosystems and Environment* 121(4): 357–364. Published: August 2007.

Nasr, A., Bruen, M., Jordan, P., **Kiely**, **G**., Moles, R., Byrne, P. (2007). A comparison of SWAT, HSPF, and SHETRAN/GOPC for modelling phosphorus export from three Irish catchments. *Water Research* 41: 1065–1073. Published: March 2007.

Voronovich, V., **Kiely**, **G**. (2007). On the gap in the spectra of surface layer atmospheric turbulence. *Boundary Layer Meteorology* 122(1): 67–83. Published January 2007.

Lawton, D., Leahy, P., **Kiely**, **G**., Byrne, K., and Calanca, P. (2006). Modelling of net ecosystem exchange and its components for a humid grassland. *Journal of Geophysical Research Biogeosciences* 111(G4): g04013. Published: November 2006.

Jaksic, V., **Kiely**, **G**., Albertson, J., Katul, G., Oren, R. (2006). Net ecosystem exchange of grassland in contrasting wet and dry years. *Agriculture and Forest Meteorology* 139: 323–334. Published: 12 October 2006.

Laine, A., Sottocornola, M., **Kiely**, **G**., Byrne, K., Wilson, D., Tuitilla, E.S. (2006). Estimating net ecosystem exchange in a patterned ecosystem: example from a blanket bog. *Agriculture and Forest Meteorology* 138: 231–243. Published: August 29.2006.

Byrne, K., **Kiely**, **G**. (2006). Partitioning of respiration in intensely managed grassland. *Plant and Soil* 281(1–2): 281–289. Published: April 2006.

Byrne K, **Kiely**, **G**., Leahy, P. (2005). CO_2 fluxes in adjacent new and permanent temperate grasslands. *Agriculture and Forest Meteorology* 135: 82–92. Published: December 2005.

Sottocornola, M., **Kiely**, **G**. (2005). An Atlantic Blanket Bog is a modest CO_2 sink. *Geophysical Research Letters* 32(23): L23804. Published 2 December 2005.

Hsieh C-I., Leahy, P., **Kiely**, **G**., Li, C. (2005). The effect of climate perturbations on N_2O Emissions from a fertilised humid grassland. *Nutrient Cycling in Agroecosystems* 73(1):15–23. Published: September 2005.

Scanlon, T., **Kiely**, **G**., Amboldi, R. (2005). Model determination of non-point source phosphorus transport pathways in a fertilised grassland. *Hydrological Processes* 19: 2801–2814. Published: September 2005.

Hsieh C-I., **Kiely**, **G**., Birkby, A., Katul, G. (2005). Photosynthetic responses of a humid grassland ecosystem to future climate perturbations. *Advances in Water Resources* 28(9): 910–916. Published: September 2005.

Jordan, P., Menary, W., Daly, K., **Kiely**, **G**., Morgan, G., Byrne, P., Moles, R. (2005). Patterns and processes of phosphorus transfer from Irish grassland soils to rivers – integration of laboratory and catchment studies. *Journal of Hydrology* 304(1–4): 20–34. Published 10 March 2005.

Leahy, P., **Kiely**, **G**., Scanlon, T. (2004). Managed grasslands: a greenhouse gas sink or source? *Geophysical Research Letters* 31: L20507. Published October 2004.

Scanlon, T., **Kiely**, **G**., Quishi, X. (2004). A nested catchment approach for defining the hydrological controls on phosphorus transport. *Journal of Hydrology* 291(3–4): 218–231. Published: 1 June 2004.

Scanlon, T., **Kiely**, **G**. (2003). Ecosystem scale measurements of nitrous oxide fluxes for an intensely grazed, fertilised grassland. *Geophysical Research Letters* 30(16): 1852. Published: August 2003.

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú
Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil
- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce
- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol
- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn
- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta
- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch
- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas
- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta
- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil
Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

EPA Research Report 227

GHG Fluxes from Terrestrial Ecosystems in Ireland

epaResearch
Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Authors: Gerard Kiely, Paul Leahy, Ciaran Lewis, Matteo Sottocornola, Anna Laine and Ann-Kristin Koehler

Identifying Pressures

Irish grazed grasslands are a sink for carbon dioxide and a source for methane and nitrous oxide. Irish forests and pristine peatlands are sinks for carbon; however degraded peatlands are sources for carbon.

The pressures on these ecosystems include:

- increasing the animal herd on grasslands which increases land-atmosphere fluxes of methane and nitrous oxide,
- lack of adequate investment incentives to increase hardwood forestry,
- Irish peatlands are under pressure from a lack of a long-term sustainable carbon policy for the preservation of pristine peatlands and management of degraded peatlands.

Informing Policy

This research was based on research projects funded by the EPA since 2002. Regarding soil carbon sequestration, future policy initiatives to increase soil carbon sequestration should target grassland soils. These have the greatest potential to sequester carbon. Pristine peatlands in Ireland should be conserved as sinks for carbon while degraded peatlands need to be examined further to identify possible restoration and sustainable management strategies for greenhouse gas emissions and carbon stock maintenance. Forest cover in Ireland has not achieved its targets for land cover and policy measures are needed to incentivise its increase on mineral soils, thereby enhancing the carbon stock in Ireland.

Developing Solutions

Land management strategies need to be identified to enable soil carbon sequestration. For Ireland to benefit from IPCC greenhouse gas accounting methods, a national research effort is required to produce evidence-based Measurement, Reporting and Verification (MRV) of carbon sequestration in Irish soils. For peatlands, strong conservation measures are required for the remaining pristine peatlands. This will enable this land cover to remain as a sink for carbon into the future although it is expected that this sink may reduce under climate change. Cut-away and degraded peatlands need to be examined further to determine the optimum sustainable management of such lands to limit their carbon losses. Possible management strategies include allowing the water table to be raised for natural colonisation with tree species such as downy birch.

EPA Research: McCumiskey House, Richiew, Clonskeagh, Dublin 14.

Phone: 01 268 0100
Twitter: @EPAResearchNews
Email: research@epa.ie

www.epa.ie

EPA Research Webpages
www.epa.ie/researchandeducation/research/